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Investigation effect of pulsed magnetic fields on pepper (*Capsicum annuum* L.) plant growth

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ABSTRACT

Pepper (*Capsicum annuum* L.) plants are extensively utilized in culinary and spice industries, rendering their cultivation pivotal in agricultural production. Enhancing their growth and yield is a critical research area for producers and horticulturists. Recent investigations have delved into the use of pulsed magnetic fields (PMFs) as a potential growth stimulant. Unlike static magnetic fields, PMFs are characterized by transient, high-intensity magnetic bursts, potentially eliciting varied responses in plants. To assess PMFs' impact on pepper plants, several experiments were setup comprising two solenoids, each wound around an 18-cm-diameter rigid plastic pipe but with differing coil turns, one with 40 and the other with 80 turns. These solenoids were utilized to generate PMFs at a frequency of 1 kHz with two intensities: 17 micro-Tesla (μT) and 34 μT. The pepper plants were situated within the PMF zone under controlled conditions, ensuring consistency in light, temperature, and moisture levels. The experimental design included three plant groups: a control group with no PMFs exposure except that of the Earth's magnetic field, and two groups subjected to 17 μT and 34 μT PMFs intensities with Earth's magnetic field, ranging between 25-65 μT. The treatment spanned 15 days, involving 6 hours of daily continuous exposure. Key growth indicators such as plant height, stem diameter, leaf area, and fresh and dry weights of both shoot and root systems were measured and analyzed. This analysis revealed significant increases in plant height, leaf area, and fresh and dry weights of the shoot, but not in root systems. Further research is warranted to deepen the understanding of PMFs' effects on pepper plants.

1. Introduction

Magnetic fields (MFs), a ubiquitous environmental factor on the Earth, exert a profound influence on the biological processes of plants. Contemporary research has increasingly focused on how plants perceive and respond to these fields. Plants exhibit rapid responses to variations in MFs, modulating their metabolic pathways, altering gene expression profiles, and consequently affecting phenotypic outcomes (Maffei 2014). The interaction of MFs with plant cells, especially their membrane structures, has garnered significant interest. This interaction is thought to facilitate enhanced absorption of water and nutrients, a hypothesis supported by studies on plant development and magnetic field interplay. Moreover, the role of paramagnetic biological molecules, such as hemoglobin, cytochrome, and ferritin, containing metal ions, is critical in understanding the influence of MFs on plant physiology (Hozayn and Qados 2010). These molecules may act as mediators in the MF-induced responses observed in plants. MFs also have far-reaching implications for molecular and cellular processes, including mRNA regulation, protein biosynthesis, and enzyme activities (Atak et al. 2003). Such changes cascade through various organ and tissue functions, implying a comprehensive impact on plant development. Despite these insights, the research field is fraught with inconsistencies and lacks a unified theoretical framework (Harris et al. 2009), leading to a spectrum of often contradictory findings regarding the effects of MFs on plant organisms. For example, improved membrane integrity and enhanced germination rates of wheat seeds have been found under static magnetic fields (SMF) (Payez et al. 2013). Conversely, rice (Oryza sativa) seeds exposed to various MF inductions exhibit significantly varying germination times due to a complex and species-specific response to MF exposure (Florez et al. 2004). Further studies indicate that the application of MFs influences seed membrane properties, leading to differential germination outcomes (Hussain et al. 2020). The variability in responses underscores the species-specific nature of MF effects and the importance of considering the type of magnetic field and its interaction with specific metabolic or molecular structures in plants. Recent scientific inquiries, notably those by Himoud et al. (2022) and Tirono and Hananto (2023), have highlighted the advantageous impact of pulsed magnetic fields (PMFs) in agriculture. These studies, extending across cellular and organismal levels, reveal that PMF significantly influences various cellular biochemical processes in plants, including alterations in membrane electro-potential, modulation of protein and enzyme activities, and enhancement in photosynthesis and pigment content. The effect of PMFs is also seen in accelerating cell division rates (Radhakrishnan 2019), moving charged particles across cell membranes (Nyakane et al. 2019), and facilitating an expedited uptake of water and nutrients (Nyakane et al. 2019). In general, recent findings show that PMF is an environmentally sustainable agricultural technique, with broader scientific consensus on its importance for sanitary applications in plants (Nair et al. 2018; Radhakrishnan 2019; Himoud et al. 2022; Tirono and Hananto 2023). For the production of resilient crops in varying climatic conditions, magnetic field applications are gaining attention for sanitizing crops from biotic pathogens. Maffei (2014) emphasizes the necessity of incorporating data on the Earth's static magnetic fields, a dimension currently underrepresented in the literature. Additionally, Đukić et al. (2017) and Bajagić et al. (2021) advocate for experimental research conducted in open fields under diverse climatic conditions to understand the effects of MFs more comprehensively. Considering these findings, the current research is directed towards investigating the effects of low frequency pulsed magnetic field stimulation on pepper plant growth and development. Although the research mentioned previously do not fully reveal that the Earth's magnetic field ranges between 25-65 µT, it is important to understand better how the Earth's MFs works on plant development. This study aims to assess the influence of two different PMFs in addition to the Earth's MF on pepper plants' height, leaf area, fresh and dry weights of shoots and roots. Given the limited knowledge on the effects of PMFs on plants, this study provides empirical insights into the dynamics of plant growth under magnetic stimuli. Our results contribute to filling a gap in understanding the physiological response of pepper plants to PMF influences.

2. Materials and Methods

2.1. Magnetic field application

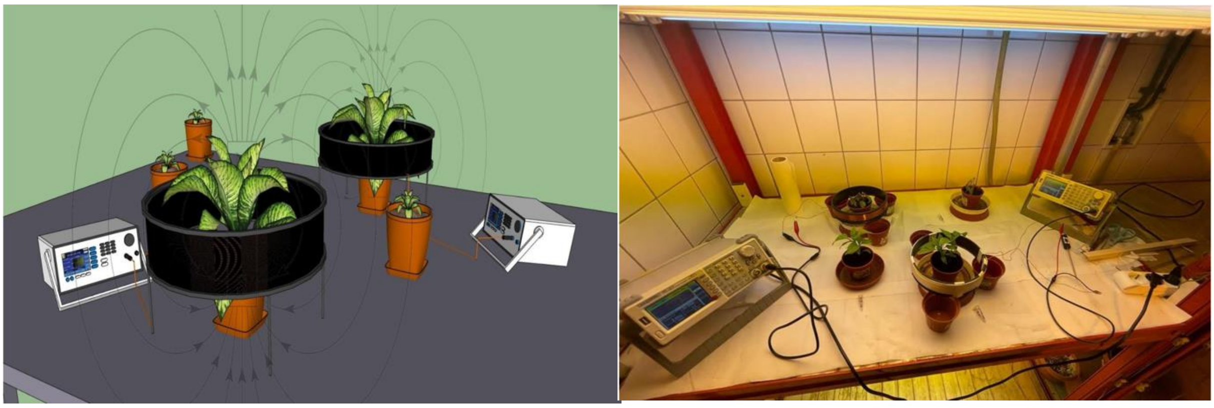
In this study, we developed a novel system to generate pulsed magnetic fields (PMFs) using two custom-built coils, each assembled around rigid plastic pipes with an 18 cm diameter. The coils differed in their configurations: one had 40 turns, and the other had 80 turns of copper wire, with each wire having a radius of 1.30 mm. As electromagnets, the magnetic field strength generated by these coils was directly proportional to the number of wire turns and the electric current passing through them. The coils' dimensions were chosen to ensure compatibility with the plant pots used in the experiment.

To measure the magnetic field strength, a high-precision HIOKI 3470 Magnetic Field HiTester gaussmeter was positioned at the center of each coil. This measurement process was consistently applied in both the control and experimental areas to establish a reliable baseline for comparison. In order to create two distinct PMF environments, AA Tech AWG-100 signal generators were configured to emit a stable peak-to-peak voltage of 6 volts at a frequency of 1 kHz. Figure 1 provides a visual overview of the experimental setup.

In this configuration, the coils with 40 and 80 turns generated magnetic fields of 17 µT and 34 µT, respectively. Three pots, each containing a pepper plant of identical age and size, were placed at the center of each coil, while the control group was kept without magnetic field exposure. The magnetic fields were applied between 8 am to 2 pm for six hours daily over a 15-day period to assess their impact on the growth and development of the pepper plants. The reasons to select these 17 µT and 34 µT PMFs include (1) closer exposure to Earth's MF, (2) cost efficiency of systems, (3) applicability of these PMFs in practical use in greenhouses and fields and (4) suggestions of preliminary studies with using lower and higher PMFs then the PMFs values used in this report (Unpublished data).

2.2. Plant material

Seeds of commercial VAT 59 F1 pepper (Anamas Seed Company, Türkiye) were surface sterilized in a solution containing sodium hypochlorite (>2.5% active chlorine) and a non-toxic wetting agent, Tween 80 (approximately 0.004%), for 5 minutes. Subsequently, the seeds were rinsed three times with distilled water and left to imbibe overnight in distilled water before being sown in standard seed vials filled with sterilized turf (Kekkila®, China). The germinated seedlings were maintained in a growth chamber set at a temperature of 27±3 ºC, with a relative humidity of 40-50%, and under a 16-hour day/8-hour night light regime providing 230 µmol with 230 µmol m^{-2} sec^{-1} of photosynthetically active radiation. Once the pepper seedlings reached the first real leaf stage, three seedlings were transplanted



(a) **(b)**

Figure 1. (a) Schematic and (b) actual view of the original experiment.

from the vials to 0.5 L plastic pots containing sterilized turf (Kekkila®, China). Each pot, housing three seedlings, was positioned in the center of the magnetic fields, with control plants maintained separately. The seedlings, both within the magnetic fields and the control group, were subjected to the previously described growth conditions, including 6 hours of daily magnetic field exposure. Daily irrigation of the pepper seedlings in individual pots was conducted with 50 ml of a nutrient solution containing Peters Professional® ensuring continuous feeding for 15 days until the experiment's conclusion. At the end of the trial, plants were carefully removed from the pots, and their roots were gently rinsed with tap water. Subsequent measurements were conducted to assess the differences among treatments. These included plant length (root and shoot), root length, leaf count, stem diameter, leaf petiole diameter, and the fresh and dry weights of roots, stems, and leaves.

3. Results and Discussion

This study revealed that the two solenoids produced PMFs of 17 and 34 µT, with the direction of the magnetic field alternating due to the applied voltage. In this specialized environment, pepper plants were subjected to various growth measurements including plant length (root and shoot), root length, number of leaves, stem diameter, leaf petiole diameter, and fresh and dry weights of roots, stems, and leaves. The statistical differences among these parameters are presented in Table 1 and Table 2. Although no significant differences were observed in the leaf petiole diameter, and fresh and dry weights of roots, a positive effect of PMFs on the aerial parts of the plants was noted. Despite the alternating direction of the magnetic fields, no side effects were detected. The influence of PMFs on the pepper seedlings showed a favorable interaction with the green parts of the plants. Throughout the experiment, the pepper plants were exposed to PMFs for six hours daily. This rigorous approach allowed for detailed observations and measurements of the plants' growth and development. Comprehensive analysis of various growth parameters, such as root and shoot lengths, leaf count, and stem diameter, revealed significant variations in the green parts of the pepper plants. Notably, marked differences in the number of leaves and both fresh and dry weights of the shoots were observed (Table 1 and Table 2). These PMFs results show that 17 µT had a better affect than 34 µT on leaf petiole diameter, stem fresh weights and stem dry weights.

These findings suggest a pronounced influence of PMFs on the above-ground parts of the plants. In contrast, parameters associated with the root system showed no significant changes. A key observation from our study is that the alternating directions of the magnetic fields had no adverse effects on the plants, suggesting the potential applicability of PMFs, particularly at 34 µT, in agricultural settings. This result matches with the Earth's magnetic field, which typically ranges between 25-65 µT (Martino 2010). Therefore, further studies could explore the effects of PMFs above 25 µT within the Earth's magnetic field range, potentially saving both time and resources for researchers. An intriguing aspect of our findings is the observed increase in plant height due to PMF exposure. However, the mechanisms by which magnetic fields contribute to this growth remain undetermined, as magnetic fields affect various aspects of plant physio-morphological parameters, including enzymes involved in stress physiology and plant metabolism (Radhakrishnan 2019). The application of magnetic fields has been shown to accelerate seed germination and both vegetative and reproductive growth in plants, possibly due to increased energy distribution to biomolecules within the cell (Radhakrishnan 2019). However, detailed molecular or cellular studies are required to elucidate these mechanisms. The absence of any detrimental effects in response to the changing directions of the magnetic fields is noteworthy. This opens possibilities for exploring magnetic fields in enhancing plant resilience against environmental stresses and modulating plant growth patterns for optimized yield. Our study indicates a correlation between PMFs exposure and increased plant height, suggesting promising prospects for further research. Future studies, incorporating advanced molecular and genetic analyses, could provide insights into how magnetic fields influence plant developmental biology. Such research may unveil new aspects of plant growth regulation, leading to innovative strategies in crop management and sustainable agriculture. In summary, this study not only highlights the immediate effects of PMFs on pepper plants but also paves the way for a new paradigm in agricultural science. By integrating concepts from physics, biology, and agronomy, we can develop methods to enhance plant growth and productivity, moving towards more sustainable and efficient agricultural systems.

In conclusion, it is hypothesized that magnetic fields influence many aspects of plant biology, including cell membrane systems, by altering ion transport, affecting cell division and elongation, and modifying hormonal balances. This research lays the groundwork for understanding the effects of PMFs exposure on the cultivation and management of pepper plants, with profound implications for future agricultural practices.

Table 1. Plant tissue measurements after 15 days of magnetic field application on pepper seedlings.

Treatments	Stem Diameter (mm)	Leaf Petiole Dimeter (mm)	Root + Shoot Length (mm)	Number of leaves
Control	2.23 *b	0.89 a	150.7 b	7.08 b
17 µT	2.49 ab	0.88 a	185.4 ab	7.83 ab
34 µT	2.68 a	0.78 b	210.6 a	8.40 a

*Means with a different letter in each column indicate significant differences according to the Duncan comparison test.

Table 2. Plant tissue weights after 15 days of magnetic field application on pepper seedlings.

Treatments	Root Fresh Weights (mg)	Root Dry Weights (mg)	Stem Fresh Weights (mg)	Stem Dry Weights (mg)	Leaf Fresh Weights (mg)	Leaf Dry Weights (mg)
Control	3470 *b	461.51 b	242.5 b	36.38 c	210.27 b	27.97 b
17 µT	4550 ab	605.15 ab	487.5 a	73.13 a	232.55 ab	31.39 a
34 µT	4870 a	647.71 a	345.0 ab	51.75 b	249.48 a	33.68 a

*Means with a different letter in each column indicate significant differences according to the Duncan comparison test.

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