Microwave for Soil Sterilization and Pest Control

Subjects: Agricultural Engineering

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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.

Keywords: microwaves heating ; pest control ; soil sterilization ; greenhouse ; energy saving ; microwaves ; heating ; sterilization ; soil ; plants

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 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][9][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].

2. 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 [12].

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 [13]. 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 [14]. 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 [14]. 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 [15]. 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.

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. [16] 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 [17]. 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.

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