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Review

Energizing Sustainable Agriculture: Advances in Greenhouse Heating through Microwave-Based Technologies

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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. Microwaves can warm plants without heating the entire greenhouse volume, which takes a significant amount of energy to compensate for heat loss in 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, the strengths and weaknesses of microwave 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 energetically sustainable agriculture; moreover, they can be used to increase plant comfort.

Keywords: microwaves heating; greenhouse heating; pest control; soil sterilization

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1. Introduction

The greenhouse is essential to agriculture because it offers a regulated environment that optimizes plant growth by controlling variables like temperature and humidity. Prolonged growing seasons, higher food yields, and defense against erratic weather patterns are some benefits of greenhouses. The high upfront expenses of greenhouse setup, worries about energy use, and possible environmental effects are some of the challenges they present. Greenhouses are essential for meeting the expanding food needs of the world's population despite these obstacles. In doing so, they enhance overall food security and meet the needs of a growing population. They also promote sustainable agriculture by facilitating year-round farming, increasing resource efficiency, and reducing the impact of climate change on crop output.

The goal of agricultural advances has been to boost cultivar yields and quicken the growth of crops. To support the workers, agricultural exoskeletons can be used for lifting heavy weights in the greenhouse in confined spaces and for harvesting [1]. The most important factor in agriculture is the environmental conditions, which can greatly affect crop results and yield. Greenhouses introduce the concept of "protected agriculture" by physically shielding crops from harsh environmental conditions while trying to control the temperature and humidity inside the greenhouse itself. The spectrum is divided into different regions based on wavelength [2].

Ultraviolet (UV) radiation is followed by visible light, which approximately corresponds to photosynthetically active radiation (PAR). Beyond visible light, there is near-infrared (NIR) radiation, and finally, far-infrared (FIR) radiation, which encompasses longer wavelengths associated with heat and thermal imaging. Greenhouse solar heating exploits the segregation of solar radiation into the greenhouse volume, increasing its inner temperature. A greenhouse is a structure with a roof and external surfaces made of transparent materials, i.e., glass, plastic, or nylon sheets. The cover material must be transparent to the short infrared waves coming from the Sun but not to radiation in the IR spectrum. The greenhouse effect happens because the ground is heated by the incoming short-wave radiation. It then reemits a portion of the energy acquired with a different wavelength in the infrared spectrum. Long-wave infrared radiation cannot cross the covering material, which absorbs it and eventually reemits the absorbed energy inside the greenhouse volume. While this effect benefits heat crops during colder seasons, the phenomenon is dependent on external atmospheric conditions, where sun irradiation is fundamental but relatively scarce compared to mild seasons. This explains why, over the years, the need for control of the greenhouse climatic conditions has increased. Therefore, the energy efficiency and consumption of a modern structure design are crucial factors. Often, there is a need to adopt measures to heat or cool the greenhouse. For instance, in the case of heating, depending on the installation area and local climatic conditions, the fuel consumption varies greatly: the energy consumption of greenhouse systems 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 [3]. To give a contextualized scenario, the cost of heating energy accounts for up to 30 to 40% of the entire cost of greenhouse crop agricultural production in Italy [4]. 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, defined as the proportion between plant production and primary energy consumed (either carbon fossil or renewable). The other two key parameters are the economic value of crop production and the carbon ratio.

Greenhouse heating systems are usually powered by electricity or fossil fuels, with a significant environmental and economic footprint. Hence, there is a need to optimize the energy performance of greenhouses using new technologies that allow one to maintain the advantages of this type of cultivation while reaching a more economically and environmentally sustainable equilibrium. Several types of technological enhancements have been introduced for this purpose, ranging from solar panels (thermals and photovoltaics) to geothermal [5], from biomass re-use [6] to cogeneration, infrared waves, and microwaves (frequencies mid ranges 3000 GHz and 3 GHz).

Among the various technologies aimed at increasing the energy efficiency of greenhouses, the application of microwaves appears very promising. This is thanks to the great flexibility of use and the possibility of combining different functions, such as heating or soil sterilization. Besides, microwave heating would permit, at least at a theoretical level, a tuning of energy based on the growth needs of the plants by modulating the supply capable of simultaneously achieving rapid vegetation and contained consumption.

The goal of this review is to demonstrate how far microwave technology has come in agriculture. Managing all the factors at once is challenging: farmers want to decrease their carbon footprint while minimizing running costs and keeping cheap investment costs and a dependable heating system. Research in the field of greenhouse microwave heating is still under development, making it difficult to forecast the industrial cost of the equipment. The carbon footprint can be minimized using renewable energy that powers efficient equipment. The high efficiency of microwave heating may be a smart green option (compared to burning fossil fuels) if the microwave generators are powered using "green energy" (from renewable sources). The efficiency of the energy production plant is another key parameter: for example, a fuel cell plant using cogeneration is one of the most efficient options for producing heat and electricity.

The overall saving that can be achieved using microwave technology also depends on how the electric energy is generated. A fuel cell plant is more efficient than a combustion plant [7]. Cogeneration enhances the efficiency of the combustion and fuel cell plants (Table 1).

Table 1. Comparison among combustion plant, fuel cell, and cogeneration plant.

	Combustion Plant	Fuel Cell Plant	Cogeneration Plant
Efficiency	40% to 45% A combustion power plant's efficiency is influenced by the fuel used, the plant layout, and the generation technology.	40% to 60% Fuel cells skip the combustion step and use an electrochemical method to convert fuel directly into electricity.	80% to 90% Combined heat and power (CHP) are very efficient. They concurrently produce energy and use the waste heat for other uses, like heating or cooling.
Environmental Impact	Due to the release of greenhouse gases such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter, combustion-based power plants have a significant negative influence on the environment.	Since fuel cells generate power through an electrochemical reaction rather than combustion, they have a moderate environmental impact. However, depending on the fuel used to power the fuel cell, the environmental impact may change.	Cogeneration facilities typically have a low to moderate impact on the environment. They increase overall efficiency and use less fuel to produce heat and electricity independently by using waste heat.
Fuel Flexibility	Combustion power plants rely on fossil fuels, such as coal, oil, or natural gas.	Fuel cells can run on hydrogen, natural gas, methanol, or biomass-based fuels.	Cogeneration plants often rely on conventional fuels such as fossil fuels or biomass.

A cogenerator or CHP, which can produce at least two power flows—thermal power recovered from the cooling oil through specific exchangers and electrical power from the generator connected to the engine—is the optimal choice when considering a greenhouse, as it requires heat and electricity. Therefore, the proposed system enables the recovery of secondary thermal energy that would otherwise be wasted, increasing the overall efficiency of the system [8–10]. The heat recovered can be used to produce hot water, which in turn can transfer heat to the root portion of the crops, which does not require high thermal gradients but benefits from the increase in temperature. The electrical energy produced by the CHP can be converted into microwaves capable of heating the vegetables. For example, depending on the cultivar, the leaf temperature should preferably be set between 10 °C and 20 °C, considering basil (essential for the agricultural economy in the Ligurian Region), using microwaves with a wavelength of 5.8 GHz. With this frequency, a shallower leaf penetration depth is guaranteed, and less energy is released into the environment [8]. Moreover, the control process and the design of the heating system are essential and can be optimized using the latest cutting-edge technologies, including artificial intelligence, which may further improve process optimization [11].

In this framework, the present work aims to gather most information available in the literature, organizing it in a review that shows the benefits associated with using microwave-based technologies in protected agriculture, from heating to soil disinfection and pest control, and invasive species reduction. Many available sources focus on specific topics, giving deep insights that can be too specific. The present work tries to broaden the analysis while preserving the most useful information.

To summarize, the intense progress that has recently accompanied the development of technology for microwave application in the agricultural field to greenhouse systems deserves to be described and analyzed in terms of technological effectiveness and possible energy consumption reduction. This is precisely the purpose of this paper. In this regard, after Section 1 provides the framework in which this work is developed, microwave application for greenhouse heating is analyzed in Section 2. Then, Section 3 examines the use of microwaves for soil sterilization in terms of energy efficiency and pollutant reduction. Section 4 briefly discusses the application of microwave thermal treatments for seed drying. Section 5 is dedicated to discussing the influence of the main parameters (irradiation uniformity, frequency, power, and time) to offer readers a reasoned analysis of the strengths and weaknesses of this technology. Section 6 presents a commentated summary of the presented work.

2. Microwave Heating

Heating is a crucial factor for plant development, given its direct and indirect roles. Maintaining the correct temperature avoids the growth of molds, fungi, and other pathogens, leading to increased growth and overall health of the crops. Among the available heating technologies, microwave heating generates an electric field with a magnetic field component [12]. While polarization leads to dielectric heating, conduction generates magnetic loss heating (Table 2). For greenhouse heating, waves between 1 GHz and 300 GHz are relevant.

Table 2. Microwave dielectric and magnetic heating.

	Electric Field	**Magnetic Field**
Phenomena	Polarization	Conduction
Heating	Dielectric	Magnetic loss
Parameters	• Dipolar polarization • Ionic conduction	• Eddy current, hysteresis • Resonance, residual losses

This range falls within the Industrial, Scientific, and Medical (ISM) band, a collection of electromagnetic spectrum areas dedicated to industrial, scientific, and medical use. Dielectric heating refers to the heating of the dielectric itself caused by an electromagnetic field. The polarized molecules in the dielectric, which continuously rotate by the magnetic field's fluctuating orientation, cause this phenomenon. The material's dielectric properties are also crucial; the propensity to reduce the strength of the internal electric field is measured by the 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 significantly impacts its dielectric characteristics. When added to pure water, salts reduce a material's dielectric constant and raise the dissipated power density. Conversely, organic compounds with low water content have less solvent available for the salts to dissolve, lowering ionic conduction by decreasing ion mobility. This is primarily a loss process, especially at low frequencies.

Water quantity and its physical presence in the medium state directly affect its relaxation frequency, i.e., 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 kHz order of magnitude.
- If the water is bound to the molecules of the (plant) biomass inside which it is located, the relaxation frequency is of the MHz order of magnitude [13–15].
- If the water is free, the relaxation frequency is of the GHz order of magnitude.

According to Henry et al. [16], the difference in power dissipation in organisms containing free water compared to those with only bound water can be up to 10^4 times. For instance, free water is found in fruits rich in juice (e.g., oranges, lemons, watermelon, and tomatoes), while bound water is primarily found in vegetables like cacti and pine tree needles.

Heredia et al. [17] investigated the feasibility of exploiting a combination of osmotic dehydration and microwave drying as a potential new process that could improve the quality of dried tomatoes. The authors investigated the interaction between microwaves and vegetable tissues, reporting that the dielectric properties of materials depend, amongst other factors, on the frequency of the electric field applied. To support this claim, Sun et al. [18] show that the microwave frequency directly impacts heating and its homogeneity: at low RF frequencies, the power loss emitted by the waves is greater, and it diminishes in the microwave regime, while at a higher frequency, the losses increase roughly linearly. For these reasons, the ideal power loss density and power penetration depth must be balanced. As the frequency increases, so too does the power loss density. The ISM band availability and the impact of the wavelength on the homogeneity of the field patterns inside the installation restrict the choice of frequency. Hence, the ISM frequencies of 915 MHz, 2450 MHz, and 5800 MHz offer the best compromise between power loss density and penetration depth.

Since air is transparent to microwaves, atmospheric temperature is unaffected because only the water inside the plant is heated. This allows the heating energy to be directed toward the vegetables rather than being dispersed in large volumes of air. The associated experimental results are generally consistent.

Teitel et al. [19] investigated the use of microwave radiation as a heating source to ripen tomatoes and peppers in a greenhouse cavity, focusing on eliminating grey mold. A shielding metal cavity that measured 0.78 m $\times$ 0.78 m $\times$ 1.7 m was used to house the microwave devices. A 2 m $\times$ 2 m $\times$ 2 m polyethylene greenhouse contained the cavity. The control group consisted of crops grown in an identical greenhouse heated conventionally. The plants were heated with a 500-watt microwave source and thermostatically controlled with thermocouples, resulting in roughly four on/off cycles every minute. The plants were heated without causing major damage or increasing their vulnerability to grey mold. The experiment duration was two weeks; considering the lifespan of the developing plants, the short test period was highly inadequate. The temperature range for the target crops was not indicated. From an energy point of view, the authors determined that the microwave system is ~75% more efficient than a hot air heater. A few years later, the experiment proposed by Teitel et al. [19] was replicated and enhanced by Guess et al. [20].

The authors set up an experiment to compare the growth of tomato plants heated by microwave (MW) with two control groups: a cold control group (CC) and hot control group (HC). The HC group received conventional hot air heating, while the CC group received no heating. The MW group underwent additional differentiation to assess how the spatial and temporal distribution of microwaves impact the growth process. A linearly polarized antenna (Antenna 1) with a 9.14 dB gain and beamwidths of 40.6° and 98.4° in the horizontal and vertical planes, respectively, was placed 35 cm away from a tomato plant on a rotating dish. A circularly polarized antenna (Antenna 2) with a 10.45 dB gain and a horizontal and vertical beamwidth of 35° was placed in front of two additional plants. To further test the influence of spatial distribution, one of the plants was placed on a rotating dish positioned 55 cm in front of the antenna's center line, while the other was positioned 55 cm away from the antenna, without any motion-inducing devices. Both Antenna 1 and Antenna 2 received a 60 W power feed.

The plant heated using linearly polarized microwaves showed an average temperature of 17.5 °C. The other two plants, exposed to the circularly polarized field, were maintained at an average temperature of 21 °C. The former displayed noticeably more burn damage despite the latter being exposed to higher power and temperature. This is explainable, considering that none of the plants were precisely aligned with the electric field, and circularly polarized fields provide superior heating uniformity. This also clearly shows that using a rotating dish does not significantly improve the thermal homogeneity between the considered samples. According to the study, tomato crops can be heated and grown successfully in greenhouses using microwaves, and the growth rate is solely based on plant temperature. The experiments revealed that the hot control plants outperformed the microwave group during the growth period (Figure 1); however, it must be considered that the microwave-heated plant group was, on average, cooler than the hot control group, likely due to insufficient MW power output [20].

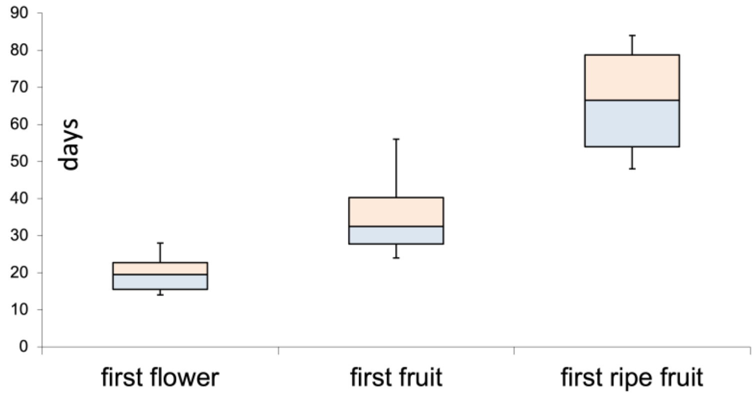

Figure 1. Growth comparison between experimental groups [20].

The output power of the amplifiers and the antenna gain can be controlled so that the power increases with the plant's growth to achieve maximum efficiency. As shown in Figure 2, circular polarization of the MW field can prevent non-uniform heating-related damage to vegetable tissues.

Figure 2. Leaf damage induced by a linearly polarized MW field.

When one considers the power requirements of microwave heating, it is necessary to keep in mind that the vast surface area and relatively thin geometries of the various morphological parts of vegetables cause the thermal energy to dissipate quickly into the environment.

Simulations and experiments revealed that a 200–300 W/m^2 power density was needed to heat plants. Plant death is caused by excessive cold (low power densities of $\leq$50 W/m^2) or excessive heat (power densities $\geq$ 500 W/m^2) [20]. To assess the potential damage induced by prolonged exposure to microwaves over a long period, Schmutz et al. [21] investigated the impact of prolonged microwave exposure on fir and beech trees. For three and a half years, four groups of trees were subjected to microwave radiation at 2.45 GHz and 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 related to leaf density on different trees—were similar among the groups. It is unknown how much microwaves may have contributed to the calcium shortage in the high-power density group during the experiment, which was not addressed in the study conclusions.

Another interesting study investigated heat transmission in leaves [22] or peels [23] exposed to microwave radiation. In a closed-circuit wind tunnel, the thermal behavior of microwave-exposed leaves from several species with constant and intermittent wind conditions was investigated. Microwave energy from a transmitter (Model EMS, Microtron 200) operating at a frequency of 2450 MHz was used to heat a single leaf. The authors investigated the heat transfer coefficient of different varieties, finding that it is dependent on the species. For instance, water hyacinth leaves displayed a two- to four-times higher transient heat transfer coefficient with respect to tobacco leaves, and leaf temperatures were in good agreement with the mathematical model predictions analyzed in the paper. The research also showed a linear relationship between wind intermittency and equilibrium leaf temperatures for dry and wet leaves. Leaves with more water were heated more by the same amount of microwaves. The Huber [24] greenhouse, heated by microwaves, is now analyzed (Figure 3)

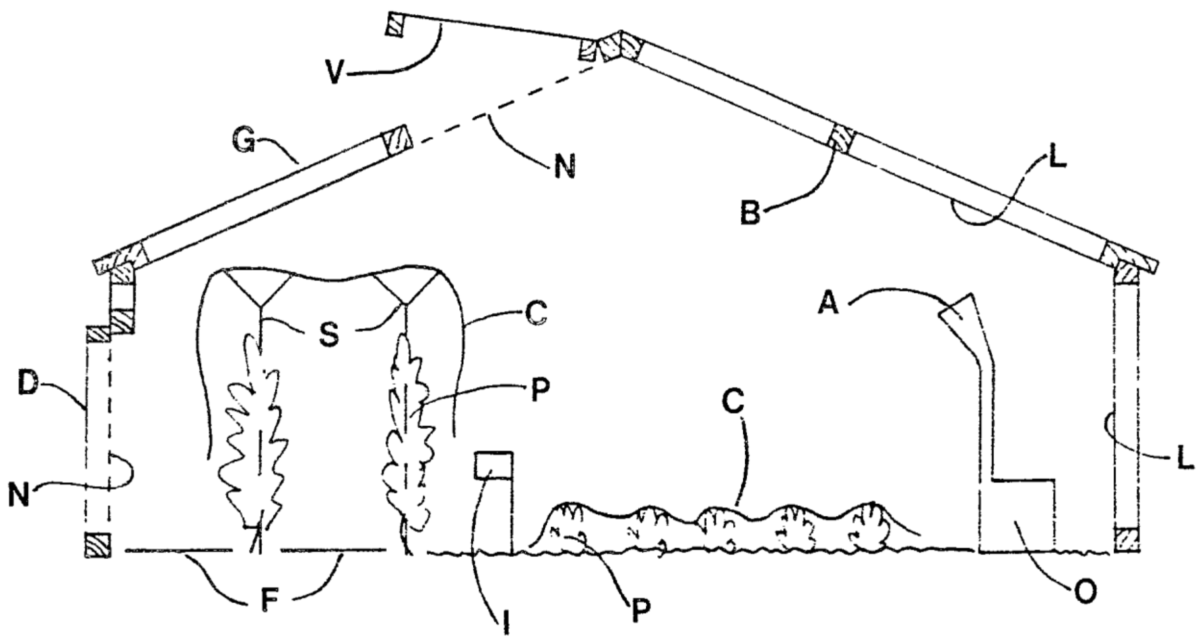

Figure 3. General system setup as proposed by Huber's patent n° GB2120065A. Meaning of letters: "D" door, "O" magnetron oscillator, "A" horn antenna, "L" reflecting liner, "G" glazing, "B" glazing bars, "V" ventilators, "N" metal mesh, "F" metal foil, "P" plants to be heated, "C" film of thin, clear, polythene sheet, "S" plant supports, "I" infra-red detector.

Crops are particularly sensitive to temperature changes. Thus, the fundamental obstacle to heating plants using microwaves has been recognized as the non-uniformity of the electric field. For this reason, Huber patented a system that aims to increase the uniformity of the microwave field, by irradiating a space lined with special reflective material, causing multiple reflections to combine and form a complex pattern of waves that fill the area.

The components adopted to create the glasshouse heating control systems are potentially subject to microwaves, heat/cold stress cycles and high humidity [25]. The major downfall of the author's proposal is that, 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 (this may be a limiting factor), and the reflected barriers proposed in the patent must be positioned above the plant causing unpleasant physical barriers to natural light.

The greenhouse's inner surfaces, coated in reflective material, can be thought of as a huge microwave cavity. 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 and the walls, the radiation reaches the crops.

An infrared sensor is used in a closed-loop feedback system to regulate the power. Huber claims that carefully designed reflecting bodies in the cavity improve the uniformity of the electromagnetic field radiating the plants; moreover, neighboring leaves exchange heat to make up for heating inequalities.

Like Huber [24], the University of Genoa proposed a microwave-heated greenhouse for growing basil in a patent titled "System and method for heating greenhouses" [8]. A sketch of the proposed system is shown in Figure 4; note that for the sake of brevity, the components listed are not extensively described.

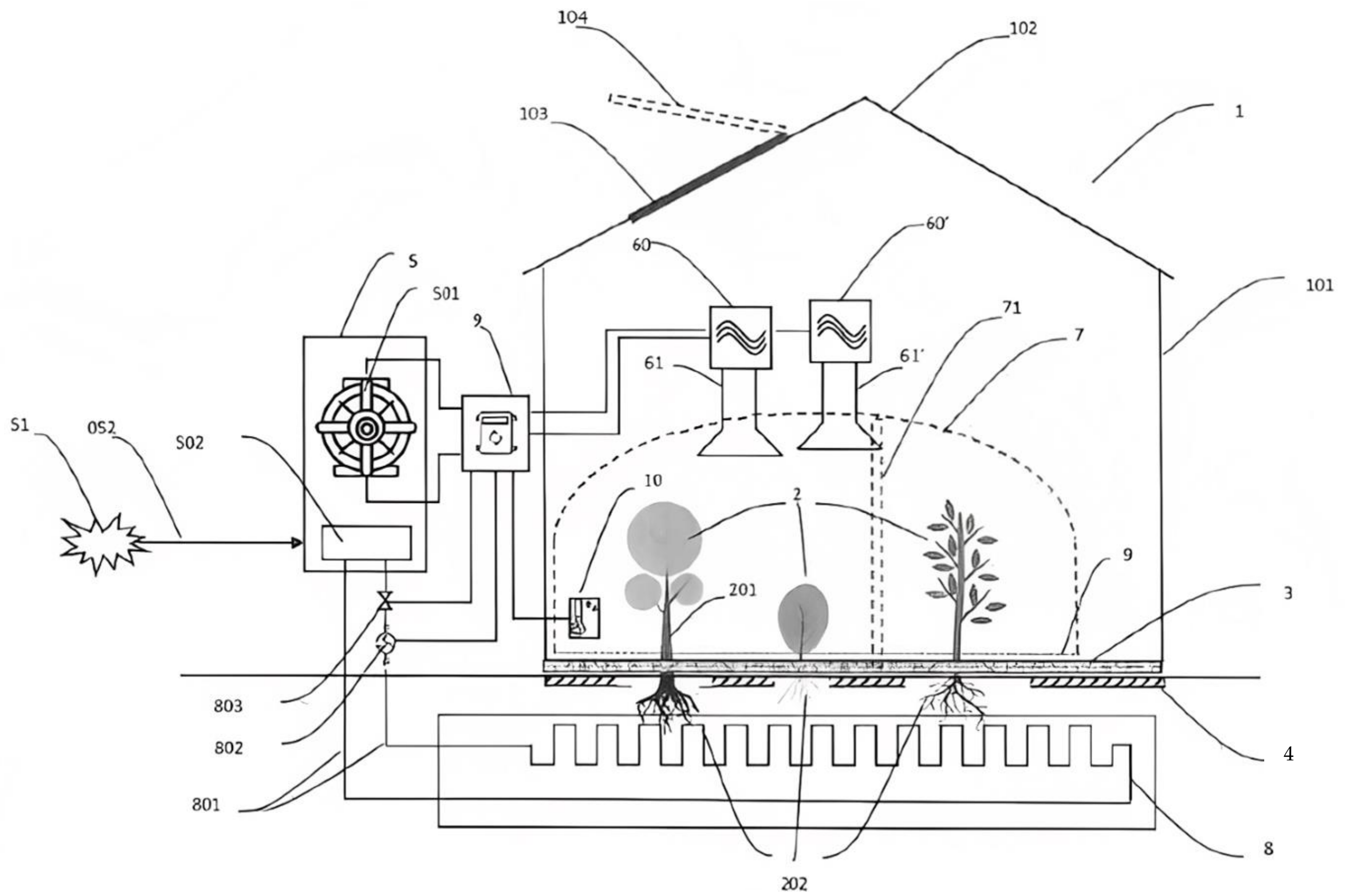

Figure 4. General system setup as proposed by Carusi et al. [8] patent n° WO2021079263A1. Meaning of symbols: "1" greenhouse, "3" soil, "4" subsoil, "101" protection structure, "102" roof, "103" opening, "104" open opening, "2" containment of plants, "201" aerial region, "202" root region, "S1" natural gas energy from anaerobic digesters, "0S2" conduits, "S" generator, "S01" electrical energy production device from natural gas, "S02" heat exchanger, "801" circulating fluid, "8" heat exchangers, "202" root regions, "2" plants. "802" hydraulic pump, "803" block valve, "60" microwave generators, "61" antenna, "10" climatic sensors, "7" membrane, "71" supports, "9" conductive sheet, "802" valve, "803" pump.

A volume above the ground is defined by a membrane that can transmit light and reflect microwaves. 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 [25]. By carefully selecting the system control parameters, it is feasible to transport heat to plants in a homogeneous way, improving the efficiency of the transmission mechanisms in comparison with conventional hot-air systems and reducing heat loss.

Another technology that can be fruitfully employed is microwave lamps, which are deemed an effective approach to promote the growth of plants with high lighting requirements. The efficiency of microwave-powered lamps that provide an intense light source for rice production has been tested in a comparative study [26], the set-up of which is sketched in Figure 5. The combined 3.4 kW output of the lights was used to illuminate a growth chamber that was ~3 m^3. Rice was cultivated using four distinct cultivars in the growing chamber and the open field with a 16-h photoperiod comparing the growth traits and crop yields. According to the findings, microwave-illuminated plants have a dry weight that is 2–3 times higher than those only exposed to sunlight.

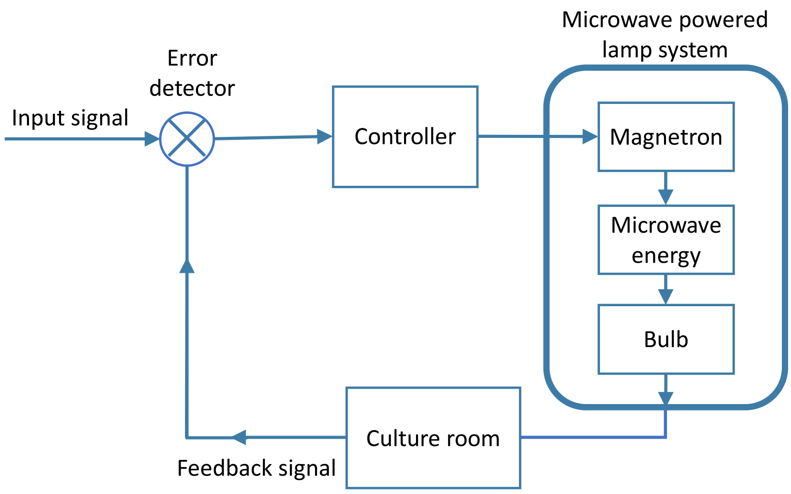

Figure 5. Experimental set-up and microwave-lamp schematic.

During photosynthesis, the plants in agricultural greenhouses solely use the visible spectrum. Plant development is impacted by the increase in greenhouse temperature brought on by the remaining solar spectrum. By absorbing the near-infrared radiation in the solar spectrum and transmitting the visible spectrum, spectrum-selective nanofluids offer an effective and long-lasting solution to this issue [27,28].

The use of microwaves in greenhouses offers benefits and limitations. Microwaves facilitate regulated settings and longer growing seasons by providing accurate dielectric heating for plant development. In comparison to traditional approaches, the experiments demonstrate potential energy savings through efficient heating with minimal damage. However, the dispersion of the electric field is not uniform, which limits scalability. Although sophisticated wave patterns and reflective surfaces are examples of innovations that attempt to address this, larger greenhouses may find it difficult to apply them. In addition, more research is necessary before widespread adoption can be achieved due to concerns about the effects of prolonged microwave exposure on plant health and possible equipment interference.

3. Use of Microwave for Soil Sterilization and Pest Control

Sterilization of soil and seeds promotes good crop growth. Microwave special molecular-level heating capabilities and their resulting enhancement on agri-food sciences have been thoroughly demonstrated. One of the most promising uses of microwaves in agriculture is pest control, which has the potential to slow down or even prevent the germination of invasive specimens [29].

At very small scales, due to the widespread use of commercial microwave ovens, thermal disinfection with microwaves is a frequent procedure used in home gardening and horticulture. The soil is put into plastic bags, sealed, and placed into the oven. When the oven is turned on, the MW radiation acts on the water in the soil and induces a temperature increment, eventually vaporizing the water. The soil may become contaminated if the temperature increases too much due to the thermal dissociation of nutrients, which can lead to the formation of toxic chemical compounds. The recommended wattage is between 600 and 650 W, and the recommended exposure time is between 90 and 120 s. The same process can also be used to sterilize compost [30]. Since microwaves heat water to ~100 °C to sterilize the soil, most of this homemade treatment consists of steaming.

When bigger scales are considered, the power and energy requests become more of a concern: large amounts of power are required to deliver sufficient energy for efficient pest management in open-field activities [31]. For instance, if a hypothetical device traveling at 1 km/h required 1500 J/cm^2 of energy to treat a 1-m broad band, the microwave power delivered to the soil would be ~4100 kW. Hence, the microwave disinfection of soil would be much more suitable for greenhouse applications because there is less material to sterilize, and the application is simpler. The alleged "nonthermal" impacts of microwaves on living things have not yet been fully shown. The fatal mechanisms appear to be thermal, and, in many cases, selective or differential dielectric heating can explain the reported outcomes attributed to "nonthermal biological consequences."

Microwave soil heating may also impact abiotic soil characteristics and soil-living organisms. Such an alteration may have an indirect effect on seedling emergence. Soil microwave treatment can reduce the appearance of invasive species seedlings by directly heating seeds and, in a subsequent phase, by altering the characteristics and functionality of the soil. There are significant inter- and intra-species differences in seed survival and seedling emergence in response to soil warmth. As a result, this approach may not be as effective in the long run for managing invasive species with high dispersal rates (i.e., specimens whose seeds can travel long distances before arriving at the germination site, like dandelions). The authors suggest that before using this approach in open-field crops, research must be conducted on how soil microwave heating affects ecosystem elements serving crucial functional functions, such as soil abiotic factors (e.g., pH, nutrient availability, and organic matter content).

Nevertheless, there is ample literature showing how pest control using microwaves is very effective, as shown by Nelson [31]. The author reported that soil microwave treatment can destroy seeds of several species due to the thermal effects induced in seeds. The seedling emergence of various species is prevented by soil microwave treatment. The effectiveness of microwave treatment depends on soil characteristics, such as soil texture and moisture, as well as treatment intensity and duration. As an example, as Nelson indicated, the soil temperature may be raised to 85 °C after 8 min of treatment with a 2-kW power source, causing up to 98% fewer seedlings to emerge than in the control group. The author suggests that the treatment is effective considering the thermophysical characteristics of the soil sample, which allows it to reach a highly homogeneous temperature profile in the treated sample.

Maynaud et al. carried out an experimental analysis aimed at investigating the effects on biological components as well as the chemical and physical characteristics of the soil. The results of a batch microwave system demonstrated the immediate impact of 915 MHz microwave treatments [32]. The microwave equipment comprised an 840 mm × 620 mm rotating chamber, with two 5 kW generators with power ratings between 1 and 10 kW used to create microwaves at a frequency of 915 MHz while cooling the magnetron using chilled water circulation. The impact of microwaves on seventeen physical, chemical, and biological soil characteristics was examined. Table 3 shows the effectiveness of the proposed treatment.

Table 3. Microwave treatment effects on microbial density and biomass compared to a control group [32].

Microwave Treatments		Microbial Biomass	Density of Total Heterotrophic Bacteria	Density of Fluorescent Pseudomonas
Power	**Time**	**mg OC/kg DS**	**log_{10} CFU/g DS**	**log10 CFU/g DS**
2 kW	4 min	223.8	7	6.5
4 kW	2 min	269.7	7.1	6.6
2 kW	8 min	114.2	6.7	4.4
4 kW	4 min	135.3	6.6	4.7
Control		342.7	7.3	6.5

Comparison between the treatment samples and controls shows that the best results were obtained with a combination of the lowest radiation power (2 kW) applied for the longest time (8 min). Overall, it is possible to infer that after the sample underwent microwave treatments, the biological indicators decreased compared to the control, up to 50% when considering the microbial biomass.

The authors also tested the effect of microwave disinfection treatment on the germination of seeds. 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 min and 4 kW/4 min, raising the soil temperature to at least 80 °C. After increasing the temperature to 50–60 °C, the two treatments (2 kW/4 min and 4 kW/2 min) did not affect seed germination. Inorganic phosphorus and dissolved organic carbon levels were likewise increased by these treatments. Only soil samples receiving the 2 kW/4 min, or 4 kW/2 min treatments saw increased nitrate concentration.

Mahdi et al. [33] performed several experiments to assess the use of microwave radiation in soil sterilization. They found that lower energy emission levels are beneficial to seed germination. High emission levels have the potential to harm seeds, which would slow down or stop germination. The radiation dosage was increased over time, demonstrating that various effects are induced by longer exposures to higher power rates.

Specific research has been developed to assess the microwave irradiation (MWI) effects on Chinese cabbage growth [34]. The effects of MWI on vermicast potency, plant growth, and biochemical activity in Biko seedlings were examined. Different microwave power output levels (0, 100, 200, 300, 400, and 800 W) were applied to 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 the 400 W treatment, followed by the 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 comparatively lower growth and yield. As a result, the MWI treatment at 400 W increased nutrient bioavailability and other elements for better plant development and yield.

By creating heat effects that stop germination, microwaves provide an efficient way to sterilize soil and seeds, especially when used for pest management. On the one hand, microwave ovens are used in home gardening on a small scale to provide effective disinfection. On the other hand, problems with energy and power requirements arise at larger sizes, making soil disinfection more appropriate for greenhouse environments. Although microwave treatment has proven effective in killing seeds and delaying the emergence of seedlings, further research is needed to determine the long-term effects on soil properties, particularly in open-field crops. Evidence indicates that thermal mechanisms predominate, notwithstanding the possibility of nonthermal effects. Microwave treatments have been shown to lower biomass and microbial density, which can impact soil health. Furthermore, studies on the growth of Chinese cabbage have revealed the ideal microwave power settings for nutrient availability and plant development.

4. Other Uses for Microwaves in Agriculture

Another possible application of microwaves in agriculture strongly correlated with energy consumption is production and seed drying. Trabelsi & Nelson [35] summarize investigations 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 drying scale of most agricultural products and the energy requirements for operation have proven too high for practical applications. Dielectric heating has not been developed to control insects that infest agricultural products for the same reasons.

Because seeds are high-value products and typically far lower quantities are handled, the application of microwave dielectric heating for seed treatment is more economical and likely practical than other agricultural applications. That is, lower RF power levels would need to be delivered, 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 sufficient to justify the costs of the RF and microwave power equipment and its operation.

Microwaves have been successfully applied for manure treatment [36–38], especially for energy harvesting processing, meaning that the MW could potentially be used for biogas production and bioenergy recovery processes to boost the sustainability of greenhouse heating further [39].

It may be possible to recover energy from animal waste to produce electricity, which in turn could be used to power MW generators or CHE generators.

Microwaves show potential in agriculture for treating manure and drying seeds. Microwave dielectric heating equipment is cost-effective for high-value seed treatment; however, it is expensive for large-scale drying. Improved qualitative features and competitive advantages are prerequisites for economic viability.

5. Discussion

There are several possible uses of microwaves in agriculture, all with important energy implications. Achieving the most consistent heating of 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 caused by the electromagnetic field that the plant radiates, which is not quite uniform throughout the body.

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

5.1. Uniformity of Heating Supply

The essential variables to obtain good results from the dielectric heating of plants are the type and frequency of polarization used and, subsequently, the wavelength. The experimental results evaluating 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 [8]. As circular polarization offers excellent thermal uniformity, it is appropriate for heating irregular bodies that are noticeably large. The relative positioning of the body and the antenna is almost entirely decoupled.

Circular polarization guarantees greater heating uniformity of the body and a smaller temperature range 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. In contrast, in the case of circular polarization, the power dissipation is more similar considering different axes.

The research performed by Guess [9] demonstrates that the various tomato plant components heat differently. The stem approaches burning while the leaves receive relatively little heat, with hotspots where the stem and leaves are joined. Microwave power can provide the leaves with the energy they need to grow properly, however, doing so will cause the stem to burn. Several tactics can increase thermal uniformity, affecting the plant's physical structure and the way the applied electromagnetic field is controlled.

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. [40], rotating the plant and using rotating blades capable of obstructing the incident electromagnetic field results in more uniform outcomes. From an industrial point of view, the authors posit that the rotation of each plant is impractical.

Gunasekaran et al. [41,42] reported how the application of a duty cycle improves the depth to which heat reaches the same wavelength. However, this places a constraint on the maximum average temperature that the body can achieve. The two proposed methods, while providing improvement from the view of heating uniformity, do not seem to provide enough benefit to solve the problem. Improper dielectric heating may lead to the burning of stems. Guess [20] suggests that to obtain better results, it is advisable not to focus on the physical level of the plant but rather on 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 plant's size and state of growth.

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, 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

Kundu et al. have studied the biological effects and potential hazards of coconuts exposed to radio frequency (RF) electromagnetic fields; a 3D model has been created to simulate the coconut behavior [43]. The selection of an appropriate operating frequency is paramount to achieve good heating of the dielectric in question. Three fundamental quantities can be defined which are useful in understanding the effects that the frequency variation causes on how the power dissipates in the dielectric [8]:

- 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;

Table 4 summarizes the dielectric constants and the dielectric loss factors of different vegetables and fruits as proposed by Venkatesh [28]. These values greatly influence how the microwave radiation interacts with the vegetable tissue and thus must be considered when the microwave antenna is designed. Moreover, the values are clearly dependent on the selected frequency.

Table 4. Dielectric constant and loss factor for different vegetables and fruits [15].

Permittivity of Fresh Fruits and Vegetables at 23.8 °C						
Fruit/Vegetable	**Moisture Content**	**Tissue Density**	**Dielectric Constant Frequency ε′**		**Dielectric Loss Factor Frequency ε″**	
name	%	g/cm^3	915 MHz	2.45 MHz	915 MHz	2.45 MHz
Apple	88	0.76	57	54	8	10
Avocado	71	0.9	47	45	16	12
Banana	78	0.4	64	60	19	18
Cantaloupe	92	0.93	68	66	14	13
Carrot	87	0.99	59	56	18	15
Cucumber	97	0.85	71	69	11	12
Grape	82	1.1	69	65	15	17
Grapefruit	91	0.83	75	73	14	15
Honeydew	89	0.95	72	69	18	17
Kiwifruit	87	0.99	70	66	18	17
Lemon	91	0.88	73	71	15	14
Lime	90	0.97	72	70	18	15
Mango	86	0.96	64	61	13	14
Onion	92	0.97	61	64	12	14
Orange	87	0.92	73	69	14	16
Papaya	88	0.96	69	67	10	14
Peach	90	0.92	70	67	12	14
Pear	84	0.94	67	64	11	13
Potato	79	1.03	62	57	22	17
Radish	96	0.76	68	67	20	15
Squash	95	0.7	63	62	15	13
Strawberry	92	0.76	73	71	14	14
Sweet potato	80	0.95	55	52	16	14
Turnip	92	0.89	63	61	13	12

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

The dielectric properties of materials, power penetration depth, power loss density, wave frequency, and wavelength are the key parameters for evaluating dielectric heating. As frequency increases, there is a higher power loss density and, consequently, more superficial heating of the exposed material [9]. The presence of dissolved salts increases the power dissipated at the surface and 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 ~20 mm, which is approximately twice that for tomatoes.

Based on these observations, it can be deduced that using waves with frequencies in the infrared spectrum leads to an almost total power dissipation 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. During this process, there would be a rapid dispersion of heat into the environment by convection or radiation, making the heating system less efficient.

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 plant to be irradiated, causing energy dissipation in the air or in objects that the wave will later penetrate, lowering the system's overall efficiency. The use of an intermediate frequency may solve the problem.

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 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 in a plant. This ensures optimal results in terms of heating uniformity and minimal energy waste [16]. Microwave heating powered by cogeneration minimizes energy, reduces the carbon footprint, and lowers operating costs. The three potentially useful ISM bands are the 896 MHz band (available in the UK, while the 915 MHz band is available in the USA), 2.45 GHz band, and 5.8 GHz band. Excluding the lower frequency band because it is not universally available, the optimal frequency seems to be the 2.45 GHz band [43]. This frequency would 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 faster operations. In this sense, power and time are key parameters when applying microwaves in agriculture for different uses (e.g., heating of plants, pest control, and soil sterilization).

The use of microwaves for sterilization and pest management relies on electromagnetic waves interacting with targeted microorganisms or insects [28]. The procedure efficacy is influenced by exposure duration and power. Overall, obtaining successful sterilization and pest control while avoiding adverse environmental impacts requires selecting the best power and time combination. According to the specific typology of organic material being sterilized and the degree of contamination, different amounts of power and time may be needed. In Table 3, a summary of the most relevant experimental results present in the literature is provided.

Table 5 shows the 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 achieve the envisaged result, limiting the side effects. Regarding the power, it greatly varies depending on the beneficial effect that is being pursued. For example, thermal sterilization requires a higher power (up to 4000 kW if the sterilization involves open-field terrain, which is not the best application for microwave sterilization), thus representing a critical factor when considering the economics of the treatment. The duration of the treatment is another essential factor that must correspond with the power applied. Even a low power level can be dangerous if applied for an incorrect amount of time, leading to economic issues. Table 3 indicates that, if heating is required, the power output must be significantly lower than in the sterilization process: microwave plant heating is generally performed using a circularly polarized field with a power request that typically ranges from 200 to < 500 W/m^2.

Table 5. Use of microwave in agriculture, key parameter values as proposed by the literature.

Application	Microwave Power	Time	Results	Reference
Soil Sterilization	2 kW	8 min	thermal sterilization	[31,44]
	4 kW	4 min	thermal sterilization	[31,44]
Pest Control	4000 kW	device speed: 1 km/h	thermal sterilization (open field)	[30]
Invasive Plant Species Control	2 kW	8 min	thermal sterilization	[44]
	2 kW	8 min	thermal sterilization	[44]
	4 kW	4 min	thermal sterilization	[44]
Plant Heating	200–300 W/m^2	indefinite	heating	[19]
	500 W	4 on/off cycles/min	heating	[18]

6. Conclusions

The subject covered by this review is broad; due to length constraints, only a limited number of publications were selected as references. Furthermore, this field of study is expanding quickly, so additional findings should be available soon. The literature reveals advancements in using microwaves for agriculture, including seed drying and manure treatment. However, challenges persist, such as high large-scale drying costs and limited practicality. Economic viability depends on competitive benefits, quality improvements, and thorough cost-benefit analyses. The impacts of microwave treatment on soil characteristics and living organisms warrant further investigation for open-field crops.

Over the past fifty years, research on the possible use of microwave dielectric heating for various agricultural applications has answered 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 in economic terms and crop selection. The identification of several of these informational sources will benefit those who wish to research new dielectric heating applications for agriculture, especially for greenhouse cultivation.

Analysis of the state of the art allows us to cast the following conclusions, which may help organize upcoming experiments:

- Considering power plant efficiency, it is possible to save between 25 and 60% of energy compared with a conventional heating system. Estimates of such savings reported in the literature vary and fluctuate depending on the market price of energy. Thus, the economic aspect must be evaluated with great care and is partially outside the scope of the present review.
- Adverse non-thermal effects in the short or long term have not been observed following the use of microwaves for heating crops. Thermal effects induce any damage to vegetable tissues, especially when poor microwave field spatial homogeneity is considered.
- The inhomogeneity of heating between different parts of the plants limits the temperature attainable by the plants; some parts may be damaged while others are under-heated. Hence, the primary challenge is to make the field irradiating the plants and their heating homogeneous.
- Thermal dishomogeneity is also intrinsic due to the anisotropy of the dielectric properties of organic materials. This effect can be mitigated, but no solutions can eliminate it.
- It is advisable to use circularly polarized antennas to obtain the most uniform heating. The quality of polarization is a factor to be closely considered. The heating generated by linearly polarized antennas is strongly directional.

The following specific recommendations are proposed:

- The frequency at which the waves are propagated is a fundamental parameter for good heating uniformity. A frequency of the ISM band that provides good results is 2450 MHz. Alternatively, 915 MHz and 5800 MHz should also be evaluated.
- 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 > 50 W/m^2 and < 500 W/m^2.
- Operating antennas on an on-off duty cycle does not provide tangible results in improving heating uniformity.
- The rotation of crops does not give tangible results in improving heating uniformity, even if it is a common practice when food heating is considered.

The state-of-the-art analysis demonstrates that it is possible to consider microwave generators as an alternative solution to traditional heating systems for greenhouse crop production. Moreover, microwaves can be exploited for disinfection and adverse species control (vegetal, insect, or microbial). From the economic point of view, there is the potential to decisively lower the energy requirements of greenhouses, given the capacity of microwaves to deliver energy directly to the leaf surface, without the need to heat all the air volume inside the greenhouse. Moreover, since microwave generators are powered by electric energy, it could be possible to integrate them with alternative and sustainable energy sources (e.g., photovoltaics) or more sustainable technologies (e.g., CHP generators). The economic analysis must be carefully carried out, given the volatility of the energy market and the instability of the world political situation. For these reasons, an accurate economic analysis is out of the scope of the present review.

As technology rapidly advances, microwave utilization in agriculture, particularly for greenhouse heating, is expected to change significantly in the years to come. Subsequent research endeavors may concentrate on optimizing economically viable large-scale drying methods. Integrating microwaves with alternative energy sources, such as photovoltaics or sustainable technologies, has the potential to improve overall efficiency and sustainability in agricultural practices.

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