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Use of Dielectric Heating in Greenhouses

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Abstract: Cogeneration helps to optimise the energy consumption in modern greenhouse systems. A cogeneration plant produces electrical and thermal energy close to the greenhouse. Thermal energy is used for heating the plants, while electric energy powers the lights. A patent from the University of Genoa proposes to use part of the electricity produced by the cogeneration system to power a low-power microwave heating system that provides additional thermal energy input to the plants. This innovative approach showcases the integration of diverse energy sources for enhanced efficiency. The project aims to create a cost-effective dielectric heating system with feasible installation expenses, underpinned by a comprehensive analysis of power requirements and electric field dynamics that are essential for optimal plant heating. Four microstrip antennas for microwave generation have been designed. Their performance has been compared. A laboratory and an industrial prototype of microwave heaters have been created. The results are discussed. The successful testing of a prototype heater in a small greenhouse environment is a significant step towards the feasibility of this heating solution. The modular heater proposed makes the product suitable for different greenhouse sizes.

Keywords: dielectric heating; cogeneration; agriculture; microwave heating

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1. Introduction

Cogeneration is a useful process that allows the exploitation of free low-temperature energy sources [1]. The international regulation introduces restrictions on the refrigerant used in heat pumps [2] to reduce the greenhouse effect. Greenhouse heating [3] can be performed using fossil fuel or renewable energy [4]. Renewable energy offers the advantage of not increasing global warming [5]. Fuel cells can be an efficient energy conversion media [6]. A smart greenhouse control can help to minimise the greenhouse's energy impact [7]. This project aims to design and test a system that is useful for reducing energy consumption and emissions in a modern greenhouse [8].

This project is focused on *basil* growth, the main ingredient of pesto dressing. *Ocinum*, commonly called *basil*, is a genus of aromatic plants including more than 60 herbaceous and shrub species, differing in form, habit, and composition of essential oils and colours. Among the various species of *Ocinum*, the most widely cultivated and used is *Ocinum Basilicum*, commonly known as *basil* or *Genovese basil*. It is a plant belonging to the *Labiatae family*, and in Liguria, reaches a height of 20–40 cm and a circumference of 30 cm. The thermal zero or vegetation zero of *basil*—the temperature value below which development processes are not activated—is at 13 °C, and the ideal temperature at which to maintain it lies between 22 and 24 °C with a minimum temperature never below 16/17 °C [9]. *Basil* grows in a protected environment in Genoa, Savona, and Imperia. It grows in the open field in the province of La Spezia. Ligurian *basil* producers keep the temperature inside their greenhouses between 16 and 22 °C in winter and between 24 and 26 °C in summer [10]. In winter, on average, between 50and 60 days pass from seeding to the first harvest, while in summer, the time is reduced to a minimum of 30 days.

Abundant and quality harvests are obtained by reducing the temperature difference between day and night of the environment and soil substrate. The plant also needs adequate

lighting and irrigation (2–4 L/m^2 of water in the soil). In the Province of Genoa, the greenhouse heating system frequently consists of diesel- or gas-fuelled hot-air generators suspended from the supporting structure of the greenhouse.

These generators allow for the even distribution of hot air, which can be further improved by connecting perforated polyethene sleeves running the lengthwise direction of the greenhouse. Such systems enable an effective remixing of air layers, by promoting a reduction in condensation of ambient moisture on leaves at night. Greenhous can be up to 7 m high. In the case of tall structures, the operator uses long tools that are heavy to carry. Cleaning panels, harvesting vegetables, and spraying phytosanitary substances can be facilitated by supporting the long-pole tools with dedicated exoskeletons [11].

This study introduces a novel approach to integrating microwave heating technology in greenhouse systems for enhanced plant growth. The research presents innovative solutions to optimise energy consumption and improve heating uniformity in modern greenhouse cultivation practises. The following partners, having different roles and expertise, are collaborating on the project:

- Department of Mechanical, Energy, Management and Transportation Engineering (DIME) of the University of Genoa,
- The Center for Agricultural Experimentation and Assistance (CeRSAA),
- The Center for Agricultural Vocational Education and Technical Assistance (CIPAT of Savona)
- The agricultural cooperative Florcoop,
- The Bertolotto Enrico horticultural enterprise.

2. Materials and Methods

Microwave heating has been selected based on its proven efficiency in providing targeted and almost uniform heat distribution, offering a distinct advantage over conventional heating approaches. Microwave heating also minimises energy consumption according to the research objective of enhancing greenhouse cultivation practises.

Several researchers have evaluated how to heat plants using infrared waves [12,13] and microwaves [14,15]. Cogeneration increases the overall efficiency, using the thermal energy generated while converting fuel to electric energy. The University of Genova suggests the use of this energy to power microwave antennas that heat the plants [16,17]. Table 1 reports a selection of the main symbols used in the manuscript.

Metallic sheets or grids protect the farmers from radiation. The plant growth substrate is maintained at an optimal temperature for plant growth (10 to 20 °C) using low-temperature thermal energy from cogeneration. The primary energy source (Figure 1, n S1), natural gas, is piped into special conduits (Figure 1, n S2) to feed a local generator (Figure 1, n S01) where the primary transformation of the energy source takes place. This transformation involves the production of heat as secondary energy, which would usually be discarded. This thermal energy is recovered through the heat exchanger (Figure 1, n S02) and is reused for heating plants.

The heat is transferred to the plant area using a special fluid circulating in ducts (Figure 1, n 801) to heat exchangers (Figure 1, n 8). The exchangers transfer the energy to the plant growth substrate. The electrical energy produced is converted into microwaves that irradiate and heat the plants. Usually, the plants are heated by the hot air coming from the heaters. In the case of microwave heating, the air remains cold and the plants are directly heated. The project objective is to design and field-test the microwave heater described in the patent.

Table 1. Nomenclature list.

Symbol	Description	Unit
ELVs	Exposure limit values	Wkg^{-1}
SAR	Specific Absorption Rate	Wkg^{-1}
f	Frequency	MHz GHz
f_r = 2.45 GHz	Resonant frequency of organic plants	MHz GHz
$f_{rc,010}$	Resonant frequency with fringing effect	MHz GHz
fr_{mn0}	Resonant frequency from cavity model	MHz GHz
f_1	Resonant frequency associated with length	MHz GHz
f_2	Resonant frequency associated with width W	MHz GHz
LA(E)	Electric field action level	Vm^{-1}
LA(B)	Magnetic field action level	μT
ϵ_r = 2.2	Dielectric constant	-
ε_{reff}	Effective constant	-
W	Optimal width of the patch	mm
ΔL	Effective length of the patch	cm
a_e	Effective radius with fringing effect	mm
H	Height of substrate	cm
L	Length of the antenna	mm
y' z'	Feed point coordinates	cm
λ	Wavelength of the signal	m
λ_0	Free-space wavelength	m
G_1, G_2	Conductance	S
Y_{in}	Total input admittance	S
X_{mn}	Zeroes of the derivative of the Bessel function	-
Q_t	Quality factor	-
P	Power of antenna	W

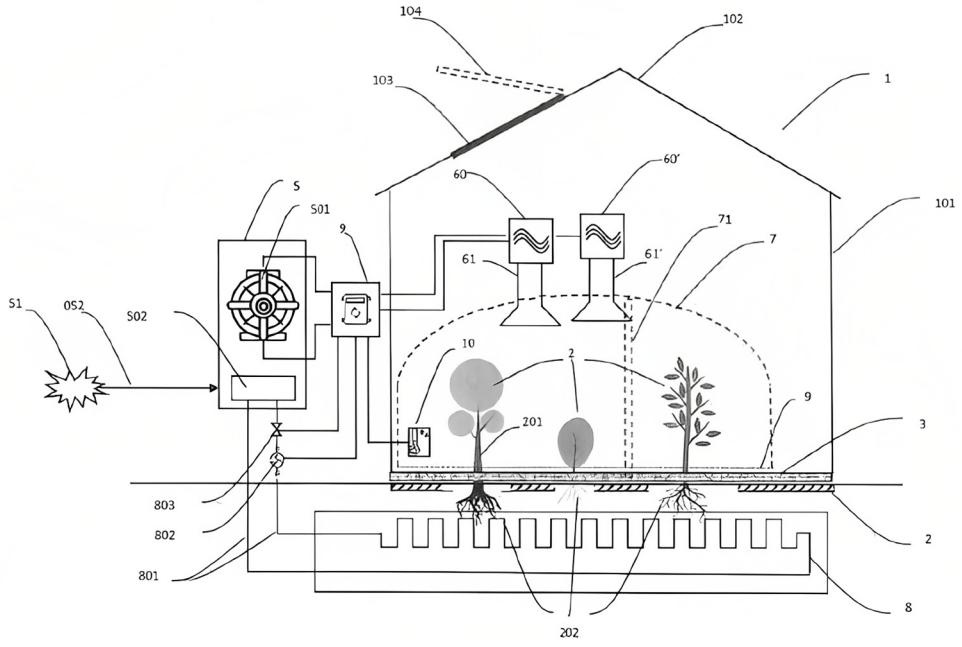


Figure 1. Greenhouse heating system and method (patent WO2021079263A1).

2.1. Health Hazards and Safety Regulations

Within the European Union, the use of electromagnetic fields that can potentially irradiate workers is regulated by Directive 2013/35/EU [18]. Paragraph 1 of Directive 89/391/EEC [19] describes the minimum requirements for workers' protection from risks to their health and safety arising, or that are likely to arise, from exposure to electromagnetic fields during work [20].

Electromagnetic waves may affect the people exposed to them. The waves may also interfere with medical devices or objects immersed in the field. Metallic or ferromagnetic objects in the field can have undesired effects. Table 2 shows the exposure limit values, relating to health effects, for frequencies between 100 kHz and 6 GHz. The specific energy absorption rate (SAR) values are averaged every six minutes.

Table 2. Human exposure limit values (ELVs) to radiation.

Exposure Limit Values (ELVs)	SAR
Whole-body heat stress ELV	0.4 Wkg^{-1}
ELV for head and trunk	10 Wkg^{-1}
ELV for the limbs	20 Wkg^{-1}

For frequencies between 0.3 and 6 GHz, the standard prescribes a localised specific energy absorption (SA) of 10 $mJkg^{-1}$. The regulation also defines the electric field LA (E) and magnetic field LA (B) action levels related to ELVs (Table 3).

Table 3. Electric field LA (E) and magnetic field LA (B) action levels.

Frequency Range	LA (E) [Vm^{-1}] (RMS)	LA (B) [μT] (RMS)
400 MHz ≤ f < 2 GHz	3×10^{-3} $f^{1/2}$	1.0×10^{-5} f
2 ≤ f <6 GHz	1.4×10^{2}	4.5×10^{-1}

The authors have created a cage with a thin metal net around the electromagnetic heater to protect the users. Field tests have proven that this solution reduces the electromagnetic field to acceptable levels.

2.2. Design of the Antenna

First, it is necessary to define the characteristics of the electromagnetic field that allow the best plant growth. Then, the type of antenna capable of producing the desired field is selected. Finally, the prototype of the microwave-heated greenhouse is created, keeping in mind the future industrial-scale implementation. Microwave waves can be generated using horns, lenses, reflectors, and microstrip antennas. The microstrip antennas have been selected as the best solution for plant heating. Four microstrip antennas have been designed (Figure 2).

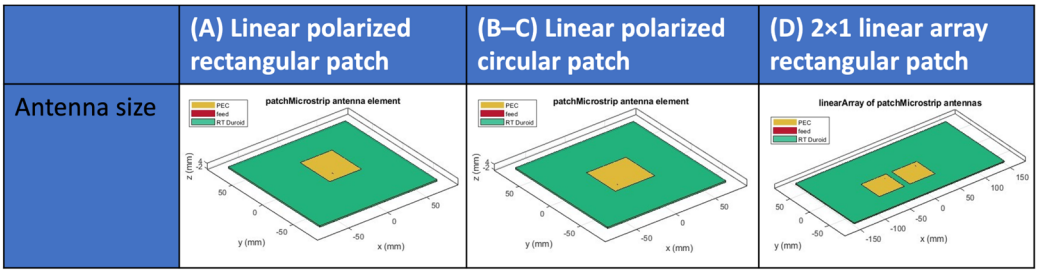


Figure 2. Size of the four microstrip microwave antennas.

Linear (antennas A and B) and circular polarisation (antennas C and D) antennas have been considered. Rectangular (antennas A, C, and D) and circular patches (antenna B) have been evaluated. An array of two circular polarised antennas has also been evaluated (antenna D).

A resonant frequency f_r = 2.45 GHz is optimal for the dielectric heating of organic plants [21,22].

All the antennas have been designed using the following substrate: RT/duroid 5880, with a height of 16 mm and a dielectric constant ϵ_r = 2.2.

2.2.1. Antenna A: Linear Polarised Circular Patch Microstrip Antenna

First, the optimal width of the patch is computed as a function of ε_r and f_r, as follows:

$$W = \frac{v_0}{2 \cdot f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} = 41.82 \text{ mm} \quad (1)$$

Then, the effective constant is computed:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot 1 + 12 \cdot \frac{h^{-\frac{1}{2}}}{W} = 2.1075 \quad (2)$$

the extension ΔL is a function of ϵ_{reff} and W, as follows:

$$\frac{\Delta L}{h} = 0.142 \cdot \frac{\left(\varepsilon_{reff} + 0.3\right) \cdot \left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right) \cdot \left(\frac{W}{h} + 0.8\right)} \quad (3)$$

Substituting the equation of the effective length of the patch:

$$\Delta L = 0.0837 \text{ cm} \quad (4)$$

in the resonant frequency equation, which considers the fringing effect, gives the following:

$$f_{rc,010} = \frac{1}{2 \cdot L_{eff} \cdot \sqrt{\varepsilon_{reff}} \cdot \sqrt{\mu_0 \cdot \varepsilon_0}} \quad (5)$$

First, the length of the patch is computed as L = 4.04 cm. Then, the conductance on the first slot is evaluated. It is equal to the conductance of the second one (Figure 3).

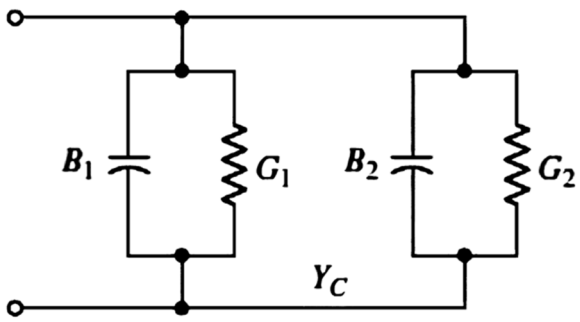


Figure 3. Transmission equivalent model for rectangular patch.

For a slot of width W, if:

$$\frac{\mathrm{h}}{\lambda_0} < \frac{1}{10} \quad (6)$$

the conductance can be computed as:

$$G_1 = G_2 = \frac{\mathrm{W}}{120} \cdot \left(1 - \frac{1}{24}\right) (k_0 \cdot h)^2 = 0.0033 \text{ S} \quad (7)$$

The total input admittance, neglecting the mutual conductance, is:

$$Y_{in} = 2 \cdot G_1 = 0.0066 \text{ S} \quad (8)$$

Therefore, the input resistance at the leading edge of the patch is R_{in} = 152 Ω.

The proposed antennas have been tested using the Antenna Designer Toolbox (ADT) from MATLAB (software version: matlab_R2022a). The antenna directivity and gain are the key features for the application considered. The ADT allowed us to maximise the

antenna gain, by selecting the optimal position of the antenna coaxial feed probe. As a simplifying hypothesis, we have imposed that all the designed antennas have no conductive or dielectric loss. For this reason, the gain is equal to the directivity. Antenna A has a peak connectivity of −4.09 dB for elevation 0 and 8.16 dB for azimuth 0.

2.2.2. Antenna B: Linear Polarised Circular Patch Microstrip Antenna

As for the case of the rectangular patch, the fringing effect makes the patch look electrically larger than it physically is. An effective radius is introduced to consider the fringing effect:

$$a_e = a \cdot \sqrt{1 + \frac{2 \cdot h}{\pi \cdot a \cdot \varepsilon_r} \cdot ln\left(\frac{\pi \cdot a}{2 \cdot h} + 1.7726\right)} \tag{9}$$

From the cavity model, it is obtained that:

$$fr_{mn0} = \frac{1}{2 \cdot \pi \cdot \sqrt{\mu \cdot \varepsilon}} \cdot \frac{X_{mn}}{a} \tag{10}$$

With X_{mn} representing the zeroes of the derivative of the Bessel function, whose first four values are 1.8412, 3.0542, 3.8318, and 4.2012. Substituting (9) in (10), for the mode, results in the following:

$$fr_{110} = \frac{1.8412 \cdot v_0}{2 \cdot \pi \cdot a_e \cdot \sqrt{\varepsilon}} \tag{11}$$

Similarly, to the case of the rectangular patch, the fringing effect makes the patch look electrically larger than it physically is. An effective radius a_e is introduced to consider the fringing effect:

$$a_e = a \cdot \sqrt{\left(1 + \frac{2 \cdot h}{\pi \cdot a \cdot \varepsilon_r}\right) \cdot ln\left(\frac{\pi \cdot a}{2 \cdot h} + 1.7726\right)} \tag{12}$$

To approximately solve (12), it is possible to compute a_e using (11) and then substitute for a_e and for an in the logarithmic function, obtaining:

$$a = \frac{F}{\sqrt{a + \frac{2 \cdot h}{\pi \cdot \varepsilon_r \cdot F} \cdot \left(ln\left(\frac{\pi \cdot f}{2 \cdot h}\right) + 1.7726\right)}} = 2.28 \text{ cm} \tag{13}$$

with:

$$F = \frac{8.791 \cdot 10^9}{f_r \cdot \sqrt{\varepsilon_r}} = 2.4191 \tag{14}$$

The antenna B peak connectivity is −4.00 dB for elevation 0 and 8.45 dB for azimuth 0.

2.2.3. Antenna C: Linear Polarised Circular Patch Microstrip Antenna

The quality factor for this antenna has been imposed to be Q_t = 14.14. The operating frequency is at the midpoint between the two resonant frequencies. The two resonant frequencies associated with L and W are:

$$f_1 = \frac{f_0}{\sqrt{1 + 1/Q_t}} = 2.37 \text{ GHz} \tag{15}$$

$$f_2 = f_0 \cdot \sqrt{1 + 1/Q_t} = 2.535 \text{ GHz} \tag{16}$$

To design an efficient radiator, the value for the width W may be computed as follows:

$$W = \frac{v_0}{2 \cdot f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \tag{17}$$

Substituting the resonant frequency f_2 into (17), the optimal width to have an efficient antenna is computed:

$$W = 4.6744 \text{ cm} \tag{18}$$

Then, the needed length of the antenna results in the following:

$$L = W \cdot \left(1 + \frac{1}{Q_t}\right) = 5.005 \text{ cm} \tag{19}$$

In the case of rectangular microstrip antennas (Figure 4), assuming the selection of $y' = 1$ cm to have the feed point along the diagonal, the needed z' point is $z' = 0.9339$ cm. Antenna C features a peak connectivity of -4.00 dB for elevation 0 and 8.37 dB for azimuth 0.

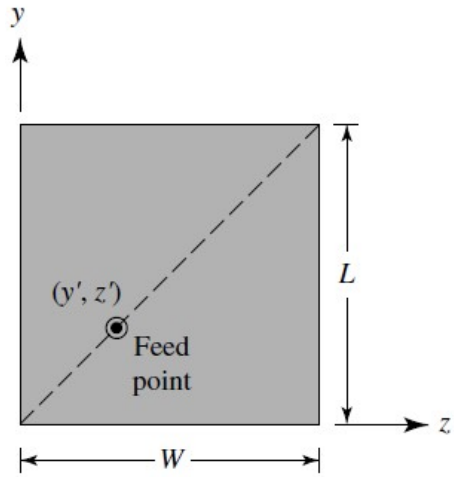


Figure 4. Single feed point arrangement for circular polarisation.

2.2.4. Antenna D: Implementation of 2 × 1 Linear Array

Antennas may also be used in arrays. The effect of using a 2 × 1 array of "antenna 3" is now discussed. Both antennas are oriented in the same direction and are fed without any phase differences to preserve the circular polarisation. The distance between the two antenna centres is $\lambda/2$. Using two well-designed antennas in an array increases the directivity and consequently the gain, with respect to a single antenna. Antenna D features a peak connectivity of -3.78 dB for elevation 0, and of 10 dB for azimuth 0.

2.3. Microwave Heating Prototypes

A lab and an industrial greenhouse prototype have been designed to test microwave heating for the growth of *basil* plants. The prototype is used to evaluate the heating performance, the growth speed, the plant quality, and the heating cost.

A cold control group helps to understand the benefits of microwave heating. The microwave-heated group and the cold group are subject to the same ambient temperature.

2.3.1. Laboratory Prototype

The laboratory prototype is now described (Figure 5). Water floor heating warms the earth to simulate the benefits of reusing the low-temperature energy from the cogeneration plant. Special LED lamps provide adequate lighting. The control group measures include the plant temperature, the soil temperature, the soil moisture, the air humidity, the air temperature, and the brightness. The plants cultivated inside the hot and cold control groups are irrigated with the same amount of water.

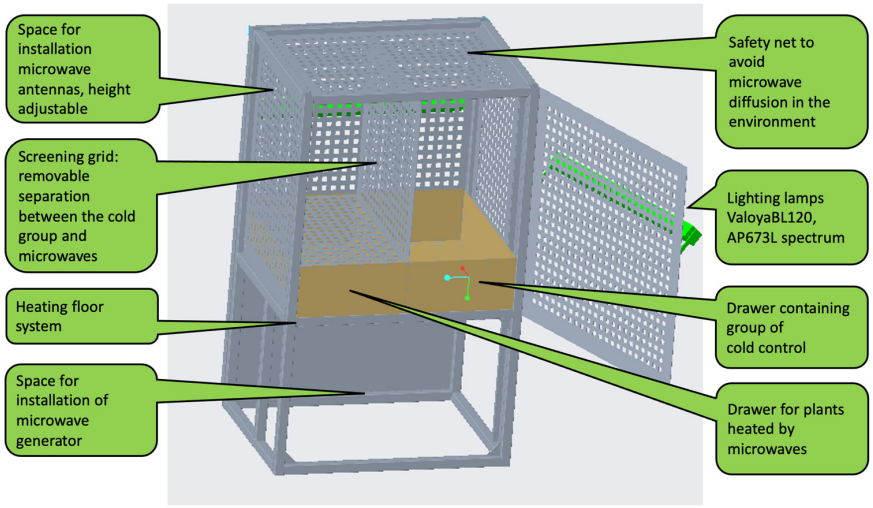


Figure 5. Microwave glasshouse lab prototype.

A shielding system protects the LED lights from the antenna's radiations. Also, the operators need to be protected from radiation. During the winter nights, the greenhouse *basil* is heated. During the daytime, the possibility to take advantage of the external heat and natural lighting maximises the overall system efficiency; for this reason, the shielding needs to be as "transparent" to the light as possible. The holes of the electro-welded mesh are small enough to shield the passage of waves and large enough to allow the entrance of natural light.

From an agronomic point of view, the optimal plant temperature is between 18 °C and 24 °C. A suitable growth bed temperature is 16 °C. The temperature of the irrigation water should be the same as that of the growth bed.

The experiment temperature has been set to 15 °C, slightly over 13 °—the thermal zero of *basil*. Experiments are conducted in a cold room under controlled temperature [23]. The lab solution adopts a waveguide to radiate multiple plants with a single antenna. A "cold" twin vessel, covered with a metal structure, is close to the microwave-heated vessel.

2.3.2. Industrial Prototype

A heating system has been developed in collaboration with the Spanish company Microbiotec, an expert in microwave devices (Figure 6). The wave-guided heater maximises the radiated surface area per antenna.

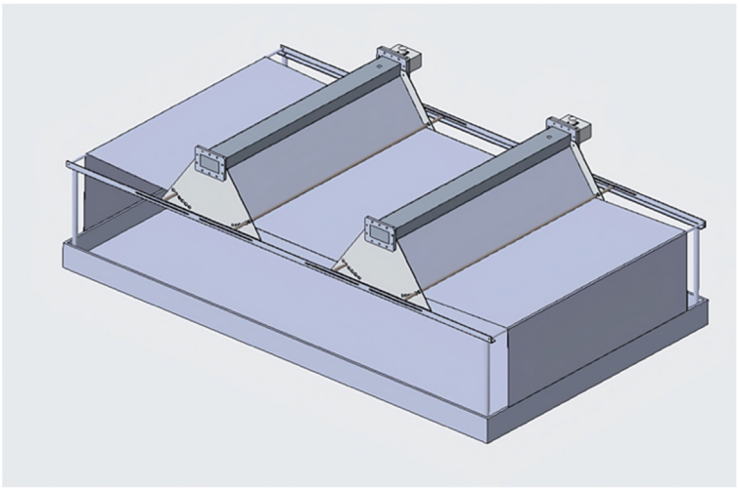


Figure 6. Microwave glasshouse industrial prototype model.

The metal structure, two metres long, has two recesses. Each recess hosts a 250 W microwave antenna. The heater is located about 50 cm from the growth bed. The electromagnetic field is evenly distributed over the entire surface below. An electro-welded metal mesh is around the industrial structure (Figure 7).

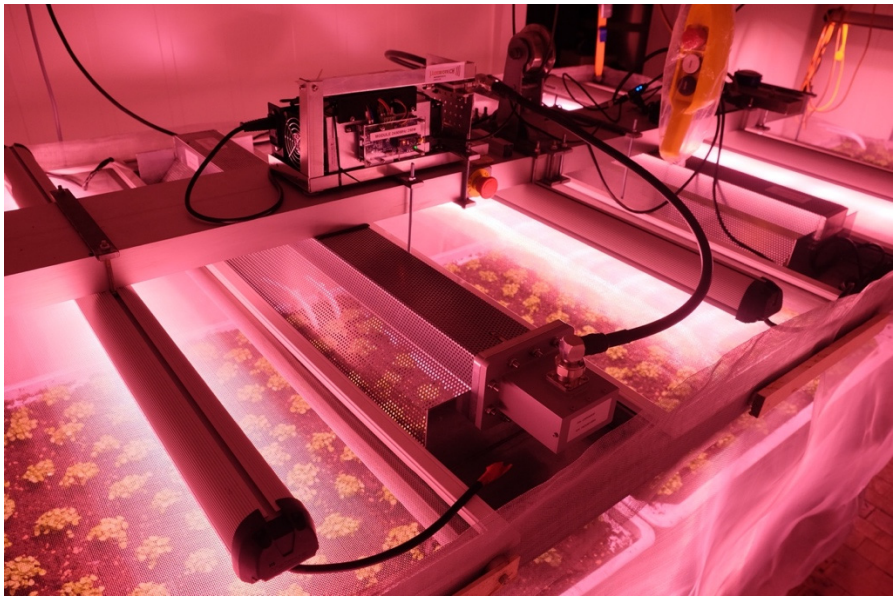


Figure 7. Microwave glasshouse industrial prototype module.

Environmental factors and variations in plant positioning need to be considered to ensure the robustness of the results. The industrial module has thermal sensors to maintain the plants at a constant temperature. The plants are evenly distributed on the ground. The heating works best if the plants under the same module have almost the same height.

3. Results

The performance of the four proposed antennas is now described and analysed. Then, the results from the test are critically discussed. Table 4 shows the main characteristics of the designed antennas and array.

Table 4. Characteristics of the four microwave antennas.

	Antenna A	**Antenna B**	**Antenna C**	**Antenna D**
Polarisation	linear	linear	circular	circular
Patch	rectangular	circular	rectangular	rectangular
Antenna Dimensions	4.04 × 4.182 cm	Radius a = 2.28 cm	4.674 × 5.001 cm	4.674 × 5.001 cm
Resonant frequency	2.45 GHz	2.45 GHz	2.45 GHz	2.45 GHz
Height of substrate	0.16 cm	0.16 cm	0.16 cm	0.16 cm
Subst. dielectric const.	2.2	2.2	2.2	2.2
Number of elements	1	1	1	2
Elements spacing				/2
Maximum Gain	8.15 dBi	8.45 dBi	8.37 dBi	10 dBi

The following key parameters for each antenna have been evaluated [24,25]: the size of each antenna, the 3D radiation pattern of directivity, the 2D radiation patterns on the horizontal and the vertical plane, and the distribution of the current density (Figure 8). All the designed antennas can potentially heat plants via dielectric heating.

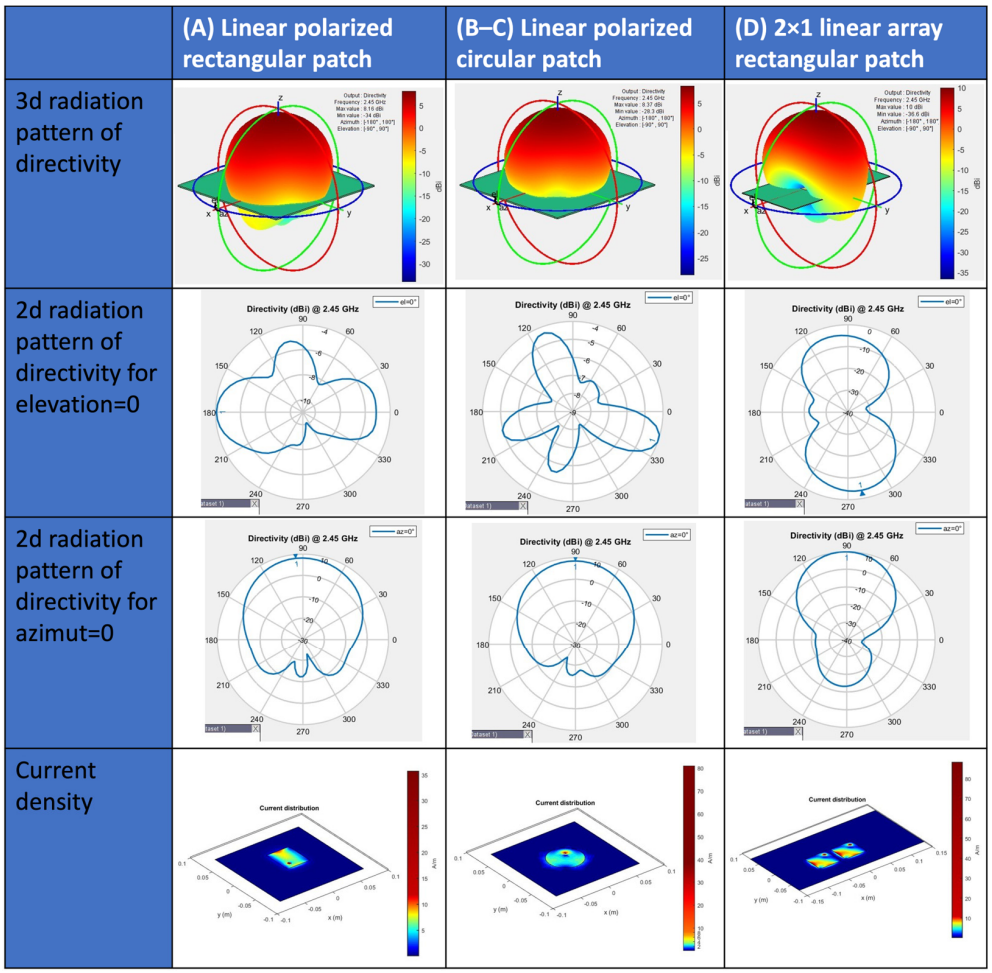


Figure 8. Microstrip antennas' radiation and current density.

Antennas A and B are linearly polarised and are suitable for the dielectric heating of very directional objects, due to the nature of the produced electromagnetic field.

These two antennas provide focused heating. However, they are not optimal for heating non-regular shapes as the linear polarisation may not distribute the electromagnetic field effectively across irregular surfaces.

Antennas C and D, being circularly polarised, can provide more uniform heating over irregular surfaces. These antennas offer consistent heating over a specific area, but have limitations in achieving heating uniformity across a larger surface area.

As emerged from the literature analysis, arranging more equal antennas in a single array increases the overall gain. Antenna D, implemented as a 2 × 1 linear array, has been selected as the final antenna for its ability to increase directivity and gain, making it well suited for applications requiring higher efficiency and coverage. This antenna requires careful design and alignment for optimal performance, as the array configuration needs a precise setup to achieve the desired heating outcomes.

The overall gain is enhanced by increasing the number of antennas per array. The most promising antenna produces circularly polarised waves at a frequency of 2450 GHz.

4. Discussion

The study of the thermal energy load of greenhouses allows for the correct sizing and use of the heating system [26]. Today, microwave dielectric heating [27,28] is a mature technology [29,30]. Microwave heating can be optimised using different methods [31,32]; for example, the rotation of a turntable improves the microwave uniformity [33]. The potential environmental impacts of using microwave heating in greenhouses, including

any long-term effects on plant health and soil conditions, have been studied by several researchers. The effects of microwaves on seeds [34], plants [35], and fruits [36] have also been studied. Microwaves have been successfully used to grow Chinese cabbage [37] and to heat oranges [38] and other plants [39]. Microwave technology can also dry fruit [40] and sterilise soil [41–43]. Spectrum splitting is a promising technology that can cool greenhouses [44].

The development of a microwave glasshouse heating system involved a collaboration with Microbiotec. The system aimed to maximise the radiated surface area per antenna for efficient heating. An industrial prototype was created with a metal structure housing multiple microwave antennas. Each is positioned to evenly distribute the electromagnetic field over the growth bed. The wave-guided heater and electro-welded metal mesh enhanced the system's heating capabilities.

The antennas, designed for the microwave glasshouse heating system, are crucial for effective plant heating through dielectric heating. Four microwave antennas were developed, each with specific characteristics such as polarisation, patch shape, dimensions, resonant frequency, and maximum gain. The antennas were evaluated based on parameters like size, radiation patterns, and current density distribution. Linearly polarised antennas were suitable for heating directional objects, while circularly polarised antennas were optimal for non-regular shapes. The use of antenna arrays was explored to increase the overall gain, focusing on circularly polarised waves at a frequency of 2450 GHz.

The development of the microwave glasshouse heating system involved a multifaceted approach, combining innovative design elements and the technical analysis of antenna performance. The microwave technology has been integrated into the heating system, leading to the creation of both lab and industrial prototypes. The industrial prototype, featuring strategically positioned antennas, demonstrated efficient heating capabilities.

The characteristics of the four microwave antennas, including polarisation, patch shape, dimensions, and resonant frequency, were carefully evaluated to ensure the effective heating of plants within the greenhouse environment. The use of linearly polarised antennas for directional heating and circularly polarised antennas for non-regular shapes showcased the system's versatility in catering to different plant types.

The exploration of antenna arrays highlighted the potential for increasing the overall gain and improving heating efficiency. By arranging multiple antennas in an array, the system could generate a higher gain and enhance plant heating performance. The emphasis on circularly polarised waves at a specific frequency underscored the system's focus on optimising heating processes for greenhouse cultivation.

Possible health issues derived from human exposure to electromagnetic waves have been assessed. An innovative design has been produced. Different antennas have been analysed. Microwave technology has been adopted to create an efficient and effective heating solution for modern greenhouses. The described research also has important limits. Despite all the performed tests, the heating uniformity is not fully satisfactory. A new set of tests will verify if a continuous change in microwave frequency can improve the plant's heating uniformity.

5. Conclusions

The work presented in this manuscript is part of a larger research project. Its goal is to define the requirements and characteristics of a dielectric heating system for modern greenhouses. The general objective is a reduction in energy consumption. During the heating design phase, several critical issues have been identified. Scalable industrial-scale heating systems have been conceived and designed. New experimental trials will be carried out in the University of Genoa laboratories. In particular, the industrial solution for continuous heating will be tested.

At the industrial level, this solution allows for the covering of the entire length of the rooting beds of a certain greenhouse, creating a long metal structure that hosts several

antennas. The modular approach includes a small metallic structure having one or two antennas. A cold room is being set up in the laboratories of the university. A single system module has been installed in the room for testing.

Several experiments will be conducted to test and improve plant uniformity, such as varying the frequency with which plants are irradiated. The system automation will be maximised to reduce the need for human presence. Some control algorithms will autonomously vary the altitude at which the metal structure is held according to plant growth, always optimising the distance between plants and antennas [45,46].

Furthermore, experiments on the intermittent heating of plants will be carried out, mainly aimed at understanding whether the application of electromagnetic fields of higher intensities than reported in the bibliography but for limited durations are bearable for plants.

The potential impact of this technology on greenhouses is high. The market has directly requested an energy-efficient and sustainable solution for heating. The fossil fuel prices are high; moreover, their use is limited by international regulations. Future research will focus on the proposed system's economic viability and installation costs. An efficiency and cost analysis will compare the proposed microwave heater with traditional heating methods. The research will also address the scalability of the prototype heater at the industrial level.

6. Patents

The work reported in this manuscript is based on "Greenhouse heating system and method", industrial patent WO2021079263A1, filing date 21/10/2019.

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