Review

Not peer-reviewed version

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Francesco Cepolina * , Francesco Silenzi , Leonardo Cirillo , Corrado Schenone * , Matteo Zoppi

Posted Date: 1 June 2023

doi: 10.20944/preprints202306.0019.v1

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Infrared Waves and Microwaves Applied to Greenhouse Agriculture

Francesco Cepolina [1], Federico Silenzi [2], Leonardo Cirillo [1], Corrado Schenone [1,*] and Matteo Zoppi [1]

[1] Department of Mechanical, Energy, Management and Transportation Engineering, University of Genoa, Via all'Opera Pia 15a, 16100, Genoa (Italy)

[2] National Institute for Nuclear Physics - Genoa Section, via Dodecanneso 33, 16145, Genoa (Italy)

* Correspondence: corrado.schenone@edu.unige.it

Abstract: For the agricultural sector to develop sustainably in the future, progress toward more environmentally friendly technologies and methods is crucial. It is necessary to increase output while reducing the demand for energy, agrochemicals, and water resources. Although greenhouses can be utilized successfully for this purpose, significant technical advancements are required, especially when it comes to heating, to lower the use of fossil fuels and boost energy efficiency. Infrared waves and microwaves, for instance, can warm plants without having to heat the entire greenhouse volume, which takes a significant amount of energy to compensate for heat loss to the outdoor environment. In this paper, through a thorough examination of the state of the art, a general overview of novel greenhouse heating systems based on radiation is reported. First, infrared heating of greenhouses is analyzed, then the strengths and weaknesses of microwave and dielectric heating are discussed, and finally the use of microwaves for soil sterilization is examined. All outcomes suggest these irradiation-based technologies can contribute significantly to an agriculture that is energetically sustainable.

Keywords: sustainable agriculture; greenhouse; innovative heating; infrared; microwaves

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1. Introduction

In the natural world, the Sun's warmth and light help seeds to flourish. Plants absorb water and nutrients from the earth. The goal of agricultural advances has been to boost cultivar yields and quicken the growth of plants. Greenhouses are typically glass or plastic constructions made for flower and/or plant cultivation. Due to the characteristics of the material used to construct a greenhouse, it can catch and hold solar energy by making use of the so-called "greenhouse effect". To maximize this effect, it is important to consider the features of the location (direction, slope of the ground, height above sea level, presence of natural defenses), as well as the meteorological and microclimatic conditions (temperature, windiness, cloudiness, etc.).

It is also important to consider economic, climate and crop-specific requirements. Greenhouses raise the temperature of their interior by absorbing solar radiation. The glass or plastic cover material must be opaque to the radiation released by the greenhouse system bodies and transparent to the short infrared waves originating from the Sun. Inside the greenhouse, the ground is warmed by the Sun's brief waves. The ground reemits a portion of the incoming radiation with a different wavelength; the long waves travel to the atmosphere, whereas the infrared emissions are reflected by the covering materials and remain inside the greenhouse.

The energy efficiency and consumption of a modern greenhouse design is a crucial factor. Depending on the installation area and the local climatic conditions, the fuel consumption for greenhouse heating varies greatly. The energy consumption of greenhouse systems, for instance, ranges from 60 to 80 kWh/m^2 per year in the Mediterranean region to 460–930 kWh/m^2 annually in central and northern Europe. Up to 30 to 40% of the entire cost of production in Italy is accounted for by the cost of energy used to heat the greenhouse system [1]. As a result, one of the primary goals of a modern agricultural enterprise is to reduce production costs and boost production efficiency by making environmentally friendly decisions that will lower fuel consumption and CO_2 emissions, while increasing crop-cycle-energy efficiency, which is defined as the proportion between plant production, weighted according to energy and vitamin input, and the amount of primary energy fuel consumed.

A precise cost/benefit analysis is necessary to determine whether the cost of heating greenhouses during the winter months, when output is most necessary, is affordable. Greenhouse heating systems are usually powered by electricity or fossil fuels, with a significant environmental and economic footprint. Hence the need to optimize the energy behavior of greenhouses, using new techniques that allow one to maintain the advantages of this type of cultivation, while reducing energy consumption and greenhouse gas emissions.

Several types of technological enhancements have been introduced for this purpose, ranging from solar panels to geothermal, from biomass re-use to combined heat production. Solar radiation can be exploited in two different ways, depending on the technology adopted, providing both thermal and electrical energy. Thermal solar panels are used to directly employ solar energy to raise the temperature of a circulating fluid (typically water) that can be used to feed a network of pipes and radiators to heat air directly inside greenhouses. Regarding the performance of a solar thermal panel and its application to a greenhouse compartment, it is calculated, in absolute value, that in Italy the thermal energy provided by an area equal to 10 percent of the protected area (greenhouse) can cover up to 30 percent of the heat requirement needed to maintain the crop during the winter night period [2].

Photovoltaic (PV) panels, mounted on a greenhouse, remove much of the natural illumination provided by the Sun, which is essential for plant growth, thus limiting the maximum area on which panels can be installed. To tackle this problem, semi-transparent modules allow the production of electricity without impairing crop growth, according to [3]. Thompson et al. present the advantages of the so-called agrivoltaics, which involves growing crops and generating electricity through solar panels on the same land. This study introduces the use of tinted solar panels to optimize the selective utilization of light wavelengths and improve biomass production. The findings suggest that adopting agrivoltaics with tinted solar panels can bring financial gains and environmental benefits without compromising agricultural production.

Geothermal energy is mainly used in greenhouses in a form of low enthalpy, even though high temperature geothermal energy is exploited [4] in specific areas. Low enthalpy geothermal energy typically involves the installation of a closed-loop geo-thermal system, which consists of a network of pipes that are buried in the ground and filled with a heat transfer fluid (usually water mixed with antifreeze). The fluid circulates through the pipes and absorbs heat from the ground in winter, providing heating for greenhouses. It can also be combined with other renewable energy technologies, such as solar panels and heat pumps, to provide a comprehensive and sustainable energy solution.

Biomasses often refer to vegetable organic materials the primary utilization of which is the production of energy via combustion processes. It is possible to use the vegetable wastes coming from the cultivation of soil itself as biomass, hence from greenhouse cultivation. The energy produced can be thermal (direct or indirect production of a hold fluid that can be used to feed a heating system) or it can be electrical if the thermal energy is used to produce steam which is then used to operate standard steam cycles. It is estimated that 3 to 4 kilograms of wood-cellulose material are enough to replace 1 kilogram of diesel fuel for the thermal conditioning of a greenhouse [5].

Cogeneration refers to the combined production of electricity and heat in a cascade, in a single plant, with better efficiency with respect to a traditional electric and thermal separated generation system. Growers who have this technology generally sell the electricity produced thereby fully recouping the investment made on gas and use the thermal energy, at virtually no cost, to heat the greenhouses. It is estimated that in the Netherlands, the country where the use of this technology is most advanced, about 2.6 trillion kilowatt hours of electricity produced by farmers through Combined Heat and Power (CHP) plants were sold in 2006 [1].

Among the various technologies aimed at increasing the energy efficiency of greenhouses, the application of infrared waves and microwaves appears to be very promising. This is thanks to the great flexibility of use and the possibility of combining different functions, such as that of soil sterilization. Besides, radiative heating would permit, at least at a theoretical level, a tuning of energy based on the growth need of the plants, with a modulation of the supply capable of achieving rapid vegetation and contained consumption at the same time.

The intense progress that has recently accompanied the development of this technology deserves to be described and analyzed, in terms of both technological effectiveness and possible reductions in energy consumption in greenhouses. This is precisely the purpose of this paper, which first describes the key elements of infrared heating of greenhouses, recounting the most recent achievements of the technology, and then focuses attention on the use of microwaves. In this regard, microwave and dielectric heating for greenhouses is first examined. Then we move on to examine the use of microwaves for soil sterilization in terms of energy efficiency and pollutant reduction. Everything is then commented and discussed, to offer readers a reasoned analysis of the strengths and weaknesses of this technology in terms of energy efficiency.

2. Infrared heating of greenhouses

Infrared (IR) waves are used to heat greenhouses, for instance in far infrared, and there are already some commercial devices on the market [6]. Such a system has undergone testing in Korea to evaluate both the advantages for agriculture and the potential for energy savings. This technique is energy efficient; compared to normal technology, it provides a 30% reduction in energy consumption.

However, several aspects of this technology are still to be explored. For infrared radiation to be efficient, surfaces must be directly exposed to them. This results in an inhomogeneous process, especially when large leaf vegetal species are involved. The strength of the radiation is dispersed quite unevenly. When IR heating is employed, air temperature gradients seem to be within a tolerable range, which can be compared to the performance of conventional hot water pipe heating systems [7] to better appreciate the potential of the technology. In comparison with overhead heating pipes, employing IR resulted in a net heat consumption that was roughly 12% lower. Knies et al. present a few IR performance tests to offer a more complete framework.

Using experimental data, Kavga et al.'s theoretical model [8] evaluates the possible benefits of infrared heating in the context of protected farming. When a greenhouse was operated using forced air heating, internal air temperatures were measured to be at or above the desired level for the plants, whereas when the greenhouse was operated using infrared heating, the internal air temperature was lowered by several degrees without a corresponding drop in plant temperature. Studies conducted using the theoretical model developed indicate that using commercially available IR sources can result in energy savings of between 45 and 50%, when compared to traditional forced-air heating.

When overall losses rise, due to the greater convective heat transfer between the roof and the outside air and greater infiltration rates, these savings are expected to increase for higher wind speeds.

These savings will significantly increase with advances in IR source radiative efficiency, making infrared heating a more alluring choice. When low plants are considered, the literature claims that infrared heating appears to be a promising alternative for greenhouse heating [9]. The consistent dispersion of heat flow appears to be the primary engineering problem for tall, non-planar crops. Artificial intelligence, applied to heat control, may further improve process optimization [10].

The energy requirements for a conventional and infrared-heated greenhouse for the growing of lettuce have been examined by the Greek Department of Greenhouse Cultivations and Floriculture in Messolonghi [11]. The daily performance comparison of two greenhouses, one with an IR heating system and the other with a traditional heating system, produced findings that backed up the benefits of IR heating. The soil warms up due to the energy that is lost and not used by the plants. This phenomenon has further advantages because the ground cools more slowly than the air outside during the beginning of the night due to its thermal inertia, as evidenced by the greater energy savings during these times. The savings from an IR system are somewhat influenced by the ambient temperature. Every 1 °C drop in the outdoor temperature results in a 0.4% savings reduction, according to regression research. To estimate overall heat loss, a total actual Ua (heat transfer coefficient) may be defined.

In addition to the qualities of the structure and covering material, the coefficient Ua also depends on wind speed and to a lesser degree on the temperature of the sky, and it reaches identical values for the two greenhouses using FA (Forced Air) and IR (InfraRed) heating. Ua is also highly dependent on the outside relative humidity, which is influenced by latent heat transfers and the buildup of condensate on the wall surface. The inside-air temperature in the IR greenhouse was not as low as it had been throughout most of the heating period during the final nights of cultivation when the lettuce plants developed quickly. Surprisingly, the percentage of heating savings was unaffected by this drop in temperature. We will investigate this issue further if we have taller plants and denser canopies.

Based on a straightforward numerical model, the application of IR heating in a production-scale greenhouse has been evaluated [11].The findings show that IR savings for ambient temperatures between 6 and 10 °C vary between 35 and 41%. Since the soil area in the production greenhouse increases as a percentage of the covered area, the decrease in energy savings in the production greenhouse relative to the experimental greenhouse must be primarily attributed to an increase in soil losses as a percentage of the total. Kavga emphasizes that infrared heating is a good substitute for the conventional heating strategy and that it can significantly reduce production costs and environmental effects. This is because all available statistics support this claim.

Knies et al. evaluated the efficiency and energy usage of an infrared heating system for tulip production in comparison to a traditional hot-water heating system [12]. With infrared, the net heat consumption was around 12% lower than with an overhead pipe heating system and 6% lower than with an overhead pipe and combined crop heating system. Different tulip ripening rates resulted from the unequal distribution of radiation intensity.

In short, the various studies reported lead us to believe that there are excellent possibilities of application for infrared radiation in heating greenhouses, which will probably become increasingly common due to the development of more effective IR sources and to their use in conjunction with radiative sources to boost photosynthesis.

3. Microwave and dielectric heating

For greenhouse warming, waves with a frequency between 1 GHz and 300 GHz are of relevance. This range falls inside the Industrial, Scientific, and Medical (ISM) band, a collection of areas of the electromagnetic spectrum set aside for industrial, scientific, and medical use. Dielectric heating refers to the heating of the dielectric itself caused by an electromagnetic field. The polar molecules in the dielectric, which continuously rotate in accordance with the magnetic field’s fluctuating orientation, are what cause this phenomenon.

To comprehend the heating phenomenon, a material’s dielectric characteristics are crucial. The material’s propensity to reduce the strength of the internal electric field is measured by its dielectric permittivity. The magnetic permeability of a substance describes its propensity to become magnetized in the presence of a magnetic field. The amount of water and free charge carriers, such as salts, in an organic material, has a major impact on its dielectric characteristics. Salts reduce a material’s dielectric constant and raise the dissipated power density when added to pure water. On the other hand, low water-content organic materials have less solvent available for the salts to dissolve in, reducing the mobility of the ions and, hence reducing ionic conduction. This loss process dominates, particularly at low frequencies.

The state in which water is found directly affects its relaxation frequency, or the frequency at which the dielectric loss factor achieves a maximum:

- if the water is in a solid state, the relaxation frequency is of the order of magnitude of kHz;
- if the water is bound to the molecules of the food inside which it is located, the relaxation frequency is of the order of magnitude of MHz;
- if the water is free, the relaxation frequency is of the order of magnitude of GHz.

According to Henry et al. [13], the difference in power dissipation in organisms containing free water compared to organisms containing only bound water can be up to 10^4 times.

As opposed to traditional heating methods that use hot water, microwave heating offers a peculiar feature. Atmospheric temperature is unaffected by microwaves; they only heat the water that is present inside the plants. This enables the heating energy to be directed towards the vegetables rather than vast areas of air. Crop energy efficiency for heating can be increased using this technique. Although there is little literature on using microwaves for heating in agriculture, the results of the numerous tests that have been reported are generally consistent.

Teitel et al. [14] investigated the use of microwave radiation as a heating source to ripen tomatoes and peppers in a greenhouse cavity, focusing on the elimination of grey mold. A shielding metal cavity that measured 0.78 × 0.78 × 1.7 m was used to house the microwave devices. A polyethylene greenhouse of 2 × 2 × 2 meters contained the cavity. Plants were planted in a twin greenhouse that was heated conventionally. The plants were heated with a 500-Watt microwave source and thermostatically controlled with thermocouples. There were roughly 4 on/off cycles, as a result, every minute. The conventionally heated plants were controlled using a similar technique, but with a higher-duty cycle. The plants were heated without causing any obvious harm or increasing their vulnerability to grey mold. Microwaves can pass through the air in the greenhouse without affecting it, heating the leaves without enclosing the temperature. When compared to hot air heating, the energy needed for microwave heating was 55% less. The experiment used mature chili plants and lasted two weeks in total. After the first and second weeks, the plants were checked for damage. While the leaves quickly heat up and cool down when exposed to microwaves, the stem and fruit do not. Considering the lifespan of the developing plants, the short (two-week) test period was extremely inadequate. Because of this, it is unclear if prolonged exposure to microwaves will have any impact on the plant. The temperature range for the target plant was not given. The hot air system utilized 75% more energy than the microwave system did overall. A power-plant efficiency is between 40 and 45%, whereas a commercial system burning fuel on-site has an efficiency of around 85%.

In their investigation into the viability of heating tomato plants, Guess et al. [15] set up an experiment with the goal of contrasting the growth of tomato plants heated by microwave (MW) with two control groups: a cold control group (CC) and a hot control group (HC). The HC group received conventional hot air heating while the CC group received no heating at all. The MW group underwent additional differentiation to look at how the growth process was impacted by the spatial and temporal distribution of microwaves. A linearly polarized antenna with a gain of 9.14 dB and beamwidths of 40.6° and 98.4° in the horizontal and vertical planes was put 35 cm away from a tomato plant on a turntable. It was an antenna. A circularly polarized antenna with a gain of 10.45 dB and a horizontal and vertical beamwidth of 35° was in front of two additional plants. This antenna received a 60 W power feed. A turntable holding one plant was positioned 55 cm in front of the antenna's center line, and a static plant was positioned 55 cm away from the antenna. The plant was heated using microwaves with linear polarization, and the average temperature was 17.5 °C. The plant temperature was 21 °C because of circular polarization microwaves. The former displayed noticeably more burn damage despite the latter plant's higher power and temperature. Because no plant is precisely aligned with the electric field, circular polarization provides superior heating uniformity. However, compared to a static plant, the use of a turntable does not significantly improve the thermal homogeneity between plant components. According to the study, tomato crops can be heated and grown successfully in greenhouses using microwaves; performance is solely based on plant temperature. The experiments revealed that the hot control plants outperformed the microwave group during the growth period, however, this is not directly related to the microwave treatment as the microwave-heated plant group was, on average, cooler than the hot control group due to insufficient power.

Microwaves are more energy-efficient than traditional heating techniques. The output power of the amplifiers and the antenna gain can be controlled so that the power increases by the growth of the plant to achieve maximum efficiency. Circular polarization can prevent non-uniform heating-related damage, but further research is needed to increase microwave power absorption so that microwave-heated plants can function on a par with those conventionally heated. It would be interesting to examine the potential effects of applying an on/off duty cycle to the microwave heating system on plant development.

New free-space microwave technology is suggested by Heredia et al. [16] and demonstrated to be feasible for volumetrically heating greenhouse crops. The heating and relative homogeneity are directly impacted by the microwave frequency. At low RF frequencies, the power loss emitted by the waves is greater, and it diminishes in the microwave regime. With higher frequency, the losses rise roughly linearly. The ideal power loss density and ideal power penetration depth need to be balanced out. As the frequency rises, so too does the power loss density. The ISM band availability and the impact of wavelength on the homogeneity of field patterns inside the installation place restrictions on the choice of frequency. The ISM frequencies of 915 MHz, 2,450 MHz and 5,800 MHz offer the best compromise between power loss density and penetration depth.

Due to the huge surface area and relatively thin geometries of the various plant components, which cause thermal energy to dissipate quickly into the cooler ambient air, growing plants have significant power requirements. Since plants are particularly sensitive to temperature changes, the fundamental obstacle to heating plants using microwaves has been recognized as the non-uniformity of the electric field.

Simulations and experiments revealed that 200–300 W/m^2 of power density was needed to heat plants [15]. Plant deaths are caused by excessive cold (low power densities of 50 W/m^2 or less), or excessive heat (power densities 500 W/m^2 or above). It is difficult to achieve plant heat homogeneity; both on/off duty cycle and plant rotation techniques fail to produce the necessary effects. Using circularly polarized antennas dramatically improves heating uniformity. On trellises with similar alignment, fruit development is enhanced when linear polarization is used as opposed to horizontal polarization, but vertical growth is constrained.

The impact of prolonged microwave exposure on fir and beech trees was investigated by Schmutz et al. [17]. For three and a half years, four groups of trees were subjected to microwave radiation at 2.45 GHz at various power densities. The group exposed to the highest power density had an average temperature that was 4 °C higher than the other groups. There were no noticeable microwave effects on the plants, and plant height and canopy transparency, a characteristic used to measure forest conditions and related to the density of leaves on different trees, were all similar among the various groups. It is unknown how much the presence of microwaves may have contributed to the calcium shortage effects that were seen in the high-power density group during the experiment but that were absent at its conclusion.

One or more microwave generators are used in Huber's patented technology [18] to irradiate a space that is lined with specialized reflective material, causing multiple reflections to combine to form a complex pattern of standing waves that fill the area. It is possible to think of a 20 m^2 greenhouse coated in foil shielding reflective material as a huge microwave cavity. Inside the cavity, the soil and plants are exposed to microwave radiation. To achieve a homogeneous radiation density, the microwaves are emitted using a horn antenna (1 kW horn antenna at 2.45 GHz) and, after being reflected from the ceiling, reach the plants. An infrared sensor is used in a closed-loop feedback system to regulate the power. Carefully designed reflecting bodies in the cavity improve the uniformity of the electromagnetic field radiating the plants. Neighboring leaves exchange heat to make up for any heating inequalities. Given the difficulty of creating a homogeneous wave pattern within the cavity, it is quite difficult to set up the system for a larger greenhouse. The components of the proposed system, which must be positioned above the plant itself, also cause unpleasant physical barriers to natural light.

The University of Genoa also suggests a microwave-heated greenhouse for growing basil in a patent titled "System and method for heating greenhouses" filed on October 21, 2019 [19]. A volume above the ground is defined by a membrane that can both transmit light and reflect microwaves. The membrane works with microwave-generating equipment and their irradiation within the defined volume. It is advantageous to combine the usage of membranes or nets with ground-covering technologies that perform microwave shielding. It is important to verify that the equipment inside the greenhouse is not damaged by the microwave duty cycle [18]. By carefully selecting the system control parameters, it is feasible to transport heat to plants in a regulated manner, improving the efficiency of the transmission mechanisms in comparison with conventional hot-air systems and thereby reducing heat loss. The size of the greenhouse, the short- and long-term energy needs, the geographic location, and other logistical considerations all influence the choice of a local electricity generator. The conversion process can be made more efficient by using renewable energy sources like geothermal and wind. A cogenerator or CHP, which can produce at least two power flows—thermal power from the cooling organs, through specific exchangers, and electrical power from the generator connected to the engine—is the optimal setup. Therefore, the suggested device enables the recovery of secondary thermal energy that would otherwise be wasted, reducing the overall efficiency of the system, and having a greater negative impact on the environment and the economy [19].

While the heat can be transferred underground to the root portion of the plants, which does not require high thermal gradients but benefits from the increase in temperature, the primary electrical energy is converted into radiation capable of heating the plants. Depending on the plant species, the temperature should preferably be set in the range between 10 °C and 20 °C. Since basil plants do not produce huge or fruity ingredients, it is possible as a result to use 5.8 GHz waves. With this frequency, a shallower penetration depth is guaranteed, and less energy is released into the environment [6].

Microwave lamps are an effective approach to promote the growth of plants with high lighting requirements while also saving energy, since they can convert most of the energy into microwaves, which reduces heat dispersions in the surrounding area. This approach lowers the cooling energy requirements while maintaining ideal internal greenhouse conditions. Rice production has been tested with microwave-powered lamps [20]. The efficiency of microwave-powered lamps to accelerate rice cultivar development rate was examined through a comparative experiment. The combined output of the lights of 3.4 kW was used to illuminate a growth chamber that was around 3 m^3 in size. Rice was cultivated using four distinct cultivars in the growing chamber and outside with a 16-hour photoperiod. To compare the growth traits and grain yields, this was essential. According to the findings, microwave-illuminated plants have a dry weight that is 2–3 times higher than those that are lit by sunshine.

Studying the heat transmission of leaves exposed to microwave radiation also produced interesting findings [21]. In a closed-circuit wind tunnel, the thermal reactions of microwave-exposed leaves from several species in constant and sporadic winds have been investigated. Microwave energy from a transmitter (Model EMS, Microtron 200) operating at a frequency of 2,450 MHz was used to heat a single leaf. For example, water hyacinth leaves displayed a transient heat transfer coefficient that was around two to four times higher than tobacco leaves, and observed leaf temperatures were in good agreement with the predictions of a mathematical model. For both dry and wet leaves, there was a linear relationship between wind intermittency and equilibrium leaf temperatures.

4. Use of microwave for soil sterilization

Sterilization of soil and seeds promotes good crop growth. Microwave special molecular-level heating capabilities and the resulting enhancement they have on agri-food sciences have been thoroughly proven. One of the most promising uses of microwaves in agriculture is pest control, together with the effects on germination [22]. Microwaves have the potential to sterilize seeds, slow or prevent germination, or even change the DNA of seeds, depending on their power and exposure period.

Due to the widespread use of commercial microwave ovens, thermal disinfection with microwaves is a frequent procedure also in home gardening and horticulture. The soil is put into plastic bags that are sealed, and the temperature rise brought on by microwave radiation sterilizes it. The soil may become contaminated if the temperature increases too much due to the thermal dissociation of soil nutrients, which can lead to the creation of toxic chemical compounds. The recommended wattage is between 600 and 650 W, and the recommended exposure time is between 90 and 120 seconds. The same process can also be used to sterilize compost. Since microwaves heat water to a temperature of about 100 °C to sterilize the soil, most of this homemade treatment consists of steaming.

To deliver sufficient energy for efficient pest management at a period suitable for field activities, large power is required [23]. For instance, if a device travelling at a speed of 1 km/h needed 1,500 J/cm^2 of energy to treat a band that was 1 m broad, the microwave power delivered to the soil would be around 4,100 kW. Because there is less material to treat in the sterilization of a greenhouse, it is simpler to use electromagnetic energy effectively. To justify its cost, this treatment must, however, provide significant benefits. The main benefit that is currently noticeable is time savings.

The alleged "nonthermal" impacts of microwaves on living things have not yet been shown in full. The fatal mechanisms appear to be thermal in nature, and, in many cases, selective or differential dielectric heating can explain the reported outcomes that are attributed to "nonthermal biological consequences".

Soil microwave treatment can destroy seeds of several species, although it is solely temperature-effective [24]. A large variety of species of seedling emergence is prevented by soil microwave treatment. Of course, the effectiveness of microwave treatments depends on soil characteristics such as soil texture and moisture, as well as treatment intensity and/or duration. The soil temperature may be raised to 85 °C after 8 minutes of treatment with a 2-kW power source, and 98% fewer seedlings emerge overall than in the control group. The homogeneous temperature of the sample makes this treatment incredibly successful.

Microwave soil heating may also have an impact on abiotic soil characteristics and soil-living organisms. Such an alteration may have an indirect effect on seedling emergence. Soil microwave treatment could reduce the appearance of seedlings of invasive species by directly heating seeds and, in a subsequent phase, by altering the characteristics and functionality of the soil. There are significant inter- and even intra-species differences in seed survival and seedling emergence in response to soil warmth. The seeds of recently arrived invasive species can still germinate after being heated in a microwave. As a result, this approach may not be as effective in the long run to manage invasive species with high dispersal rates. Before using the approach in the field, it is crucial to research how soil microwave heating affects ecosystem elements serving crucial functional functions, such as some soil abiotic factors (such as pH, nutrient availability, and organic matter content).

The results of testing on a batch microwave system demonstrate the immediate impact of 915 MHz microwave treatments [25]. The microwave equipment is an 840 mm x 620 mm rotating table-equipped stainless steel 304-L chamber. It can support a maximum weight of 30 kg and a maximum volume of 154 mm by 400 mm by 250 mm. Two 5 kW generators with power ratings between 1 and 10 kW are used to create 915 MHz while cooling the magnetron using chilled water circulation. The impact of microwaves on seventeen physical, chemical, and biological characteristics of soil were examined. On alluvial soil from a grassland, four 915 MHz microwave treatments combining power and exposure time were applied using Festuca seeds as an internal reference. Festuca seed germination was entirely suppressed by two treatments, 2 kW-8 and 4 kW-4 min, which also raised the soil temperature to at least 80 °C. While elevating the temperature to 50–60 °C, the two treatments, 2 kW-4 and 4 kW-2 min, did not affect seed germination. When the 2 kW-8 min and 4 kW-4 min treatments were used, biological indicators decreased in comparison with the control. Inorganic phosphorus and dissolved organic carbon levels were likewise raised by these treatments. On the other hand, only soil samples treated with the 2 kW-4 and 4 kW-2 min treatments saw an increase in nitrate concentration.

Mahdi et al. [26] performed several experiments to assess the use of microwave radiation in soil sterilization; it was found that seed germination is beneficial at lower energy emission levels. High emission levels have the potential to harm seeds, which would essentially slow down or stop germination. The radiation dosage was increased over time, demonstrating that various effects are being produced by longer exposures to higher power rates.

Specific research has been developed to assess the microwave irradiation (MWI) effects on Chinese cabbage growth [27]. The effects of MWI on vermicast potency, plant growth, and biochemical activity in Biko seedlings were examined in the study. Microwave power output levels of 0, 100, 200, 300, 400, and 800 W were used on fresh, moist vermicasts. The amount of total aerobic plate content, nutrients, and water loss were evaluated. Although the total aerobic microbial plate count was highest for 200-W and 300-W MWI treatments, the optimum overall environment for growth was provided by 400-W treatment, followed by 800-W treatment. This result indicated an inhibiting factor with excess nutrients present and its detrimental effect on the overall growth of the cabbage plant. Plants cultivated in the fresh, moist vermicast medium showed lower growth and yield in comparison. As a result, the MWI treatment at 400 W made more nutrients bioavailable as well as other elements for better plant development and yield.

Another possible application of microwaves in agriculture strongly correlated with energy consumption is product and seed drying. Nelson [28] provides a summary of the investigation on radio frequency and microwave dielectric heating in agriculture. The cost of lower frequency Radio Frequency (RF) and microwave dielectric heating equipment with capacities large enough for the practical scale drying of most agricultural products and the energy requirements for operation have proven too high for use in practical applications. Dielectric heating has not been developed for use in practice to control insects that infest agricultural products for the same reasons.

Because seed is a high-value product and typically far lower quantities need to be handled, the application of RF and microwave dielectric heating for the treatment of seed is more economically likely to be practicable than other agricultural applications. As a result, equipment would not need to deliver as much RF power, which might lower equipment prices. The advantages of new procedures must be assessed considering costs and marketing factors, as with any commercial development. If the competitive benefits are adequate, improved quality attributes of items due to dielectric heating procedures might be enough to justify the costs connected with the RF and microwave power equipment and its operation.

5. Discussion

There are several possible uses of infrared and microwaves in agriculture, all with important implications of an energy nature Achieving the most consistent heating on exposed bodies is the key challenge when using radiative heating in greenhouses. This issue involves many different aspects and technologies.

The anisotropy of the material's dielectric characteristics is a fundamental subject that contributes to non-uniformity in the dielectric heating of organic materials. As a result, the spread of heat in various directions is intrinsically inhomogeneous. Further inhomogeneity is brought on by the electromagnetic field that the plant radiates, which is not quite uniform throughout the entire body.

A second key topic is the effect of frequency on dielectric heating. How are different species of vegetables affected by the wavelength of irradiate energy? And how is frequency spectrum relevant in achieving an effective temperature distribution? The state of the art about this subject is discussed in the following.

5.1. Uniformity of heating supply

The essential variables to obtain good results from the dielectric heating of plants are the kind and frequency of polarization used (and subsequently the wavelength). The findings of experiments to evaluate the best selection of these factors are consistent.

Electromagnetic wave polarization affects how the heat is dissipated within the dielectric. The relative location of the radiated item and the antenna affects the field created by linearly polarized waves. Strong directionality heat is produced by linearly polarized waves, which are unsuitable for growing plants. Waves that are elliptically polarized improve heat diffusion.

Finally, the best heat conformity is provided by circularly polarized waves [6]. Because circular polarization offers excellent thermal uniformity over the body, it is appropriate for heating irregular bodies whose size is noticeably larger than the others. The relative positioning of the body and the antenna is almost entirely decoupled. Circular polarization guarantees greater heating uniformity in the body and a smaller temperature range both within the body and between different samples exposed to the same field. In the case of linear polarization, the volume loss density is much higher in one direction than in the others, whereas in the case of circular polarization, the power dissipation is more similar considering different axes.

The research performed by Guess [6] demonstrates how the various tomato plant components heated up very differently. The stem approaches burning while the leaves receive relatively little heat, with hotspots where the stem and leaves are joined. Microwave power could be used to provide the leaves with the energy they need to grow properly, but doing so would cause the stem to burn.

Several tactics can be used to increase thermal uniformity, and they can affect both the plant's physical structure and the way the applied electromagnetic field is controlled.

Clearly, choosing an appropriate wavelength and, in the case of irregularly shaped items, circular polarization of the wave itself are necessary to provide good heating uniformity. According to Geedipalli et al. [29], rotating the plant and using rotating blades capable of obstructing the incident electromagnetic field results in more uniform outcomes.

Gunasekaran et al. [30,31] report how the application of a duty cycle succeeds in improving the depth to which heat reaches the same wavelength. However, this places a constraint on the maximum average temperature that the body can reach. The two proposed methods, while providing some improvement from the point of view of heating uniformity, do not seem to provide enough improvement to solve the problem. Guess [15] suggests, in order to obtain better results, that it is advisable not to work at a physical level on the plant, but at the level of control of the incident wave. It is possible to:

- control and vary the power during the different growth phases of the plant, possibly also with a feedback control system capable of controlling the latter according to the temperature.
- control and vary the wavelength of the field according to the size and state of growth of the plant.

In particular, with the onset and growth of even large fruits, it could be useful to lower the frequency of the incident field to increase the depth of heat penetration, while in the early stages, better results could be obtained by using a higher frequency, as there are no large bodies to irradiate it is possible to irradiate the bodies with two antennas positioned on opposite sides producing electric fields that are out of phase with each other.

5.2. Effect of frequency on dielectric heating

The selection of an appropriate operating frequency is of paramount importance to achieve good heating of the dielectric in question. Three fundamental quantities can be defined which are useful in understanding the effects that the variation of the frequency, with which the wave oscillates causes on how the power dissipates in the dielectric [6]:

- the attenuation factor of the wave p:
- depth at which the electric field is attenuated by a factor of 1/e.
- depth at which the power is attenuated by a factor of 1/e.

The temperature distribution resulting from heating is strongly influenced by these closely related parameters. If the penetration depth is very shallow, all the power is dissipated at the surface, causing a strong in-homogeneity in the temperature distribution. A good value of the power penetration depth for a spherical element is equal to its radius, thus guaranteeing an almost homogeneous power distribution [16].

The dielectric properties of materials, the power penetration depth, the power loss density, the wave frequency, and the wavelength are the key parameters for the evaluation of the goodness of dielectric heating.

As frequency increases, there is a higher power loss density and consequently more superficial heating of the material exposed [6]. The presence of dissolved salts increases the power dissipated at the surface and consequently decreases the heat penetration depth. Considering, for example, a frequency of 2.45 GHz (belonging to the ISM band) in pure water, where no dissolved salts are present, the power penetration depth is about 20 mm while in tomatoes the value recorded is about half that.

Based on these observations, it can be deduced that the use of waves with frequencies belonging to the infrared spectrum leads to an almost total dissipation of power at the surface level. The inside of irradiated bodies would be heated by conduction of the heat present on the surface. However, this process in organic materials is significantly slower than heating by electromagnetic waves and during this process there would be a rapid dispersion of heat into the environment by convention or radiation, making the heating system less efficient. The temperature distribution resulting from heating by infrared waves would be extremely uneven.

Using electromagnetic waves with frequencies belonging to the radio-frequency spectrum, the power penetration depth would be significantly higher than with infrared. This would ensure that the irradiated bodies are heated to an adequate depth, guaranteeing a more homogeneous temperature distribution. However, the power penetration depth is almost always greater than the largest size of the plant to be irradiated, causing energy dissipation in the air or in objects that the wave will later penetrate, lowering the overall efficiency of the system.

In addition, the radio frequency spectrum is used extensively in communication and sensor technology, and the usable ISM band is extremely limited. This leads to very high design costs due to the stringent design constraints that must be met.

Therefore, the optimal choice for agricultural applications falls within the microwave spectrum, particularly the lower frequency spectrum where the power penetration depth is approximately equal to the largest element size found in a plant. This ensures optimal results, in terms of heating uniformity and minimal energy waste [16].

The three ISM bands of possible use are the 896 MHz band (available in the UK, while the 915 MHz band is available in the USA), the 2.45 GHz band and the 5.8 GHz band. Excluding the lower frequency band because it is not universally available, from what has emerged from the literature, the optimal frequency would seem to be the 2.45 GHz band [1]. This frequency would seem to guarantee the best compromise between the depth of power penetration and the density of power dispersed in the plant.

5.3. Effect of irradiation power and time

Other aspects that must be considered include comparisons of the total energy requirements as well as the value of the time saved by quicker operations. In this sense, power and time are key parameters in applying microwaves in agriculture for all different uses: heating of plants, pest control, and soil sterilization.

The use of microwaves for sterilization and pest management relies on electromagnetic waves interacting with microorganisms that are targeted [23]. The procedure efficacy is influenced by exposure duration and power. To ensure that all germs are killed during soil sterilization, a higher power and longer exposure period are typically necessary. Overall, obtaining successful sterilization and pest control while avoiding any adverse impacts on the environment, requires finding the best power and time combination. According to the kind of organic material being sterilized and the degree of contamination, different amounts of power and time may be needed; power typically ranges from 600 W to 4 kW, while sterilization time ranges from 2 to 8 minutes. Microwave plant heating is generally performed using circular polarized field, the power typically ranges from 200 to 500 W/m2. (Table 1).

Table 1. Use of microwave in agriculture, key parameters from the literature.

Application	Power	Time	Results	Reference
Soil Sterilization	2 kW	8 min	thermal sterilization	[24]
	4 kW	4 min	thermal sterilization	[24]
Pest Control	4000 kW	device speed: 1 km/h	thermal sterilization	[23]
Invasive Plant Species Control	2 kW	8 min	thermal sterilization	[24]
	2 kW	8 min	thermal sterilization	[24]
	4 kW	4 min	thermal sterilization	[24]
Plant Heating	500 W/m^2 peak	indefinite	heating	[15]
	200–300 W/m^2	indefinite	heating	[14]

Table 1 shows power and irradiation time used for different applications. The applications considered are soil sterilization, pest and invasive species control, and heating. The results show that it is necessary to adequately select the time and power intensity to be applied to achieve the envisaged result, limiting the side effects. As regards the power, it greatly varies depending on the beneficial effect which is being pursued. Thermal sterilization requires higher power applied (up to 4,000 kW if the sterilization involves open field terrain) thus being a huge factor whenever the economics of the treatment are involved. The time of use is another essential factor that must match the power applied. In fact, even low power level can be very dangerous if applied for an incorrect amount of time. The table highlights that if heating is required, then the power output must be significantly lower than in the sterilization process. Overall, the table presents a range of applications involving the use of thermal sterilization and heating processes. The power levels, time durations, and results vary depending on the specific application. The information provided can serve as a starting point for further analysis or research on these techniques and their implications in various scientific fields.

6. Conclusions

Over the past fifty years, research on the possible use of infrared and microwave dielectric heating for a variety of agricultural applications has provided answers to many of the questions that arise when considering such uses. In particular, the employment of these technologies in heating greenhouses has been studied, where energy consumption plays a leading role both in economic terms and in terms of crop selection. It is hoped that the identification of several of these informational sources in the research investigations will be beneficial to individuals thinking about new dielectric heating applications for agricultural and especially for greenhouse cultivation.

The analysis of the state of the art enabled the following conclusions, which may help organize the upcoming experiments:

- it is possible to save between 25 and 60% of energy compared to using a conventional heating system. Estimates of such savings reported in the literature are varied and fluctuate depending on the market price of energy, but they are certainly not negligible.
- negative non-thermal effects in either the short or long term have been observed following the use of microwave plants for heating. Any problems in the growth of microwave-heated plants appear to be exclusively related to thermal problems.
- what limits the temperature attainable by the plants is the in-homogeneity of heating between different parts of the plants; some parts may come close to burning while other parts are under-heated. The main difficulty is to make the field irradiating the plants and their heating as homogeneous as possible.
- the intrinsic anisotropy of the dielectric properties of organic materials causes in-homogeneity in heating. This effect can be mitigated but there are no solutions that can eliminate it.
- it is advisable to use circularly polarized antennas to obtain the most uniform heating possible. The quality of polarization is a factor to be taken into great consideration. The heating generated by linearly polarized antennas is strongly directional.

The following specific recommendations can be outlined:

- the frequency at which the waves are propagated is a fundamental parameter for good heating uniformity. A frequency belonging to the ISM band that provides good results is 2,450 MHz. Alternatively, two other frequencies to be evaluated are 915 MHz and 5,800 MHz.
- it is estimated that the power required to achieve a temperature difference of 10 °C between room and plants is approximately 200–300 W/m^2. The power per unit area must be greater than 50 W/m^2 and less than 500 W/m^2.
- the introduction of an antenna activation duty cycle does not seem to give tangible results in terms of improving heating uniformity.
- rotation of the antennas does not seem to give tangible results in terms of improving heating uniformity.

The above shows that, in the global effort to reduce greenhouse gas emissions, irradiation-based technologies in agriculture also play a very important role. If greenhouse cultivation demands a specific energy consumption, there are suitable infrared and microwave techniques that can mitigate or even cancel the related carbon footprint. The analysis of the state-of-the-art demonstrates that this is already possible today and that radiative technologies capable of increasing energy efficiency and obtaining excellent crop yields are ready. A future can be based on these techniques in which the greenhouse becomes a zero-emission cultivation method, helping to feed man even in areas with harsh climate without altering the earth's climate.

Funding: The research has been funded by the Italian research program: "Rural Development Program 2014-2020 of the Liguria Region" M16.02 "Support for pilot projects and the development of new products, practices, processes and technologies" Agricultural sector.

Conflicts of Interest: The authors declare no conflict of interest.

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