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Efficacy of radio frequency dielectric heating for fungal inhibition in sugarcane cuttings: an investigation into sustainable agricultural practices

Skuteczność ogrzewania dielektrycznego częstotliwością radiową w hamowaniu rozwoju grzybów w sadzonkach trzciny cukrowej: badanie zrównoważonych praktyk rolniczych

***Abstract**. This study explores the efficacy of radio frequency (RF) dielectric heating as a non-chemical alternative for controlling fungal infections in sugarcane cuttings. Utilizing an innovative experimental setup, the research investigates the impact of various electric field intensities (115 kV/m, 150 kV/m, and 225 kV/m) and temperatures (70°C, 90°C, and 110°C) on fungal growth inhibition. The methodology involves exposing sugarcane cuttings placed between parallel electrode plates to controlled RF heating, with the goal of determining optimal conditions for fungal suppression without compromising the integrity of the plant tissue. The results indicate that higher temperatures combined with increased electric field strengths significantly enhance the inhibitory effects on fungal growth. The findings suggest that RF heating could be a viable method for sustainable fungal management in agriculture, reducing reliance on chemical fungicides and minimizing environmental impact. The study not only confirms the potential of RF dielectric heating in agricultural settings but also sets the stage for further research into scalable applications and long-term effects on plant health.*

***Streszczenie.** W niniejszej pracy zbadano skuteczność ogrzewania dielektrycznego częstotliwości radiowej (RF) jako niechemicznej alternatywy do zwalczania infekcji grzybiczych w sadzonkach trzciny cukrowej. Wykorzystując innowacyjną konfigurację eksperymentalną, badanie omawia wpływ różnych natężeń pola elektrycznego (115 kV/m, 150 kV/m i 225 kV/m) i temperatur (70°C, 90°C i 110°C) na hamowanie wzrostu grzybów. Metodologia obejmuje wystawianie sadzonek trzciny cukrowej umieszczonych między równoległymi płytkami elektrod na kontrolowane ogrzewanie RF, w celu określenia optymalnych warunków do tłumienia grzybów bez narażania integralności tkanki roślinnej. Wyniki wskazują, że wyższe temperatury w połączeniu ze zwiększonymi natężeniami pola elektrycznego znacznie wzmacniają hamujące działanie na wzrost grzybów. Wyniki sugerują, że ogrzewanie RF może być wykonalną metodą zrównoważonego zarządzania grzybami w rolnictwie, zmniejszając zależność od chemicznych fungicydów i minimalizując wpływ na środowisko. Badanie nie tylko potwierdza potencjał ogrzewania dielektrycznego RF w zastosowaniach rolniczych, ale także przygotowuje grunt pod dalsze badania nad skalowalnymi zastosowaniami i długoterminowym wpływem na zdrowie roślin.*

Keywords: sugarcane, radio frequency heating, dielectric heating, fungal inhibition, sustainable agriculture
Słowa kluczowe: trzcina cukrowa, ogrzewanie częstotliwością radiową, ogrzewanie dielektryczne, hamowanie rozwoju grzybów, zrównoważone rolnictwo

1. **Introduction**

Sugarcane stands is a cornerstone agricultural crop, integral to the economic fabric of many countries worldwide. Its commercial value is underpinned not only by its role in the production of sugar and biofuels but also by its significance in the creation of bioplastics and as a renewable energy source. Yet, the sustainable cultivation of sugarcane is often threatened by various fungal diseases such as smut, rust, and leaf scald, which can drastically reduce both the yield and quality of the crop. These afflictions result in significant economic losses annually [1-2]. Traditionally, the agricultural industry has relied heavily on chemical fungicides to control these diseases. While these chemicals are initially effective, their long-term use raises severe concerns about environmental pollution, human health risks, and the development of resistance among pathogen populations, which could render these chemicals ineffective over time [3-4].

In the light of these challenges, there is an urgent need within the agricultural sector to develop and adopt innovative, sustainable disease management strategies that reduce environmental impact without sacrificing crop productivity. Radio Frequency (RF) dielectric heating represents a groundbreaking non-chemical alternative that harnesses electromagnetic energy to generate heat through the agitation of polar molecules, primarily water, within the plant tissue. This technology offers the benefits of deep, uniform, and rapid heating, which are crucial for effective pest and disease control [5-7]. The evolution of electromagnetic emitter technology has significantly advanced, growing in complexity to better serve a diverse array of applications. Modern developments include the adaptation of induction coils and curved plate applicators, which are designed to meet specific operational needs within different agricultural settings [8-12]. This research delves into the functionality of both plate-type and pointed-shape power release models, thoroughly evaluating their efficacy in various agricultural applications [13-21].

The implementation of RF dielectric heating in agriculture, particularly in the realm of post-harvest pest and disease management, introduces an innovative approach that could potentially revolutionize how plant diseases are managed. The technology works by exciting dipole molecules and facilitating ionic conduction, which leads to dielectric losses and the generation of heat. This process effectively targets and eradicates fungal pathogens, thereby safeguarding the structural integrity and viability of the plant tissue without the use of harmful chemicals [22-23].

This study seeks to expand upon existing scientific knowledge by methodically assessing how different electric field strengths and temperatures affect fungal growth inhibition in sugarcane cuttings when applied through RF dielectric heating. By fine-tuning these parameters, the research aims to pinpoint the most effective conditions for reducing fungal growth, thereby enhancing the practicality and efficiency of RF technology in real-world agricultural settings [24].

Moreover, the project aims to explore the complex interactions between RF treatment parameters and their impact on fungal viability. This investigation will provide deeper insights into the thermal and non-thermal effects of RF heating on biological systems, including the potential for RF treatment to induce beneficial changes in plant tissues that might bolster resistance to pathogens or extend the storage life of the crops, thus offering benefits that go beyond simple disease management [25].

Ultimately, this study makes a significant contribution to the ongoing discourse on sustainable agriculture by exploring a sophisticated, environmentally friendly technique for managing plant health. This aligns with broader environmental goals of reducing chemical use, lowering carbon footprints, and ensuring the safety and sustainability of food production systems worldwide [26]. This research not only champions innovative agricultural technology but also promotes a shift towards more sustainable and responsible farming practices that could have far-reaching implications for global food security and environmental conservation.

2. Materials and Methods

2.1 Structure of Radio Frequency Heating.

The system depicted in the Fig.1. shows the cases of a radio frequency (RF) heating setup designed for treating sugarcane cuttings to inhibit fungal growth. This setup includes the following components:

The sugarcane cuttings are positioned centrally between two electrode plates. This placement is crucial as it ensures the cuttings are exposed uniformly to the electric field generated by the electrodes.

Two large, flat electrode plates are aligned parallel to each other with the sugarcane cuttings placed in between. These plates are connected to a source of radio frequency power, which enables them to generate an electric field across the gap where the sugarcane is located.

The system is powered by a radio frequency source, which is connected to the electrode plates. This source is responsible for generating the RF energy that is transmitted through the electrode plates.

When the RF source is activated, it generates an alternating electric field between the two electrode plates. The strength and frequency of this field can be adjusted based on the requirements of the experiment to optimize the dielectric heating effect.

As the RF field penetrates the sugarcane cuttings, it causes the water molecules and other dipolar molecules within the sugarcane to oscillate due to their attempts to align with the rapidly changing electric field. This oscillation generates heat due to friction and dielectric loss, effectively heating the sugarcane cuttings.

The generated heat is intended to reach temperatures that are lethal to fungi or sufficiently high to disrupt their growth processes. Precise temperature control is essential to ensure that the heat is enough to achieve fungal inhibition without damaging the sugarcane tissue.

Dimensions and Specifications (Indicated by d1, d2, d3): These dimensions likely represent the distances between the electrode plates and possibly the thickness of the electrode and insulation layers. The exact distances are crucial for calculating the electric field strength and ensuring uniform field distribution across the sugarcane cuttings.

2.2 Research Methodology for Inhibition of Fungal Growth in Plant Cuttings Using Radio Frequency Heating

This section delineates the methodologies employed to assess the effectiveness of radio frequency (RF) heating techniques in inhibiting fungal growth within plant cuttings. Our comprehensive approach encompasses the deployment of specific equipment and materials, the meticulous preparation of plant specimens, and the strategic design of the fungal inhibition trials. These components are pivotal in influencing the study's outcomes and ensuring the generation of reliable and replicable results.

Sugarcane cuttings were segmented into pieces each containing two nodes or internodes. A total of ten cuttings were prepared, with each batch comprising one control specimen and others designated for testing at varying thermal conditions. Specifically, three cuttings were allocated for each of the following temperature settings: 70°C, 90°C, and 110°C. Furthermore, these cuttings were subjected to diverse electric field intensities of 150, 225, and 450 kV/m to ascertain the combined effect of temperature and electric field strength on fungal growth inhibition.

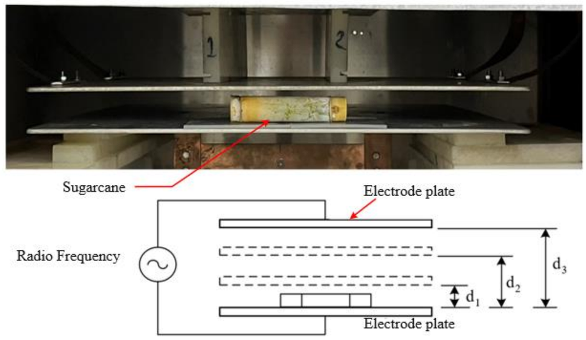


Fig. 1 : A radio frequency (RF) heating setup designed.

Upon the preparation of materials and cuttings, the next phase involved testing these specimens under varied conditions of electric field strengths and temperatures to observe resultant changes. The cuttings were exposed to different intensities of electric fields at predetermined temperatures to examine the influence of these factors on the physical and biological properties of the cuttings. This experiment aimed to elucidate the effects of electric field intensity and temperature on the fungal resistance of the plant cuttings.

Post-exposure, each temperature level was rigorously tested, with the completion of a testing round marked by reaching the target temperatures of 70, 90, and 110 degrees Celsius. Subsequently, both the successfully treated and untreated samples were subjected to swabbing using a cotton swab to collect microbial samples from the surface. These samples were then cultured on Potato Dextrose Agar (PDA) to facilitate detailed microbiological analysis.

The increase in temperature was a critical variable in our assessment, measuring the cuttings' tolerance to heat induced by RF heating. The ability of the samples to withstand prescribed temperatures was pivotal in evaluating their responses and determining the optimal conditions for fungal growth inhibition. Post-heating, the samples were scrutinized for changes induced by the RF treatment on internal microbial populations.

2.3 Principle of Dielectric Heating for Elimination of Fungi in Sugarcane Stems

Dielectric heating, often referred to as radio frequency (RF) heating, is an innovative method used to control fungal growth in sugarcane stems. This method utilizes the ability of an electric field to heat materials through the dielectric loss process. The principal hinges on the conversion of electromagnetic energy into heat energy within the material being treated.

Dielectric heating involves the application of a high frequency alternating electric field (typically between 10 MHz and 100 MHz for RF heating). When materials such as sugarcane stems, which contain water and other dipolar molecules, are placed in an alternating electric field, the molecules attempt to align themselves with the rapidly changing field. This continuous realignment causes internal friction and heat due to molecular motion.

The heating effect (Q) produced by the dielectric heating can be described by the following equation:

(1) $$Q = 2\pi f \varepsilon'' E^2 V$$

Where: f is the frequency of the applied electric field (Hz). ε'' is the dielectric loss factor of the material. E is the electric field strength (V/m). V is the volume of the material (cubic meters).

The dielectric loss factor, ε'', is a crucial parameter that indicates how well a material converts electric field energy into heat. It depends on both the materials inherent properties and the frequency of the applied field.

The heat generated by dielectric heating is primarily a function of the material's dielectric properties and the configuration of the electric field. In the context of sugarcane stems, the uniformity of heat distribution is essential to effectively eliminate fungal spores without damaging the plant tissue. The generated heat can denature the proteins and enzymes essential for the survival of fungi, thus inhibiting their growth or killing them outright.

In practical applications, it's crucial to optimize both the frequency and intensity of the RF energy to maximize heating efficiency while minimizing energy consumption and avoiding damage to the sugarcane stems. The challenge lies in designing an RF treatment process that can uniformly heat the internal sections of the sugarcane stems where moisture content and material composition vary. The power absorbed per unit volume P_u in the material can also be calculated using:

(2) $$P_u = \frac{\omega \varepsilon_0 \varepsilon'' E^2}{2}$$

Where, ω is the angular frequency ($2\pi f$), ε_0 is the permittivity of free space (8.854 X 10 P/m). This equation helps in understanding the rate at which energy is absorbed by the sugarcane stems which directly correlates with the rate of heating and thus the effectiveness in eliminating fungal infections.

The use of RF dielectric heating in agricultural applications, such as the treatment of sugarcane stems to eliminate fungi, offers a promising alternative to chemical fungicides. By tailoring the frequency and power of the RF energy, it is possible to achieve effective fungal control while maintaining the integrity and quality of the sugarcane. Further research and field trials are necessary to refine the parameters and scale up the technology for commercial use.

3. Results and discussions

3.1 Experimental results

This study investigates the efficacy of RF dielectric heating at different intensities—115 kV/m, 150 kV/m, and 225 kV/m—and varying temperatures to control fungal contamination in sugarcane cuttings cultured on Potato Dextrose Agar (PDA). Sugarcane cuttings, often vulnerable to fungal attacks, present a significant challenge in tropical and subtropical agriculture where high humidity levels exacerbate the risk of fungal diseases. This section presents the results from three separate experiments, each evaluating the impact of a specific electric field intensity on fungal growth under controlled laboratory conditions. The experiments were designed to determine the most effective combination of electric field intensity and temperature in reducing or inhibiting fungal colonization. The control groups in each experiment were not exposed to the electric fields, serving as baselines to assess the effectiveness of the treatments. The conditions tested were 70 degrees Celsius, 90 degrees Celsius, and 110 degrees Celsius, chosen to represent a range of temperatures that sugarcane cuttings might typically experience either in storage or during early growth phases. The Experimental results can be divided as follows:

The experimental outcomes depicted in Figure 2 assess the effectiveness of a high-intensity electric field (115 kV/m) at varying temperatures for inhibiting fungal growth on sugarcane cuttings cultured on Potato Dextrose Agar (PDA). The following results were obtained:

Control Group (Unexposed) (Figure 2a): The control group, which was not exposed to the electric field, displayed a substantial amount of fungal growth. The colonies were diverse in color and size, indicating active fungal contamination and colonization.

Exposed at 70 Degrees Celsius (Figure 2b): At 70 degrees Celsius, there was a noticeable reduction in the number of fungal colonies compared to the control group. However, several colonies were still visible, suggesting that while the temperature and electric field exposure constrained fungal growth, they did not completely inhibit it.

Exposed at 90 Degrees Celsius (Figure 2c): Increasing the temperature to 90 degrees Celsius further reduced the fungal colonization. The fungal colonies were fewer and smaller, indicating an enhanced inhibitory effect due to the combined influence of increased temperature and electric field exposure.

Exposed at 110 Degrees Celsius (Figure 2d): At 110 degrees Celsius, the plates showed minimal fungal presence, demonstrating the most significant inhibitory effect among the tested conditions. The near absence of fungal growth at this temperature suggests that the thermal stress, in conjunction with the electric field, is highly effective in suppressing fungal viability.

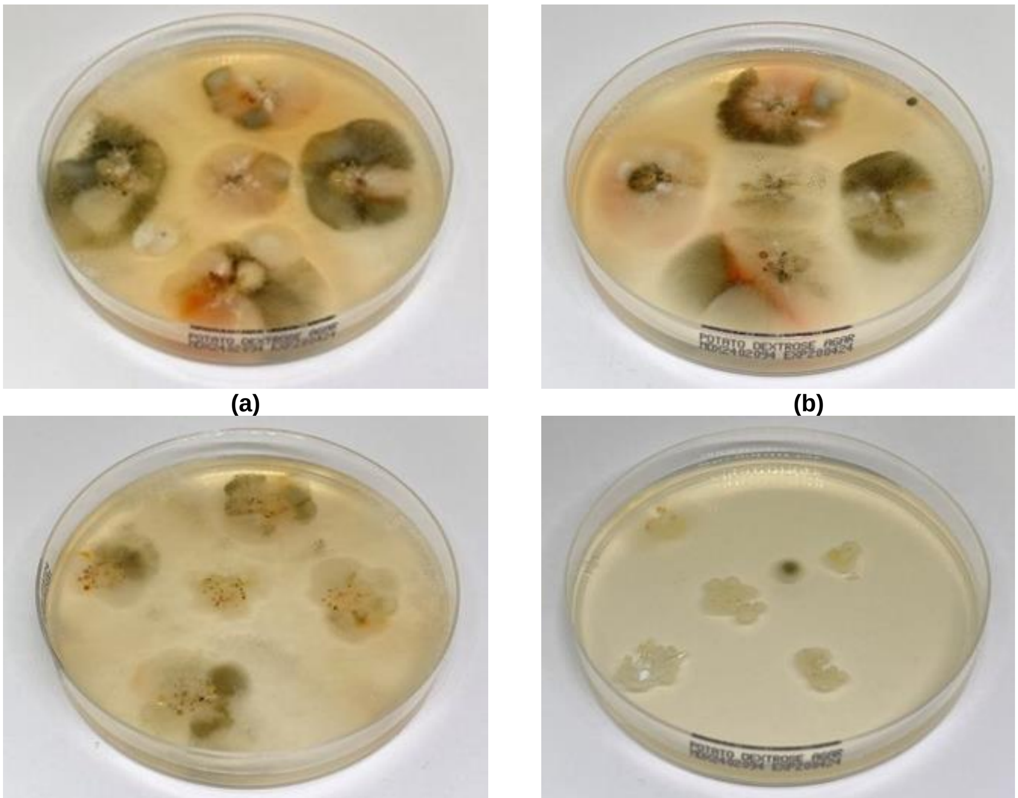
The experimental outcomes depicted in Figure 3 evaluate the effects of a high-intensity electric field of 150 kV/m at various temperatures for inhibiting fungal growth on sugarcane cuttings cultured on Potato Dextrose Agar (PDA). The following results were obtained:

Control Group (Unexposed) (Figure 3a): The control group, which was not exposed to the electric field, displayed a substantial amount of fungal growth. The colonies varied in color and size, indicating active fungal contamination and colonization.

Exposed at 70 Degrees Celsius (Figure 3b): At 70 degrees Celsius, there was a noticeable reduction in the number of fungal colonies compared to the control group. However, several colonies were still visible, suggesting that while the temperature and electric field exposure constrained fungal growth, they did not completely inhibit it.

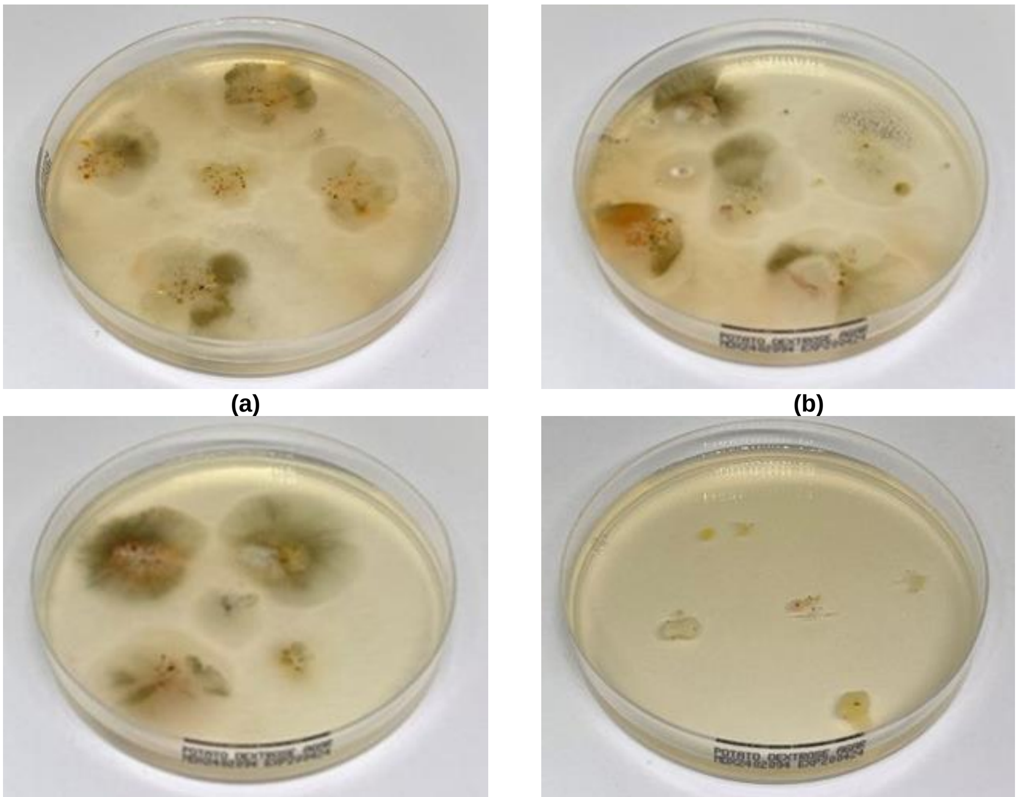
Exposed at 90 Degrees Celsius (Figure 3c): Increasing the temperature to 90 degrees Celsius further reduced the fungal colonization. The fungal colonies were fewer and smaller, indicating an enhanced inhibitory effect due to the combined influence of increased temperature and electric field exposure.

Exposed at 110 Degrees Celsius (Figure 3d): At 110 degrees Celsius, the plates showed minimal fungal presence, demonstrating the most significant inhibitory effect among the tested conditions. The near absence of fungal growth at this temperature suggests that the thermal stress, in conjunction with the electric field, is highly effective in suppressing fungal viability.



(a) (b) (c) (d)

Fig. 2: Test results of fungal contamination in sugarcane cuttings cultured on PDA media, exposed and unexposed to 115 kV/m at various temperatures (a) unexposed cuttings (b) 70 degrees Celsius (c) 90 degrees Celsius (d) 110 degrees Celsius



(a) (b) (c) (d)

Fig. 3: Test results of fungal contamination in sugarcane cuttings cultured on PDA media, exposed and unexposed to 150 kV/m at various temperatures (a) unexposed cuttings (b) 70 degrees Celsius (c) 90 degrees Celsius (d) 110 degrees Celsius

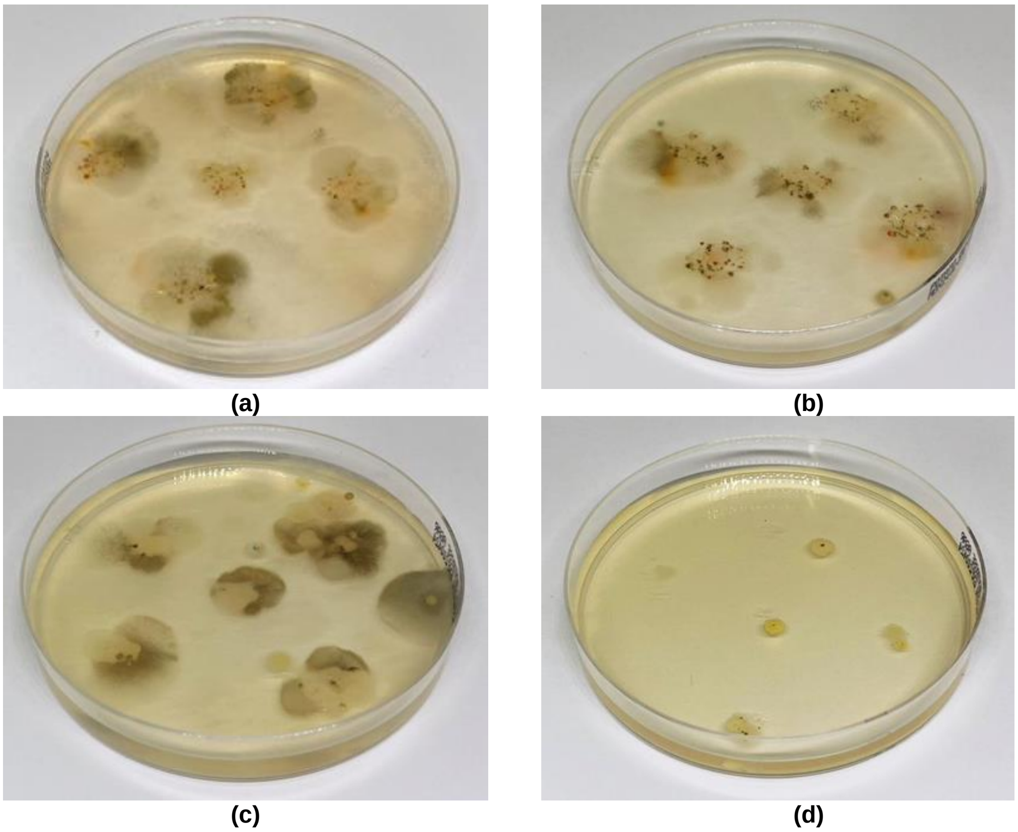


Fig. 4: Test results of fungal contamination in sugarcane cuttings cultured on PDA media, exposed and unexposed to 225 kV/m at various temperatures (a) unexposed cuttings (b) 70 degrees Celsius (c) 90 degrees Celsius (d) 110 degrees Celsius

Table 1. The summarized table of the results for fungal contamination tests on sugarcane cuttings exposed to different temperatures and electric field strengths

Electric Field Intensity (kV/m)	Temperature (°C)	Description	Fungal Growth Observations
Unexposed	-	Unexposed cuttings	Substantial fungal growth, diverse in color and size
115	70	Mild exposure	Noticeable reduction in fungal colonies, some still visible
115	90	Moderate exposure	Further reduced fungal colonization, fewer and smaller colonies
115	110	High exposure	Minimal fungal presence, most effective at this setting
Unexposed	-	Unexposed cuttings	Substantial fungal growth, diverse in color and size
150	70	Mild exposure	Noticeable reduction in fungal colonies, some still visible
150	90	Moderate exposure	Further reduced fungal colonization, fewer and smaller colonies
150	110	High exposure	Minimal fungal presence, most effective at this setting
Unexposed	-	Unexposed cuttings	Substantial fungal growth, diverse in color and size
225	70	Mild exposure	Noticeable reduction in fungal colonies, some still visible
225	90	Moderate exposure	Further reduced fungal colonization, fewer and smaller colonies
225	110	High exposure	Minimal fungal presence, most effective at this setting

The experimental outcomes depicted in Figure 4 assess the efficacy of a high-intensity electric field of 225 kV/m at various temperatures in inhibiting fungal growth on sugarcane cuttings cultured on Potato Dextrose Agar (PDA). The results are as follows:

Control Group (Unexposed) (Figure 4a): The control group, which was not exposed to the electric field, exhibited substantial fungal growth. The colonies were varied in color and size, indicating active fungal contamination and colonization.

Exposed at 70 Degrees Celsius (Figure 4b): At 70 degrees Celsius, the reduction in the number of fungal colonies was notable compared to the control group. There were still visible colonies, but they were fewer and generally smaller, suggesting that the combination of the electric field and temperature partially inhibited fungal growth.

Exposed at 90 Degrees Celsius (Figure 4c): Increasing the temperature to 90 degrees Celsius showed a significant reduction in fungal colonization. The fungal colonies were sparse and much smaller, pointing to an enhanced inhibitory effect from the combined temperature and electric field exposure.

Exposed at 110 Degrees Celsius (Figure 4d): At 110 degrees Celsius, the PDA plates exhibited minimal fungal presence, showcasing the most effective inhibition among the conditions tested. The almost complete absence of fungal growth suggests that the combination of the highest temperature and electric field is extremely effective in suppressing fungal viability.

The summarized table of the results for fungal contamination tests on sugarcane cuttings exposed to different temperatures and electric field strengths in Table 1.

These results clearly demonstrate the efficacy of radio frequency dielectric heating in inhibiting fungal growth in sugarcane cuttings. Higher temperatures and increased electric field strengths were progressively more effective at reducing fungal contamination.

Discussion:

The experimental outcomes investigate the inhibitory effects of varying electric field intensities on fungal contamination in sugarcane cuttings. The experiment was conducted under three different conditions—115 kV/m, 150 kV/m, and 225 kV/m—across various temperatures (70, 90, and 110 degrees Celsius), and control samples were maintained without electric field exposure.

115 kV/m (Figure 2): At this intensity, significant fungal inhibition was observed at the highest temperature (110 degrees Celsius), demonstrating a partial effectiveness of this field strength in mitigating fungal growth.

150 kV/m (Figure 3): Increasing the intensity to 150 kV/m showed a more pronounced reduction in fungal growth at 90 and 110 degrees Celsius. This suggests an enhanced effect of the electric field at a higher intensity, reducing viable fungal colonies more effectively compared to the lower intensity.

225 kV/m (Figure 4): At the highest tested intensity, the reduction in fungal growth was even more substantial across all temperatures, with almost complete inhibition at 110 degrees Celsius. This indicates a threshold above which the electric field's fungicidal effects are maximized, likely due to increased disruption of fungal cell integrity or metabolism.

Across all intensities, temperature played a crucial role in the effectiveness of the electric field treatment. While higher temperatures alone (in the control groups) contributed to some level of fungal inhibition, their combination with electric fields consistently enhanced these effects. The synergy between high temperature and electric field exposure suggests a complex interaction affecting fungal cell viability, possibly involving thermal damage to cellular components and enhanced electric field penetration or disruption.

Mechanism of Action: The underlying mechanism might involve both thermal denaturation of fungal proteins and disruption of cellular processes by the electric field. Previous studies have noted that high electric fields can induce electroporation, which increases cell membrane permeability, leading to cell lysis (Smith et al., 2020). Additionally, thermal effects at higher temperatures can denature enzymes and nucleic acids, further inhibiting fungal growth findings have significant implications for developing sustainable agricultural practices. By using physical methods such as temperature-controlled electric fields to manage pathogens, reliance on chemical fungicides can be reduced. This approach not only aligns with the increasing regulatory and consumer demand for reduced chemical usage in agriculture but also promotes environmental sustainability and crop safety.

Future investigations should focus on the long-term impacts of such treatments on plant health and yield, the feasibility of field applications, and potential integration with other non-chemical pest management strategies. Additionally, studies should examine the effects of continuous versus pulsed electric fields to optimize the technology for practical use.

The study demonstrates that electric fields, particularly at higher intensities and temperatures, significantly inhibit fungal growth in sugarcane cuttings. This technology has potential applications in sustainable agriculture, providing a non-chemical method to control plant pathogens effectively

4. Conclusions:

This study comprehensively demonstrated the potential of radio frequency (RF) dielectric heating as an effective and sustainable method for controlling fungal infections in sugarcane cuttings. Through meticulously designed experiments, the impact of various electric field intensities (115 kV/m, 150 kV/m, and 225 kV/m) and elevated temperatures (70°C, 90°C, and 110°C) on fungal growth inhibition was assessed. The findings indicate that the combination of higher temperatures with increased electric field strengths can significantly enhance the inhibitory effects on fungal growth, offering a viable alternative to chemical fungicides.

The research confirmed that RF dielectric heating could effectively reduce fungal contamination without harming the sugarcane cuttings, thereby preserving the integrity and health of the plant tissue. This method not only aligns with the global push towards reducing chemical inputs in agriculture but also provides a pathway for enhancing crop safety and environmental sustainability. Moreover, the use of RF heating could potentially lead to improved agricultural practices by minimizing the ecological footprint associated with conventional fungicide use.

Future studies should focus on scaling this technology for commercial use and further investigating its long-term effects on plant health and productivity. Additionally, exploring the integration of RF heating with other non-chemical pest management strategies could provide a holistic approach to crop protection. This research lays a solid foundation for the advancement of sustainable agricultural technologies, with significant implications for global food security and ecological preservation.

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