

Microwave heater in greenhouse

— Tests on sweet basil cultivation —

Francesco CEPOLINA ^{1,*}, Matteo ZOPPI ¹, Giovanni MINUTO ²,
Andrea MINUTO ², Andrea BOGLIOLO ², Ares FERRARI ¹

Abstract

This research designs and tests a novel microwave heating system to reduce energy consumption and harmful emissions in greenhouses. Unlike traditional methods, microwaves provide a chemical-free solution for air conditioning and soil disinfection, replacing fossil fuels. The project specifically focuses on applying dielectric heating to plants. Its goal was to create a cost-effective system with reasonable initial installation expenses. This paper details the entire process, including the design, simulation, and practical testing of a pilot microwave heater. Results demonstrate that the operational heating cost of this new solution is roughly half that of using common fossil fuels. A functional prototype was constructed and successfully evaluated in a pilot greenhouse. The developed product is now considered almost ready for full-scale industrialization.

[Keywords] renewable sources, microwave heating, greenhouse climate control systems, energy efficiency, sustainable agriculture

1. Introduction

The impact on production costs due to the use of primary energy is greater when the crop requires strict thermo-hygrometric management of the environment, as is the case of greenhouse crops (Sanford, 2011). The aspects connected with the life cycle of these structures and plants must also be considered (Ouazzani Chahidi et al., 2021). It is necessary to disseminate a culture of innovation and energy efficiency among operators in the primary sector (Molfino et al., 2024). Sometimes, the erratic results achieved with occasional and disharmonious trials lead to the loss of investments that, in perspective, would determine a significant reduction in production costs.

In the Mediterranean basin, the energy consumption of greenhouse systems is between 5 and 7 kg of oil equivalent (koe) (1 koe = 11.63 kWh) per year, or 60–80 kWh/m², while in central and northern Europe, from Germany to Holland, it reaches 40–80 koe (460–930 kWh/(m² a)). In Italy, 30% of greenhouse production costs are due to heating (Viola et al., 2012). The use of fossil fuels for heating greenhouses also causes a significant impact on the emissions of climate-altering substances like CO₂ (Marttila et al., 2021). Agricultural logistics also has a strong environmental impact: the proximity to the customers (Sanyé-Mengual et al., 2013) and delivery optimization (Cepolina et al., 2021) are the key elements.

One of the main objectives of a modern agricultural company that operates in the protected crops supply chain is, on the one hand, the lowering of production costs and, on the other, the

increase in production efficiency. The rational use of energy is one of the most important prerequisites for achieving this objective, considering the weight of the energy cost on the production cycles under greenhouse conditions. Faced with progressive increases in energy costs and growing competition in international markets, operators are looking for solutions to reduce the company's energy needs, use energy more efficiently, and reduce the cost of energy (Kavga et al., 2012) from production to logistics (Cepolina et al., 2011). Microwaves have already been successfully used in the food industry (Guo et al., 2017). This technology is also adopted to extract organic contaminants from food (Moret et al., 2019). This research aims to test the effectiveness and efficiency of a microwave heater for protected environments (Guess, 2011; Guess et al., 2011). Greenhouses usually use electric energy to power lights, open/close vents, turn on irrigation, and force ventilation or dehumidification systems. The authors propose the use of electric energy to power a low-energy microwave heating system that provides thermal energy to the plants (El Khaled et al., 2018; Cepolina et al., 2023).

Greenhouse environment conditioning is expensive; the most common solutions involve using gas (methane), biomass or, still in some cases, diesel. There are high costs related to fuel use and the equipment needed to produce the heat and its transport (where necessary) from the boiler to the protected environment. The hybrid solar heating system is an interesting eco-sustainable greenhouse heating alternative (Kıyan et al.

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¹ PMAR Robotics Group, Department of Mechanical, Energetic, Management and Transport Engineering (DIME) of the University of Genoa, Italy

² The Centre for Experimentation and Assistance in Agriculture (CeRSAA), Italy

* Corresponding author: francesco.cepolina@edu.unige.it

2013; Gorjian et al. 2021). The use of geothermal energy, which is particularly interesting and competitive from an energy point of view, is only applicable in lowlands areas featuring deep water tables (Bakos et al., 1999). In non-flat areas, the drilling and installation costs are not competitive with traditional systems. It seems pertinent to demonstrate the effectiveness of alternative tools and systems to those currently available on the market, proposing a potential innovation for agricultural companies.

This project proposes microwave emission antennas with a wavelength and power that is only enough to heat the plants without damaging them (Cepolina et al., 2024). Microwaves increase the tissue water temperature. This work focuses on the biomass production of sweet basil, the main pesto sauce ingredient, grown in a greenhouse. To obtain AOP (Appellation d'Origine Protégée) (protected designation of origin) Genovese basil, Ligurian producers maintain the temperature inside their greenhouses between 16 and 22 °C in winter and 24 and 26 °C in summer. Sweet basil effectively tolerates thermal excesses, even above 32–35 °C, but cannot tolerate temperature drops, which interrupt its growth at temperatures lower than 14–15 °C. At the same time, the quality of the product decreases significantly if the crop is subjected to intense temperature changes over 24 h (Garibaldi et al., 1997). Furthermore, under greenhouse conditions, night-time temperature drop induces the condensation of atmospheric humidity on the plants, favoring the establishment and spread of pathogens, including *Botrytis cinerea* and *Peronospora belbahrii* (Collina et al., 2016). During winter, about 50–60 days pass from sowing to the first harvest, while, in the summer, this time is reduced to 30 days. Rich, quality crops are obtained by reducing the differences in temperature between day and night of the greenhouse volume and the soil. Sweet basil also requires adequate daylighting, irrigation (2–4 L/m² of water per day), and nutrition. In the presented research, the air in the cultivation environment remains cold, and the plants are heated directly using microwaves.

First, an optimal configuration is identified and implemented at the level of architectural verification for efficient energy production. Then, the microwave generation system is designed, integrated, and tested for localized crop heating. The digital design allows for the identification of the plant configuration and the respective control of the efficient production and distribution of thermal inputs, including microwaves. This project tested this solution by setting up a custom-made pilot plant that guarantees the replicability and scalability of the collected data and safety in the microwave production and distribution phase. The researchers have collected various requests from growers on the needed plant performance. The proposed solution is prototyped. The plants are heated even in the absence of heating in the cultivation environment, guaranteeing a significant reduction in energy consumption.

The proposed solution is scalable for different cultivation scenarios.

2. Materials and methods

2.1. Climatic chamber

A climatic chamber is built to simulate winter and summer climate conditions. Regarding climate control, the project envisages demonstrating the effectiveness and efficiency of a microwave generation system for localized crop heating. The prototype for the microwave heating system is developed, tested, and integrated with a control system using a greenhouse simulacrum, which is applicable in the floricultural and horticultural greenhouse reality. The climatic chamber is a NT cold room (Normal Temperature, i.e., which does not drop below 0 °C) with the dimensions of (236 × 470 × 320 [height]) cm. The NT climatic chamber is a refrigerated room designed for temperatures at or above 0 °C. This is the ideal range for simulating cool winter or mild spring/autumn conditions in a greenhouse without risking frost damage to plants

The refrigeration machines control the seasonal simulation temperature, while the dryer controls the air humidity. The growth beds (benches) are equipped with heating pipes potentially heated by cogeneration cooling water. Two refrigeration units (980 W) power the cold room, each having a nominal output of 3,355 W at 7 °C.

2.2. Microwave heating

This activity involves testing the effectiveness of a microwave generation system aimed at heating protected environments. Optimized energy production with high-efficiency systems is tested in real conditions in the Ligurian territory to generate energy flows to heat a greenhouse. The energy flows are controlled by management systems that use a model based on the thermodynamic and climatic data of the Ligurian area and the special needs of sweet basil. The electrical part of the cogeneration is transferred to the plants in the form of heat generated directly inside the tissues, using microwave “illumination” carried out by appropriately designing the antenna and the distribution system, where the microwave dosage attributed to each plant is controlled over time to keep the temperature of the plant tissues constant at the desired value (Gunasekaran et al., 2007).

Traditional microwave heating methods provide limited heating uniformity. For this reason, kitchen microwaves have a rotating dish. Usually, it is not possible to rotate the crops relative to the microwave antenna. Some researchers propose using circularly polarised electromagnetic fields to increase the crop's heating homogeneity (Teitel et al. 2000). Circular polarisation waves have a constant magnitude and rotate at a constant rate in a plane perpendicular to the direction of the wave.

The authors wish to improve the homogeneity of the wave distribution using a different principle. The proposed microwave generator produces waves that, instead of rotating, have a frequency that continuously changes following a wave path. The authors have tested the effectiveness of this approach with simulation and on the field.

The distance between the antennas and the crop needs to be constantly maintained during the growth of the plants to obtain uniform heating. The characteristics of the industrial prototype are satisfactory.

2.3. Design of the microwave heater

An industrial prototype of microwave heating is tested in the climate chamber where basil is grown. Several experiments are conducted to test the uniformity of plant heating with regard to the distance between the antennas and the plant leaves. It could be useful to create a control algorithm that independently varies the altitude at which the metal structure is kept depending on the growth of the plants, always optimizing the distance between the crop and the antenna. An integrated module, which includes lights and heating antennas, is produced and studied. At the industrial level, the length of the benches of a given greenhouse can be covered simply by aligning several modules in a row.

The microwave heater (200–300 W/m²) was developed thanks to a collaboration with the Spanish company Microbiotec S. L., which specializes in microwave devices. The objective is to perform a small proof-of-concept (PoC) device to scale up the microwave heating of the live plants. A multiphysics simulation (COMSOL Inc., USA) environment is used to simulate the microwave heating distribution on plants with different heights. The volume loss density distribution is the energy absorption area where heating occurs (Fig. 1).

The pattern shown in Fig. 1 has a good distribution that can be further improved. When two electromagnetic sources are available, the reference of the electromagnetic wave phase

between two sources can be changed. When only a single source is available, the operation frequency can be changed around the available bandwidth (2.4–2.5 GHz). The researchers chose the second option because it enables reduced cost, and the effects are similar in both options in any case. Some electromagnetic simulations are performed to evaluate the performance of the electromagnetic heater both in an open and closed (i.e., a heater confined with side walls) environment.

In an open structure, the energy is focused on the center. In contrast, a closed structure allows for a more homogeneous heating distribution. In the case of the close structure, the corners are easily reached by modifying the microwave frequency. The close structure enhances safety and functionality. If necessary, the heater can also operate in an open structure. For safety reasons, in the case of using the open structure, a safety distance of 4 m is mandatory. The optimal distance between the microwave generator and the plants is studied (Fig. 2).

This distance is known as the cold space clearance. The results show that a clearance of 400 mm is the most promising configuration under the described trial conditions. It provides optimal homogeneity to the electromagnetic field.

The microwave penetration depth is limited. For this reason, the authors have designed liftable microwaves to reduce the air gap between the plant and the emitter. Tall crops are more difficult to heat homogeneously: the part of the plant too far from the emitter will stay relatively cold. The simulation results have shown a good accordance with the experimental tests. Simulation can also help find the best settings for crops other than basil.

The power supply system consists of one electromagnetic source and one power divider, which distributes the power in each waveguide. The waveguide heater is intended to maximize the radiated surface area per antenna. The power system is centrally located at the top of the structure for both symmetry

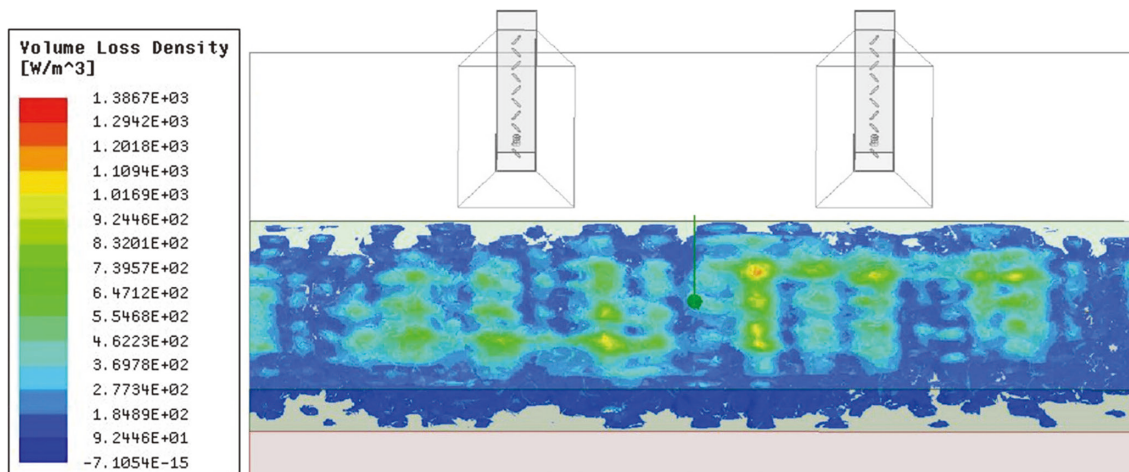


Fig. 1 Lateral view of volume loss density pattern

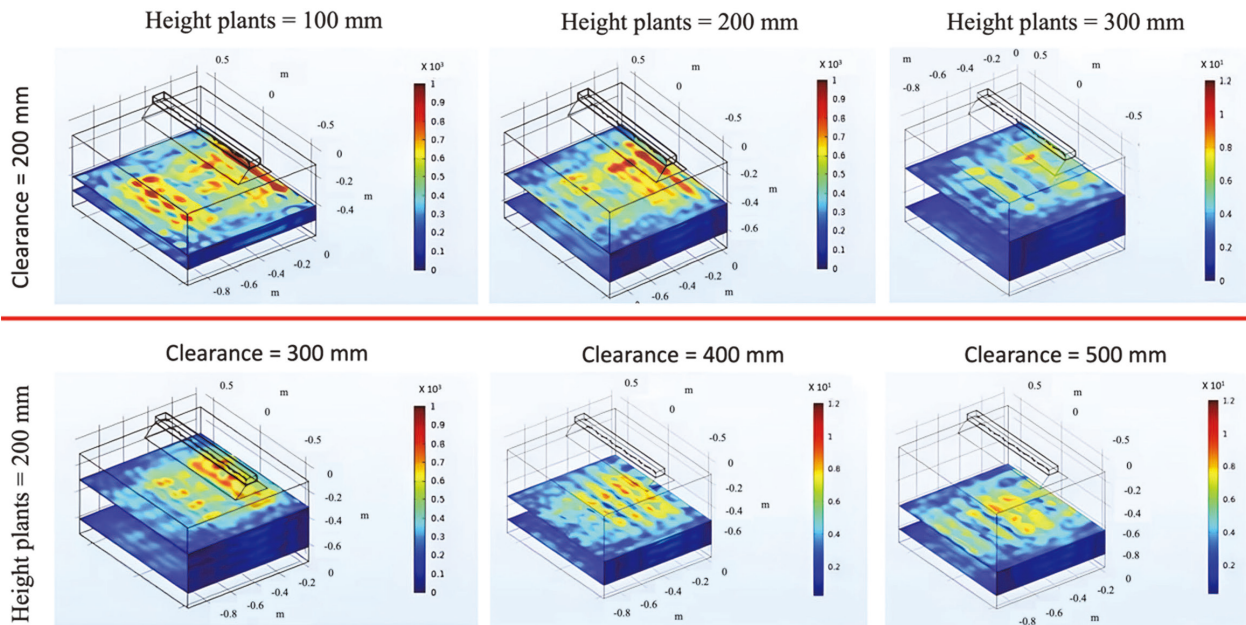


Fig. 2 Simulation of microwave heating uniformity with different clearance and plant heights

and reachability. Two coaxial wires connect the electromagnetic wave source with the waveguides. A trumpet is inserted below the applicator to improve the adaptation properties. Two waveguide applicators completely cover the area. Each heating module needs to be displaced at a distance of 400 mm from the center of the (2×1) m area. The two modules are rotated 180° to improve the homogeneity.

2.4. Prototyping of the microwave heater

The microwave heater with integrated lights is now described (Fig. 3).

The metal structure, which is two meters long, has a sequence of recesses. Each niche houses a 250 W microwave antenna. The heater is located approximately 50 cm from the grow bed. The electromagnetic field is uniformly distributed over the entire underlying surface. The electro-welded metal mesh is placed around the industrial structure.

Great attention is paid to the human health problems that may arise from electromagnetic waves; attempts are made to understand how to minimize these risks. For safety reasons, the heater is surrounded by walls made of a shielded net to protect the operators from radiation. The control system consists of a laptop to control the microwave generator and a thermographic camera for checking the heating distribution and system functionality. The EATON-EASY series PLC (Eaton Corp., USA) integrates all the functions in a centralized way, thus simplifying the control and log. The EATON-EASY series is a compact family of programmable logic controllers for small to medium-sized automation tasks. The objective is to simulate the stability of an industrial system and the precision of an experimental system. Closed-loop electromechanical controls oversee the process parameters (Castellini et al., 2017).

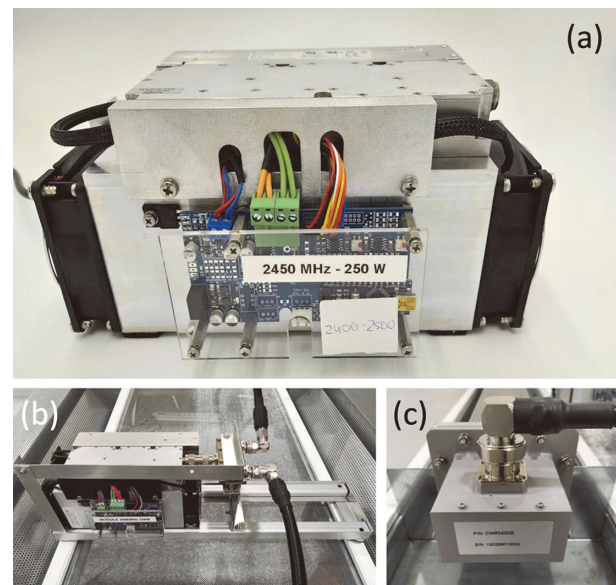


Fig. 3 Microwave generator: main body (a), two coaxial cables (b), link to the slot antenna (c)

2.5. Test setup and data collection

To evaluate the effectiveness of the microwave heating system, a carefully designed experimental setup was established within a climatic chamber that simulated real-world growing conditions for sweet basil. The climatic chamber housed a total of 158 groups of basil plants, each consisting of ten plants, arranged across three separate benches. Of these, two benches included a total of 104 groups of plants exposed to the microwave heating (referred to as the “hot group”), while the third bench contained 54 groups of plants maintained without any heating (the “cold group”). This arrangement allowed for a

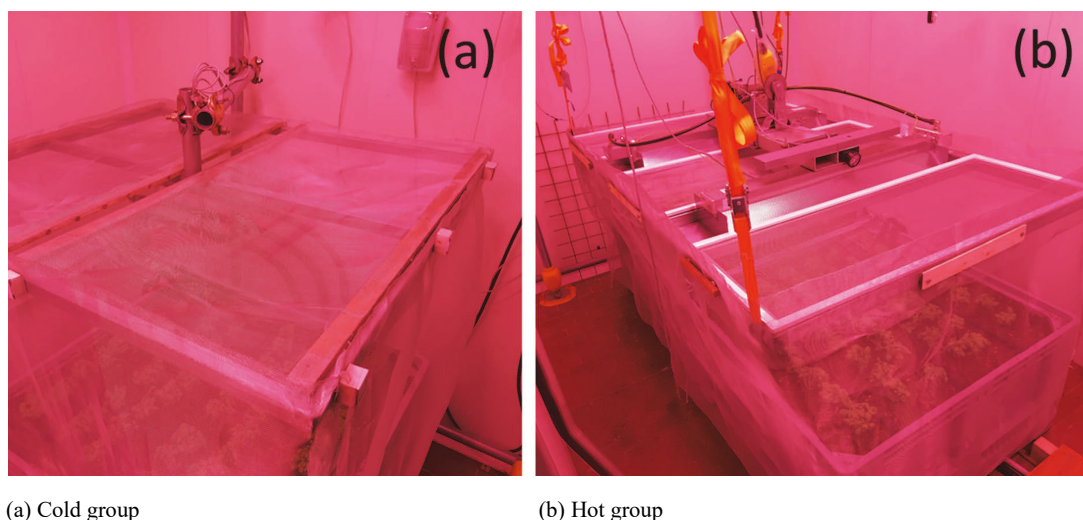


Fig. 4 Test setup: cold group (a), hot group (b)

comparative analysis between the two environmental conditions.

The plants within the climatic chamber were subjected to controlled environmental parameters, including temperature, humidity, and light exposure, tailored to the specific needs of sweet basil. The temperature was maintained at 15–16 °C, which was deemed optimal following preliminary tests that indicated adverse effects on plant health when temperatures dropped below that threshold.

The growth of basil plants was monitored at regular intervals, specifically every 14 to 21 days. Several growth parameters were measured, including plant height, diameter, and weight, to assess the impact of microwave heating on biomass production. Each measurement was recorded meticulously to facilitate statistical analysis.

Overall 5 tests have been performed. The latest experiment, referred to as Test V, involved heating plants using traditional fossil heating. The primary purpose of Test V was to conduct a comparative analysis directly between microwave heating (specifically Test III) and traditional fossil fuel-based heating methods. This allowed for an evaluation of differences in efficiency and cost between the two heating approaches.

Data analysis was performed using appropriate statistical methods, including variance analysis, to determine significant differences between the hot and cold groups. The results of these analyses are summarized in tables, with specific attention given to documenting variations in growth parameters over time.

Furthermore, to assess any potential phytotoxic effects of microwave exposure, observations were made regarding the physiological condition of the plants, including leaf color, shape, potential necrotic areas, and overall plant vitality. Notably, the disease situation was observed to be similar in both the microwave-heated and non-heated groups, indicating that microwave exposure did not amplify the presence of diseases.

This qualitative assessment complemented the quantitative measurements and provided insights into the safety and efficacy of the microwave heating methodology.

In the interest of replicability and robust experimental design, all trials were conducted with appropriate controls and randomization to minimize bias. The integration of a centralized control system, utilizing sensors and automated data collection tools, ensured accurate and consistent monitoring of the experimental conditions.

Overall, this structured methodology provided a rigorous framework for evaluating the performance of the microwave heating system, facilitating a comprehensive understanding of its effects on the growth and development of sweet basil.

3. Results and discussion

Table 1 reports the main information relating to the five experimental tests carried out on basil using microwave heating. The first two trials are used to fine-tune the microwave heating system, fine-tune the duration of the LED lighting, and verify the possible appearance of phytotoxicity phenomena that affect the basil plants. After the first two tests, the ambient temperature of the cell was set at 15–16 °C because the temperature of 14 °C, set in the first two tests, was considered insufficient to allow for the regular development of the unheated plants. The latter became clear when the plants showed extensive yellowing and deformations of the younger leaves, which is caused by temperatures that are too close to the “freezing temperature” of the species.

During the trials, in the microwave-heated plots, an increase in plant development (diameter and height) was constantly observed. During the last experiment, the plants have been heated using traditional fossil heating. Table 2 shows the data from the last measurement of each test.

Due to the increased plant development (the hot group), an

Table 1 Main parameters of the microwave heating tests

Test number	I	II	III	IV	V
Start date	18/10/2023	28/11/2023	05/03/2024	09/07/2024	23/04/2025
End date	28/11/2023	13/02/2024	07/05/2024	13/08/2024	25/06/2025
Air Temp. (°C)	14 (±0.6)	14 (±0.8)	15 (±0.6)	16 (±0.6)	21 (±0.6)
Temp. of irrigation water (°C)	20	20	20	20	20
Temp. of substrate under MW (°C)	-	-	21	19	21
Temp. of substrate (control) (°C)	-	-	16	16	16
Irrigation frequency	as needed	as needed	as needed	as needed	as needed
RH dryer (%)	70	70	70	70	70
Daylight (h)	16	12	12	12	12
Clearance (cm)	40	43	40	40	40
Power of lamp (W)	250	250	250	200	250

Table 2 Height and diameter of basil plants at the end of each test

Test number	Heating	Plant height (cm) *		Plant diameter (cm) **	
		Hot group	Cold group	Hot group	Cold group
I	Microwave	10.2 (s: 0.51)	7.0 (s: 0.31)	10.5 (s: 0.50)	8.3 (s: 0.29)
II	Microwave	12.8 (s: 0.29)	10.5 (s: 0.59)	10.9 (s: 0.38)	9.0 (s: 0.25)
III	Microwave	8.2 (s: 0.35)	7.1 (s: 1.47)	9.7 (s: 0.15)	7.1 (s: 0.56)
IV	Microwave	13.5 (s: 0.30)	10.5 (s: 0.15)	15.1 (s: 0.46)	11.4 (s: 0.44)
V	Diesel	8.5 (s: 0.33)	-	9.4 (s: 0.41)	-

* Average height (cm) of plants at transplanting: 6 (I); 4.5 (II); 6 (III); 9.5 (IV), 6.2 (V).

** Average diameter (cm) of plants at transplanting: 8 (I); 6.5 (II); 7 (III); 10.5 (IV); 10.1 (V).

s: standard deviation.

Table 3 Average plant weight at the end of tests

Test number	Heating	Average plant weight at the start of tests (g/plant)	Average plant weight at the end of tests (g/plant)	
		Hot and cold group	Hot group	Cold group
I	Microwave	5.5	10.6 (s: 0.46)	6.4 (s: 0.14)
II	Microwave	7.0	24.3 (s: 0.38)	16.9 (s: 0.68)
III	Microwave	7.5	86.0 (s: 0.15)	22.0 (s: 0.56)
IV	Microwave	9.0	48.0 (s: 0.51)	39.4 (s: 0.80)
V	Diesel	7.8	93.0 (s: 0.14)	-

s: standard deviation.

increase in plant weight (biomass production) is constantly observed (Table 3).

Figure 5 illustrates the difference in development and quality of basil plants heated in the microwave (hot group) compared to the cold group.

Phytotoxicity phenomena in the treated plots with microwaves (the hot group) appeared during the first two tests, with necrosis and burning of the tissues of the youngest leaves and

yellowing phenomena of the vegetative apex. The wavefront distribution improvement and the emitted power management significantly reduced these phenomena in the third test until their complete disappearance in the fourth.

Compared with the control bench, on the two benches heated with microwaves, additional phenomena, which are potentially very interesting for growers, were observed: (1) a visible reduction in the presence of substrate insects (the so-called shot

flies), which can cause aesthetic damage to basil leaves; (2) an absence of moss growth on the surface of the substrate; (3) the absence of attacks by *Rhizoctonia solani*, the causal agent of basil dumping-off. This pathogen was probably introduced into the growing substrate with the transplanting operations of the young plants and increased its presence on the control bench during the tests. Microwaves affected the spread of the pathogen on the treated benches.

The choice of frequencies, the power applied, the distribution of wavefronts, and the consequent thermal variations imposed provided interesting results. The trials demonstrated that basil plants can grow very effectively using microwave heating. This method makes it possible to reduce heating costs (Muñoz et al.,



(a) Cold group



(b) Hot group

Fig. 5 Results of test IV: cold group (a), hot group (b)

2022). The seedlings not subjected to heating (the cold group) grow much slower than those heated with microwaves (the hot group).

The experimental tests conducted allow for a direct comparison between microwave heating and traditional (fossil fuel-based) heating methods. By comparing Test III (microwave heating) with Test V (conventional fossil fuel heating), significant differences in efficiency and cost emerge. The microwave-based heating system reduces heating costs by 46 % compared to the conventional method. Under identical growth durations, basil plants (*Ocimum basilicum*) reached an average weight of 86 g per plant using microwave heating, whereas those grown under conventional heating reached 93 g per plant—representing an 8 % increase in biomass. However, when comparing energy consumption at equal production levels, microwave heating demonstrates a substantial advantage). This results in a 41 % reduction in energy consumption per gram of biomass produced, as the microwave system uses 54 % of the energy cost to achieve 92 % of the biomass yield of the conventional system ($0.54 / 0.92 = 0.587$. Then, $1 - 0.587 = 0.413$).

These findings suggest that, while conventional heating may slightly enhance growth rate or biomass accumulation, microwave heating offers considerable economic and energetic benefits, making it a promising alternative for sustainable agricultural practices.

Considering a full-scale greenhouse, microwave heating allows for roughly a 50 % reduction in heating expenses compared with fossil heating (Table 4). The data from the Table 4 is provided by the author Giovanni Minuto. Giovanni is leading the CeRSAA “Agricultural Testing and Assistance Centre”.

4. Conclusions

The energy costs and environmental constraints are making

Table 4 Comparison between generic heating and microwave heating costs

Environment	Generic greenhouse	Microwave heated greenhouse
Greenhouse material	iron glass	any material
Greenhouse size	surface = 1,000 m ² , height = 4 m (volume = 4,000 m ³)	surface = 1,000 m ² , height = any cultivated = 900 m ²
Thermal gap	10 °C (difference inside/outside)	10 °C (difference inside/outside)
Data	100 kcal/m ³ to reach the thermal setup 50 kcal/m ³ to keep the thermal setup	250 W/m ² for plants favourable growth
Energy request	400,000 kcal to make the thermal jump 50 kg of diesel/h to reach the temperature 25 kg of diesel/h to maintain the temperature	900 m ² × 250 W × 5 h = 1,125 kWh
Daily heat requirement	1 h to reach temperature → 50 kg of diesel 4 h to maintain → 100 kg of diesel	5 h → 225 W × 5 h = 1,125 kWh/day
Total consumption	150 kg/day × 1.5 €/kg of diesel = 225 €/day	1,125 kWh/day × 0.1 €/kWh = 113 €/day
30 days (heat 5 h/day)	4,500 kg/month × 1.5 €/kg of diesel = 6,750 €/month	33,750 kWh/month × 0.1 €/kWh = 3,375 €/month

traditional heating out of the market. Traditional heating is no more a futureproof option. Microwave heating allows for the heating of plants only, without heating the air inside the greenhouse, which guarantees a reduction in energy consumption. The human-machine performance indicators allow holistic and easy monitoring of the entire system, even for non-expert personnel. The optimal configuration is tested on sweet basil crops. The quality of plants grown with microwave heating is comparable with that of plants grown under greenhouses with traditional heating. The developed simple, flexible, and scalable solution can be adopted in different cultivation scenarios.

The tests demonstrated that microwave heating offers significant economic and energetic benefits compared to traditional fossil fuel-based heating methods, despite conventional heating slightly enhancing biomass accumulation

The climatic chamber used in this research is an important test bench for collecting real data about the performance of the electromagnetic heater. The next step is to replicate the tests inside a standard greenhouse. For such a task, both the technical scalability and the financial feasibility should be carefully evaluated. Ease of installation, system reliability, and real operating costs would also need to be assessed.

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