Çukurova Tarım Gıda Bil. Der. *Çukurova J. Agric. Food Sci.*
41(1): *55-70*
doi: 10.36846/CJAFS.2026.220

Research Article

Effects of Electromagnetic Field on Growth and Food Quality of Hot Ornamental Pepper (*Capsicum annuum*)

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ABSTRACT

It is known that the electromagnetic field (EMF) has different effects on different plants. Studies in the literature, especially the studies on plant germination, draw attention. In this context, it is important to reveal the effects of EMF in the process from the germination stage to product yield and product content on a product basis. This study investigated the effects of EMF application on hot ornamental pepper plants (*Capsicum annuum*). In this context, first of all, a bobbin pot design was made in which a low-voltage EMF can be created. Afterwards, bobbin pots were produced within the framework of bobbin pot design parameters and short-term EMF formation was ensured. Hot ornamental peppers were grown by exposing them to short-term treatments in a low EMF at 10 and 20 V AC for 15 minutes, three days per week. The morphological development of the hot ornamental pepper grown by exposure to different EMFs and the nutritional analyses of the obtained products were investigated. As a result of the analysis, in comparison to the control group, the products grown in EMFs with an 10V AC voltage yielded a difference statistically and have positive effects in terms of the number of leaves, root length, carbohydrates, crude oil, dietary fiber, and calcium. On the other hand, statistical differences were found in the number of leaves, leaf width and length, stem diameter, root and stem length, pepper and leaf color, and potassium amount of products grown in an EMF with a 20V AC voltage value. These differences show the effectiveness of the EMF on hot ornamental pepper growth. However, the results showed that the applied EMF treatments did not cause a statistically significant change in the total fruit yield compared to the control group. Researchers and producers may consider short-term low-voltage EMF treatments to enhance certain growth and nutritional parameters, but further optimization is needed to increase total fruit yield.

Keywords: Low-Voltage, Alternating Current, Plant Physiology, Nutrient Composition, *Capsicum*

Elektromanyetik Alanın Acı Süs Biberinin (*Capsicum annuum*) Büyümesi ve Gıda Kalitesi Üzerindeki Etkileri

ÖZ

Elektromanyetik alanın (EMA) farklı bitkiler üzerinde farklı etkileri olduğu bilinmektedir. Literatürde, özellikle bitki çimlenmesi üzerine yapılan çalışmalar dikkat çekmektedir. Bu bağlamda, EMA'ın çimlenme aşamasından ürün üretimine ve ürün içeriğine kadar olan süreçteki etkilerinin ürün bazında ortaya konulması önemlidir. Bu çalışmada, EMA'ın acı süs biberi bitkileri (*Capsicum annuum*) üzerindeki etkileri incelenmiştir. Bu bağlamda, öncelikle düşük voltajlı bir EMA oluşturulabilen bir bobin saksı tasarımı yapılmıştır. Daha sonra, bobin saksı tasarım parametreleri çerçevesinde bobin saksılar üretilmiş ve kısa süreli EMA oluşumu sağlanmıştır. Acı süs biberleri, düşük yoğunluklu 10 ve 20 V AC değerlerinde EMA'a, haftada üç gün ve her seferinde 15 dakika olmak üzere kısa süreli uygulamalara maruz bırakılarak yetiştirilmiştir. Farklı EMA'lara maruz bırakılarak yetiştirilen acı süs biberinin morfolojik gelişimi ve elde edilen ürünlerin besin değerleri analiz edilmiştir. Kontrol grubu ile karşılaştırmalı analiz sonucunda, 10V AC voltaj ile EMA uygulamasında yetiştirilen ürünlerin yaprak sayısı, kök uzunluğu, karbonhidrat, ham yağ, diyet lifi ve kalsiyum açısından istatistiksel olarak fark yarattığı ve olumlu etkilere sahip olduğu bulunmuştur. Öte yandan, 20V AC gerilim ile EMA uygulamasında yetiştirilen ürünlerin yaprak sayısı, yaprak eni ve uzunluğu, gövde çapı, kök ve gövde uzunluğu, biber ve yaprak rengi ile potasyum miktarında istatistiksel olarak farklılıklar bulunmuştur. Bu

Yayın Kuruluna Geliş Tarihi: 07.08.2025
Kabul Tarihi: 02.06.2026

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farklılıklar, EMA'ın acı süs biberi yetiştiriciliğindeki etkinliğini göstermektedir. Bununla birlikte, uygulanan EMA uygulamalarının toplam meyve verimi üzerinde kontrol grubuna göre istatistiksel olarak anlamlı bir değişime neden olmadığı belirlenmiştir. Araştırmacılar ve üreticiler, kısa süreli düşük voltajlı EMA uygulamalarını bazı büyüme ve besin parametrelerini artırmak için değerlendirebilir; ancak toplam meyve verimini artırmak için koşulların optimize edilmesi gerekmektedir.
Anahtar Kelimeler: Düşük Voltaj, Alternatif Akım, Bitki Fizyolojisi, Besin Bileşimi, *Capsicum*

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Introduction

In order to meet the nutritional needs, which are the most basic requirements of the rapidly increasing world population today, agricultural production needs to be increased and accelerated by various methods. Climate change and unusual weather events negatively affect agricultural productivity, food production and natural resources. This situation also has an impact on food systems and rural livelihoods and leads to a decrease in the number of farmers (FAO et al., 2019). Significant new challenges arise in the production, distribution and consumption of food around the world and in food safety, nutrition and health.

Many studies are carried out under the name of "Innovative Food Processing Technologies and Food Biotechnology" in order to prevent health problems caused by increasing irregular and unhealthy diets and to produce enough healthy products for humanity. Considering the researches on innovative food processing technologies; the improvement and development studies in the fields of supercritical extraction, encapsulation, drying, alternative food processing technologies (omic heating, electrolyzed water, pulsed Ultraviolet (UV) systems, cold plasma, ozone) draw attention (Tübitak, 2020).

Food biotechnology, on the other hand, is the branch of food science in which modern biotechnological methods are applied, and it deals with fermentation and enzyme studies, plant and animal cultures and genetically modified foods (Karasu et al. 2015; Mehenktaş and Bayaz, 2004). In the processes that progress with biotechnological applications, abundant, cheap, high quality and nutritious food products can be obtained.

When the effects of electromagnetic field (EMF) on agricultural products are examined; it is seen that various studies are carried out to meet the food needs of the increasing world population. With the advancing technology, the use of technological tools has increased rapidly. Accordingly, the EMF created by electronic devices and high voltage lines creates various effects on many living things. These effects are also effective in the process until the agricultural products reach the consumer. However, in different studies, it has been determined that EMF shows variable results on plants. Some studies on EMF and plant growth are shown in Table 1.

Ornamental peppers were chosen for this study because they are widely cultivated not only for their aesthetic value but also for their nutritional and health benefits. The food quality of pepper, including parameters such as vitamin content, capsaicin concentration, and overall nutrient composition, is crucial for consumer health and market value. Understanding how experimental treatments influence these quality traits is essential as they directly affect the nutritional value, taste, and commercial acceptability of the crop. They contain high levels of vitamins, antioxidants, and carotenoids, which support human health by enhancing immune function, reducing oxidative stress and providing anti-inflammatory effects. These characteristics make ornamental peppers a suitable model for evaluating how EMF applications may influence both plant growth and nutritional quality.

Table 1. Some previous studies on the effects of electromagnetic field (EMF) and magnetic field (MF) on plant growth

EMF / MF	Exposure details	Plant species / Variety	Result	Reference
Pulsed MF on pepper plants	17 µT & 34 µT, 6 h/day for 15 days	*Capsicum annuum L.*	Increases plant height, leaf area, shoot fresh/dry weight observed	Kaya et al., 2024
MF + ultrasound (US) applications on pepper seedlings	0–1.1 T MF + 40 Hz US, various durations	*Capsicum annuum*	MF and US increased endogenous melatonin and stress tolerance	Yakupoğlu, 2023
0 Hz, 160 mT	15 and 20 min	Onion seed (cv Red Creole)	160 mT for 15 min had a positive effect on germination, seedling formation and plant growth.	Souza et al., 2014
132 kV (high voltage line)	-	Mustard seeds (*Brassica juncea*)	Products (plant height, fruit growth, etc.) at 20 m below the tension line have a positive effect.	Bhattacharya and Barman, 2013
60 mT, 120 mT, 180 mT	5, 10, 15 min	Pea seed (*Pisum sativum* L. cv. Climax)	5 min at 60 mT and 180 mT significantly increased the germination parameters.	Iqbal et al., 2012
10, 50 and 100 mT Static MF Alternative MF generated from a 1.5 T (tesla) magnetic resonance (MR) device.	30, 60, 120, 180, 240 and 360 min 1, 5, 10 and 15 min	Date seed (*Phoenix dactylifera* L.)	Proline concentration increased at 10 mT, 240 min. Proline decreased as the exposure time increased at 50 and 100 mT. AMF, 1 min proline decreased.	Dhawi and Al-Khayri, 2008
60 Hz, 50 miliTesla (mT) sinusoidal, 48 mT Static MF	6 and 15 days	Radish (*Raphanus sativus* L.)	Exposure to MF caused early growth of seedlings, while short-term exposure to MF did not change CO_2 uptake	Yano et al., 2004

Although several studies exist on the effects of EMF on germination and early growth of plants, few address plant development as well as the nutritional value of harvested produce under controlled electromagnetic conditions. In this study, a new bobbin pot system that can generate an EMF with low voltage was built and applied to hot ornamental pepper plants on alternating current at 10V and 20V. The novelty of this research is the simultaneous evaluation of plant morphological development as well as food quality parameters of *Capsicum annuum* plants in a controlled electromagnetic environment for cultivation. Therefore, the aim of this study was to investigate the effects of low-voltage alternating current EMFs (10V and 20V) on the morphological growth, yield, and nutritional quality parameters of *Capsicum annuum* plants grown under controlled conditions.

Materials and Methods

Materials

The bobbins produced within the scope of the study consist of Polyvinyl Chloride (PVC) plastic

pipes, upper and lower cap parts produced in the 3D printing machine, transparent plastic lower strainer, press tape, and enameled copper wire. Other devices used are variac (Reksan Regulator, 2.5 kV, Türkiye) gauss meter (PCE-MFM 3000, PCE Instruments, Meschede, Germany), chlorophyll meter (Spad-502 Plus, Konica Minolta, Tokyo, Japan), temperature meter (Fluke-62 MAX+ IR, Fluke Corporation, Everett, WA, USA), automatic digital lux meter, solar irradiance meter (CEM DT-1307, CEM Instruments, Shenzhen, China), digital temperature-relative humidity meter (UNI-T UT-333S, UNI-T, Dongguan, China). General seedling growing peat, sand-gravel and vermicompost were used in the soil mixture. Standard seeds of hot ornamental pepper (*Capsicum annuum*) were used as plant material. The cultivar used in this study was 'Alpçelik', obtained from the Western Mediterranean Agricultural Research Institute, BATEM (Antalya, Türkiye).

Methods

In the study, primarily bobbin pot drawings and manufacturing were carried out for hot ornamental peppers grown in the laboratory environment (Figure 1). After manufacturing, a system arrangement was made for bobbin pots and a parallel circuit was established to create an equal magnetic field (MF) (Figure 2).



Figure 1. Bobbin pot manufacturing



Figure 2. Bobbin pot manufacturing

As soil preparation, a mixture of peat for growing seedlings, vermicompost for increasing efficiency and pebble stone for soil drainage was prepared. In order to reach the field capacity, hot pepper seeds were planted at a depth of 0.5-1 cm 24 hours after the soil became saturated with water. In total, 5 g of ornamental hot pepper seeds were used. Hot ornamental peppers were exposed to EMF in bobbin pots with 10 replications according to random plots and observed until the product was obtained. In order to minimize the interaction of EMFs in bobbin pots, the pots were placed 20 cm away from each other (Baykan and Ünal, 2019). The control group, on the other hand, was placed in an area away from the EMF environment in the same environment. Bobbin pots consist of two parts. The first part consists of PVC pipes with a diameter of 10 cm and a length of 20 cm with a wall thickness of 2 mm. The inner diameter of the second part is 12 cm and other features are the same. For the EMF created by applying 10 and 20 volts on the second part, 0.80 mm diameter enamel-coated copper wire is used to form a coil by spinning 6 times as a result of the calculations made to create a pressband and EMF when 0.20 mm thick. The equation used to determine the number of spires is given below (Görkem, 1993):

$$N = \frac{V_1 \, x \, 10^8}{4{,}44 \, x \, B \, x \, S_n x \, f} \qquad (1)$$

where;
N: Number of turns
V_1: Output power (V)
B: Magnetic field, MF (Tesla)
S_n: Core cross-sectional area (m^2)
F: Frequency (Hz)

The experimental setup consists of two experimental groups and one control group in a laboratory environment. While 10V AC (alternating current) was applied to one group, 20V AC was applied to the other group. The AC voltage levels of 10 V and 20 V were selected based on preliminary trials and previous studies in which low-intensity EMFs were effective on plant growth without causing stress or damage (Radhakrishnan et al., 2019; Sarraf et al., 2020; Shabrangy, 2024). Short-term application durations were applied to avoid potential adverse effects on the plants, while still allowing measurable changes in morphological and nutritional parameters. The selected voltages and exposure times aimed to provide a balance between safety and efficacy, enabling the evaluation of EMF effects under controlled low-intensity conditions. Each group consists of 10 pots and a total of 30 pots with the same characteristics were used. Crops grown in pots were exposed to EMF for 15 minutes, three days a week (Mosa, 2019). The crops were irrigated in such a way that the soil remained moist. The study was continued until the product was obtained and after harvesting, morphological and microbiological analyzes were made on the products. Statistical analyzes were performed using JMP (John's Macintosh Project) statistical discovery software (version 7.0; SAS Institute Inc., Cary, NC, USA). Bobbin pot design is given in Figure 3.

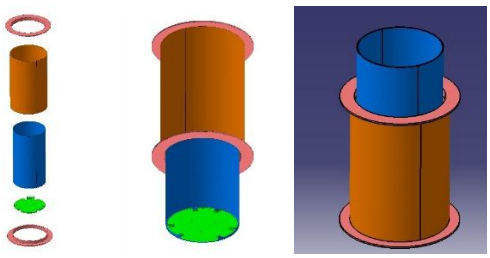


Figure 3. Bobbin pot design

EMF Measurements

The EMF (mT) formed in the voltage (V) values of the products exposed to the EMF was measured and recorded with an alternating current / direct current (AC/DC) magnetic meter (PCE-MFM 3000, PCE Instruments, Meschede, Germany). EMF measurements in the bobbin pot were made from the x, y, z points shown in Figure 4.

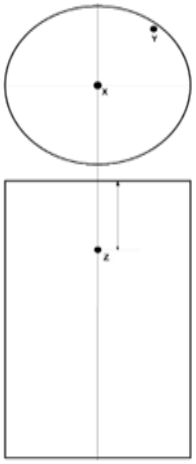


Figure 4. EMF measuring points

Trial Environment and Soil Measurements

The experiments were carried out in a laboratory environment using only daylight, and the light intensity of the environment was measured in Lux and Wm^{-2}, the humidity of the environment in percent (%) and the ambient temperature in °C. Soil moisture, soil bottom and top surface temperatures were also measured regularly. Care was taken to ensure an average ambient temperature of 25 °C and relative humidity in the range of 50-70% in the experimental environment.

Determination of Germination Rate and Speed of Seeds Used

The seeds used in the experiment were germinated for 14 days at an average of 25 °C (International Seed Testing Association ISTA, 1996). The seedlings that were healthy and exceeded 2 mm in development on the 14th day were determined and expressed as a percentage (%). The average germination time (AGT-day) was calculated with daily counts during the germination period (ISTA, 1996; Ulaş, 2019).

$$AGT = \frac{(\sum nD)}{\sum n} \qquad (2)$$

where;
AGT: Average germination time
N: number of seeds germinated in D day
D: Number of days since the start of the germination test

Morphological Characteristics of Hot Pepper Seedlings

Morphological measurements were carried out on three seedlings in the 12th week when the hot ornamental peppers became seedlings after their true leaves emerged. In morphological observations, plant height, root length, number of leaves, leaf width and height measurements were made with the help of digital caliper and statistically evaluated (Poşta et al., 2016).

Calculation of Fresh and Dry Weights of Root and Vegetative Parts (g/plant)

Plants that have reached harvest maturity are divided into vegetative parts (leaf + stem) and root after harvest. Fresh weight was calculated by weighing the vegetative parts of all plants. After the roots were cleared from the soil, they were washed in deionized water, dried, and the wet weight was determined on a precision balance. The vegetative parts of which the wet weight was determined were dried in paper bags in an oven at 70 °C until they reached a constant weight. After drying, the samples were weighed on a precision scale and their dry weights were determined. Root-stem ratio was found by dividing dry roots by dry stem weight (Luo et al., 2021; Ulaş, 2019).

Determination of Root and Stem Length, Number of Lateral Branches and Leaves, Leaf Area, Fruit Yield, Fruit Number, and Average Fruit Weight

Three plants were selected from each treatment applied, and the stem of the plants was measured with a meter starting from the root collar of the plants to the apex. As a result of the treatments applied, the number of side branches and leaves on the harvested plants was counted and determined as number.plant^{-1} (Luo et al., 2021; Ulaş, 2019). At the end of the experiment, 10 leaves that reached average maturity were taken from each harvested group. The leaves were scanned using Adobe Photoshop CS6 Extended and the leaf area was calculated by proportioning the total scanned area pixels with the leaf pixels and expressed as mm^2.plant^{-1} (Dhawi, 2018). Ripe hot ornamental peppers were harvested and weighed using a precision balance and total fruit yield was recorded as g plant^{-1}. The number of fruits per plant was determined by counting the fruits of hot ornamental pepper seedlings in each pot and expressed as number.plant^{-1}. The average fruit weight (g.plant^{-1}) was calculated by dividing the total fruit weight obtained from the harvested plants by the total fruit number.

Leaf Chlorophyll İndex and Color Measurement

Chlorophylls are the pigments that give the plant its green color, and they absorb sunlight and convert it into chemical energy. Chlorophyll a and b can be studied by various methods. In this study, chlorophyll index was measured using a chlorophyll meter 5 days a week for 9 months. The first decision about food quality is often made by looking at the color of the product. It is necessary to examine the color properties of the product and the changes in the color during the process. For this reason, 3nh colorimeter (Shenzhen 3nh Technology Co., Ltd., Shenzhen, China) was used to measure the color change in hot ornamental peppers growing in the EMF. Color measurements were made with 10 replications when each fruit reached maturity. L*, a*, b*, C, α°, ΔE* values were evaluated statistically. L* represents the lightness in the three-dimensional CIELAB color space (lightness–darkness scale), while positive and negative a* values indicate redness and greenness, and positive and negative b* values indicate yellowness and blueness, respectively. Measurements were made on the outer surface of the samples after initial calibration against standard white and black surface plates. ΔE* refers to the total color difference between the two samples. The larger the ΔE* value, the greater the difference between the colors being compared. The C chroma value represents the color saturation. The higher the value, the brighter the color, and the smaller the value, the more opaque it is observed. C chroma value, tone angle α° and ΔE* values were calculated using the equations below (İzli et al., 2017):

$$C = \sqrt{(a^*)^2 + (b^*)^2} \quad (3)$$

$$\alpha^\circ = tan^{-1}(b^*/a^*) \quad (4)$$

$$\Delta E^* = \sqrt{(\Delta L^*)^2} + \sqrt{(\Delta a^*)^2} + \sqrt{(\Delta b^*)^2} \quad (5)$$

where;
C: Chroma value
a*: Red/green coordinate
b*: Yellow/blue coordinate
α°: Hue angle,
L*: Lightness
ΔE*: Total difference
ΔL*: L* sample - L* standard
Δa*: a* sample - a* standard
Δb*: b* sample - b* standard

Method of Examination of Nutrient Contents

Iron (Fe), Calcium (Ca), and Potassium (K) analyses were performed using an ICP-MS (Inductively Coupled Plasma Mass Spectrometry) device according to the NMKL 186 analysis method (Nordic Committee on Food Analysis), with service procurement from the Food and Feed Control Central Research Institute of the T.C. Ministry of Agriculture and Forestry (Bursa, Türkiye). Food energy method analysis and conversion factors method source and energy determination calculation in plant foods were made using American Oil Chemists' Society (AOCS) official procedure Am 5-04, ANKOM Technology (ANKOM Technology, Macedon, NY, USA) method-Version 1/30/09. Total fat amount determination by AOAC 920.39 method and protein amount determination by Kjeldahl method as well as food energy method analysis and conversion factors-2003 (Atwater method) AOAC 968.28; Carbohydrate analysis was carried out with the TS EN ISO 10520 method. Fiber determination was made using the enzymatic technique with the ANKOM Rapid Test method source, and dry matter was determined using the physical method with the TS 1129 ISO 1026 method source.

Statistical Analsis

Statistical analyses were performed using JMP Statistical Discovery Software (version 7.0; SAS Institute Inc., Cary, NC, USA). Data were checked for normality and homogeneity of variances before analysis. Differences among treatments were evaluated using one-way ANOVA and means were compared with Tukey's Honestly Significant Difference (HSD) test at a 5% probability level ($p<0.05$). All values are presented as mean ± standard deviation.

Results and Discussion

Hot peppers grown under the influence of EMFs in a controlled manner within the scope of the study are shown in Figure 5 and their positions in the bobbin pot are shown in Figure 6.



Figure 5. Hot ornamental peppers grown in an electromagnetic field (EMF)



Figure 6. The positions of hot ornamental peppers in the bobbin pot

Electromagnetic Field (EMF)

Two different electrical circuits connected to the national electricity network via variac were created as two independent groups with bobbin pots. One of them is 10V AC group and the other is 20V AC group. The third bobbin pot group is the control group and is not connected with an electrical circuit. Since no electrical treatment was applied to the control group in the bobbin pots, it was placed away from the EMF. The EMF values at x and y positions shown in Figure 4 are given graphically in Figure 7.

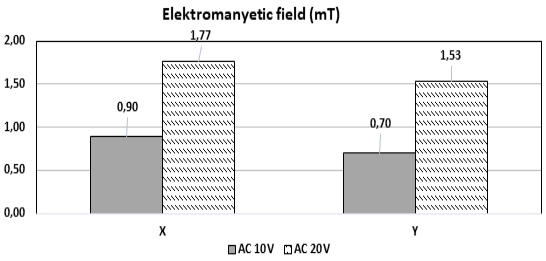


Figure 7. Electromagnetic field (EMF) (mT: miliTesla)

While the EMF values in the x-y position of 10V AC occurred in the range of 0.90-0.70 mT, these

values occurred in the range of 1.77 mT to 1.53 mT at 20V AC. These obtained EMF values are within the low EMF scope for which the study is envisaged.

Trial Environment and Soil

The experimental environment was kept at the ideal temperature and humidity values for the growth of pepper. Figure 8 shows the temperature and humidity values of the experimental environment during the period between planting and harvesting of peppers.

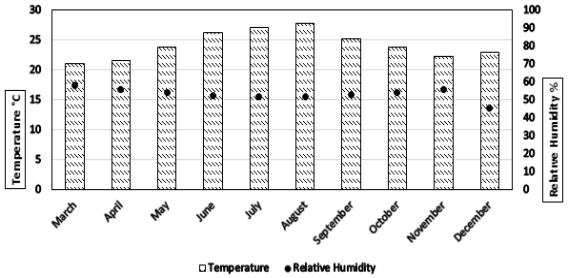


Figure 8. Monthly average temperature and relative humidity values of the trial environment

Here, the highest values are seen in June, July and August in terms of temperature, while the lowest temperatures are observed in March and November. The relative humidity values in the environment decreased with the increase in temperature between March and June and reached the lowest value in July and August. In November, it started to rise with the decrease in temperature. Temperature is directly proportional to air humidity and inversely proportional to relative humidity (Parlak, 2014). In studies conducted in protected open cultivation conditions in a vegetable research farm in India, it has been stated that the maximum and minimum values of the temperature throughout the year are 15-37 °C and the relative humidity is 65-93% (Sran and Jindal, 2022). Morphological and physiological properties are affected by high radiation (Hoffman at al., 2015). Radiation values falling on hot ornamental peppers were measured as both Lux and W.m^{-2} (Figure 9).

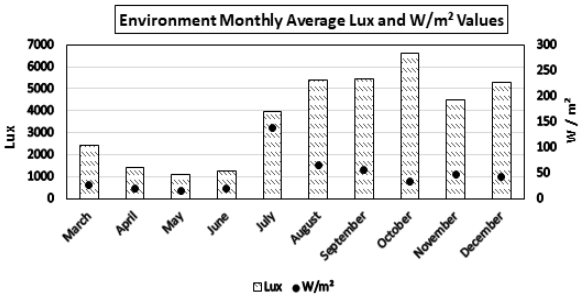


Figure 9. Average monthly light values falling on the environment

As seen in Figure 9, it was observed that there was a decrease in lux and Wm^{-2} values between March and June. As of July, lux and Wm^{-2} values have increased. As of August, it was observed that Wm^{-2} values decreased while lux values increased. The reason for the inconsistency between Lux and Wm^{-2} is the cloudiness of the weather and the changes in wavelengths accordingly.

The monthly average temperature and moisture change values of the soil obtained within the scope of the study are given in Figure 10. Temperature values were measured separately both in the soil (depth) and at the soil surface. The moisture value in Figure 10 shows the soil moisture.

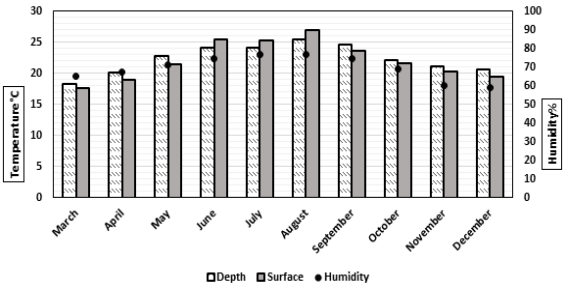


Figure 10. Soil monthly average temperature and moisture change

Soil temperature and moisture were measured regularly using a digital temperature meter (Fluke-62 MAX+ IR, Fluke Corporation, Everett, WA, USA). Based on the recorded data, it was found that exposure to the EMF increased the soil temperature by approximately 1.3 °C compared to the control group.

In a measurement made on the rose leaf in a previous study, it was stated that the MF increased the temperature by 0.1 °C in about 16 minutes (Grémiaux et al., 2016). In addition, electromagnetic heaters are used in direct soil analysis (Liu et al., 2020). In this case, small cracks form on the surface of the sown seeds and germination occurs in a shorter time (Singh et al., 2021). When Figure 10 is examined, it is seen that

the soil depth temperatures are high between March-June and September-November. It is observed that the surface temperature increased in June-August. In the studies conducted by Mahmood et al. (2012), it was stated that the relationship between soil moisture and surface temperature is uncertain. It is stated that soil depth temperatures in the range of 5-30 cm are 13.2-39.7 °C in protected open cultivation studies conducted in India (Sran and Jindal, 2022).

Determination of Germination Rate and Germination Time in Seeds Used

In the statistical analyzes related to the mean germination rate and germination time in seeds, no significant difference was observed in the relationship of average germination time (AGT) and germination rate with EMF (Table 2).

Table 2. Effect of electromagnetic field (EMF) created in bobbin pots on germination rate and germination time (mean ± SD, n = 10)

Treatment	Average germination time (days)	Germination rate (%)
Control	6.4 ± 0.3^{a}	84.3 ± 2.1^{a}
10V AC	6.9 ± 0.3^{b}	84.0 ± 1.8^{a}
20V AC	6.5 ± 0.3^{a}	86.0 ± 2.0^{a}

Values with different letters within a column indicate statistically significant differences (Tukey's test, $p < 0.05$)

While the average germination time was between 6.4 to 6.9 days, the germination rate ranged between 84.0% and 86.0%. Sudsiri et al. (2023) reported that in their study on date palm germination under a rotating MF, the treatment group reached 100% total germination after 37 days and the maximum daily germination rate was estimated at about 6.46% ± 0.04% per day based on a logistic model. These results demonstrate that MF treatments can accelerate the germination process without affecting the final germination percentage.

3.4. Morphological Characteristics of Hot Ornamental Pepper Seedlings

The results regarding the number of leaves, leaf width and length, stem diameter and root length of hot ornamental pepper grown in EMF are given in Tables 3 and 4. These tables also include statistical results.

Table 3. Mean squares of electromagnetic field (EMF) treatments

Variance Source	DF	Number of Leaves	Leaf Width (mm)	Leaf Length (mm)	Stem Diameter (mm)	Root Length (mm)
Treatment	2	55.60*	337.56*	1614.17*	5.47*	7350.18*
Error	27	1.17	10.03	29.25	0.09	446.07

*: Significant at 0.05 probability level, DF: Degrees of Freedom

Table 4. The effect of electromagnetic field (EMF) treatments on morphological characteristics on hot pepper seedlings.

Treatment	Number of Leaves	Leaf Width (mm)	Leaf Length (mm)	Stem Diameter (mm)	Root Length (mm)
Control	2.80 ± 0.20^{c}	11.51 ± 0.8^{c}	19.45 ± 1.1^{c}	1.00 ± 0.05^{c}	23.90 ± 1.5^{b}
10V AC	4.20 ± 0.25^{b}	16.07 ± 1.2^{b}	25.51 ± 1.5^{b}	1.37 ± 0.08^{b}	61.39 ± 3.1^{a}
20V AC	7.40 ± 0.30^{a}	23.05 ± 1.5^{a}	43.85 ± 2.0^{a}	2.43 ± 0.10^{a}	76.57 ± 4.2^{a}
LSD(%)	0.98	2.89	4.94	0.27	19.31

Values with different letters within a column indicate statistically significant differences ($p<0.05$)

As seen in Tables 3 and 4, statistically significant differences were found between the treatments at the 5% probability level. As a result of the grouping (LSD), it is seen that 20V AC has the highest values in the number of leaves, leaf width and height, and stem diameter compared to the

control group. When the root length is examined, 10V AC and 20V AC have high values, remain in the same statistical group and do not show any significance between each other. The control group has a lower value. Volkov et al. (2020) stated in their study that radiofrequency capacitors can be used to increase the germination rate of seeds, increase the growth rate of plant seedlings, and increase the pores of bio-tissue surfaces.

Fresh and Dry Weights of Root and Vegetative Part

The fresh and dry weight of the root, the fresh and dry weight of the vegetative part, and the root/stem ratio values are given in Table 5. As a result of the statistical evaluation, no statistically significant difference was found between the root fresh and dry weights and root/stem ratios. In the vegetative part, the wet weight control group differed according to 20V AC and the dry weight control differed according to both treatment applications.

Table 5. Effect of AC current pattern on root and vegetative parts

Treatment	Root		Vegetative Part		
	Age Weight (g.plant^{-1})	Dry Weight (g.plant^{-1})	Wet (Fresh) Weight (g.plant^{-1})	Dry Weight (g.plant^{-1})	Root/Stem Ratio
Control	6.9 ± 0.3^{b}	1.1 ± 0.1^{b}	42.8 ± 2.5^{a}	8.4 ± 0.5^{a}	0.13 ± 0.02^{b}
10V AC	7.4 ± 0.3^{a}	1.4 ± 0.1^{b}	35.3 ± 2.0^{b}	6.8 ± 0.4^{b}	0.23 ± 0.03^{a}
20V AC	7.1 ± 0.3^{ab}	1.1 ± 0.1^{b}	40.0 ± 2.3^{ab}	7.0 ± 0.5^{b}	0.16 ± 0.02^{ab}

Values with different letters within a column indicate statistically significant differences ($p<0.05$)

Upadhyaya et al. (2022) reported that tomato plants exposed to non-ionizing radiation at 1800 MHz for 12, 60, and 120 hours showed a consistent reduction in dry weight by 19.56%, 41%, 30%, and 47.8%, respectively.

Calculation of root and stem length, Number of lateral branches and leaves per plant, Total fruit yield, Number of fruits per plant and Average fruit weight

Root and stem length (cm.plant^{-1}), plant lateral branch and number of plant leaves (pieces.plant^{-1}) are given in Table 6.

Table 6. Effect of electromagnetic field (EMF) on root and stem length, number of lateral branches and leaves

Treatment	Root Length (cm.plant^{-1})*	Stem Length (cm.plant^{-1})*	Number of Side Branches (pieces.plant^{-1})	Number of Leaves (pieces.plant^{-1})
Control	31.1 ± 1.5^{b}	71.7 ± 2.3^{b}	18.2 ± 1.1^{a}	160.5 ± 5.2^{a}
10V AC	37.6 ± 2.1^{ab}	83.6 ± 2.5^{a}	19.8 ± 1.2^{a}	177.1 ± 6.0^{a}
20V AC	42.2 ± 2.4^{a}	84.3 ± 2.7^{a}	18.9 ± 1.3^{a}	221.5 ± 6.8^{a}

*: Significant at 0.05 probability level

Values with different letters within a column indicate statistically significant differences ($p<0.05$)

As a result of the statistical evaluation, root and trunk length were found to be significant, while the number of lateral branches and the number of leaves were found to be insignificant. While the highest average in root length belonged to 20V AC, the lowest average was seen in the control group.

In the body length, the highest value belongs to 10V AC and 20V AC, and the lowest value was found in the control group. Kumar et al. (2020) also; examined root growth in onions exposed to 900 mHz (millihertz) and 1800 mHz and observed that roots exposed to EMF for more than 2 hours decreased in length. They found an increase in root thickness. In the same study, an increase in the mitotic index was also observed.

The effects of EMF on fruit yield were investigated. As the average of the first 2 harvests, the total fruit yield, the number of fruit per plant, and the average fruit weight values in the bobbin pot groups are given in Table 7.

Table 7. Effect of electromagnetic field (EMF) treatments on pepper yield (average of 2 harvests)

Treatment	Total Fruit Yield (g.plant^{-1})	Number of fruits per plant (number.plant^{-1})	Average Fruit Weight (g.fruit^{-1})
Control	5.0 ± 0.3^{a}	4.6 ± 0.4^{a}	1± 0.05^{a}
10V AC	3.3 ± 0.2^{b}	3.5 ± 0.3^{b}	1± 0.04^{a}
20V AC	2.3 ± 0.3^{c}	4.9 ± 0.5^{a}	1± 0.05^{a}

* Different letters (a, b, c) indicate significant differences at $p < 0.05$

The effect of the EMF created in bobbin pots on fruit yield was found to be statistically significant. Although the differences were statistically significant, the magnitude of the treatment effects on yield components was biologically limited. Pietruszewski (1996), in his study titled Effects of magnetic biosimulation of wheat seeds on germination, yield and proteins, stated that the orientation of the seeds in the MF during pre-sowing biostimulation did not affect the crop yield and the percentage of albumin and gluten in wheat seeds.

Leaf Area, Leaf Chlorophyll Index and Color Measurement

The effects of the EMF on the leaf area are given in Table 8.

Table 8. Effects of electromagnetic field (EMF) on leaf area

Variance Source	DF	SS	MS	F	Leaf Area (mm^2)	
General	29	62.105	-	-		
					Control	7.02 ± 0.21^{a}
Treatment	2	45.915	22.957*	38.287	**AC10V**	5.86 ± 0.18^{b}
					AC20V	4.01 ± 0.15^{c}
Error	27	16.189	0.599			

*: Significant at 0.05% probability level

Values with different letters within a column indicate statistically significant differences ($p<0.05$). DF: Degrees of Freedom, SS: Sum of Squares, MS: Mean Square

It was observed that the treatments applied in the area calculations of pepper leaves grown in bobbin pots were effective at $p<0.05$ probability level. In the evaluation between the groups, the highest value belongs to the control group and the lowest value belongs to 20V AC. When the effect of the EMF on the chlorophyll increase index was analyzed statistically, the treatments were found to be insignificant at the $p<0.05$ probability level. In Figure 11, monthly chlorophyll increase amount of the bobbin pot control group, AC 10 V and AC 20 V is given. In the graph given in Figure 11, the highest value was observed in September with 52.2, while the lowest value was observed in May, which is the seedling period of hot ornamental pepper. Looking at the monthly chlorophyll index of 10V AC in the graph given, September and October show the highest values, while May shows the lowest values. Looking at the monthly chlorophyll index of 20V AC, it is understood that while it has the lowest chlorophyll value in seedling in May, it has the highest chlorophyll value in September. In general, while the chlorophyll index was the lowest in the control group, the highest value was observed in 20V AC measurements.

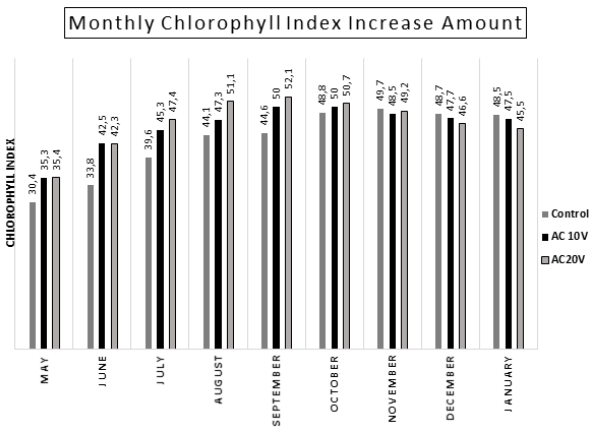


Figure 11. Bobbin pot control group, 10V AC, 20V AC chlorophyll index

The absorbance (A) values, which indicate the amount of light absorbed by pigments in the leaf, were measured at 470, 645, 652, and 663 nm wavelengths to determine total chlorophyll, chlorophyll a and b, and carotenoid contents. The results are presented in Table 9.

Table 9. Total chlorophyll, chlorophyll a and b (Chl-a, Chl-b) and carotenoid values in the leaf

Treatment	Total chlorophyll	Chl-a	Chl-b	Carotenoid
Control	0.22 ± 0.01[a]	1.46 ± 0.05[a]	1.81 ± 0.07[a]	0.51 ± 0.02[a]
10V AC	0.25 ± 0.02[a]	1.48 ± 0.06[a]	2.24 ± 0.08[a]	0.55 ± 0.03[a]
20V AC	0.26 ± 0.01[a]	1.97 ± 0.07[a]	1.80 ± 0.06[a]	0.68 ± 0.02[a]

Different letters in each column indicate significant differences at $p < 0.05$

As a result of the statistical analysis, it was observed that the EMF did not have a significant effect on the leaf total chlorophyll, chlorophyll a and b and carotenoid values. Chlorophyll values may vary according to the growth stage. Chlorophyll a has an excitation between 360-460 nm, while chlorophyll b has an excitation between 420-480 nm (Shin et al., 2018; Manolopoulou et al., 2016).

Table 10. Average effect of electromagnetic field (EMF) treatments on leaf color of hot ornamental pepper seedlings.

Treatment	L*	a*	b*	C	α°	ΔE
Control	40.4 ± 1.2[a]	-10.3 ± 0.5[b]	16.3 ± 0.8[a]	19.3 ± 1.0[a]	-57.6 ± 2.1[a]	-
10V AC	38.9 ± 1.0[b]	-8.4 ± 0.4[a]	13.7 ± 0.6[b]	16.1 ± 0.9[b]	-58.5 ± 1.8[a]	34.3 ± 1.8 [a]
20V AC	38.3 ± 0.9[b]	-7.9 ± 0.5[a]	14.3 ± 0.7[b]	16.4 ± 0.8[b]	-61.0 ± 2.0[b]	37.6 ± 1.8 [a]

Values with different letters within a column indicate statistically significant differences ($p<0.05$) (Tukey's test). SD: Standard deviation.

The effect of EMF treatments on leaf color change was found to be statistically significant (Table 10). The illuminance value L*, 10V AC and 20V AC remained in the same group compared to the control group and has a lower value. Therefore, the control group was brighter than the other groups. On the other hand, -a*, which indicates the greenness value, was not significantly different between treatments, as 10V AC and 20V AC were in the same group compared to the control group. It showed less greenery than the control group. In the expression of yellowness-blueness, the highest b* value was observed in the control group, indicating that the control group was closer to yellow. When the chroma (color saturation) value and hue angle were examined, the control group had the highest values. The control group was brighter and closer to green than the other groups. ΔE showed no significant difference between the colors compared. The average effect of the EMF on hot pepper fruit color is presented in Table 11.

Table 11. Average effect of electromagnetic field (EMF) treatments on hot ornamental pepper fruit color

Treatment	L*	a*	b*	C	α°	ΔE
Control	52.5 ± 1.4[a]	4.0 ± 0.6[b]	28.7 ± 1.0[a]	29.8 ± 1.2[a]	28.3 ± 1.5[a]	-
10V AC	49.0 ± 1.2[a]	8.3 ± 0.8[ab]	26.3 ± 0.8[a]	29.1 ± 1.1[a]	18.7 ± 1.3 [b]	51.4 ± 2.0[a]
20V AC	42.9 ± 1.3[b]	15.1 ± 0.7[a]	23.1 ± 0.9[b]	28.8 ± 1.1[a]	39.8 ± 1.7[a]	48.7 ± 1.9[a]

Values with different letters within a column indicate statistically significant differences ($p<0.05$)

At the $p<0.05$ probability level of the EMF, the L*, a* and b* values of pepper color were found to be statistically significant, whereas the other color parameters were statistically insignificant. Similarly, Lee et al. (2020) reported that pulsed light plasma treatment (6.3 min, plasma voltage 10 kV, IPL voltage 2 kV, and frequency 3.8 Hz) did not cause any color change in red pepper powder.

Nutrient Content Analysis

The results obtained in the nutrient content analyzes carried out within the scope of the study are given in Table 12.

Table 12. Nutrient content analysis results

Analyzes	Control	10V AC	20V AC
Carbohydrate, %	1.05 ± 0.05^{b}	1.80 ± 0.08^{a}	1.27 ± 0.06^{b}
Protein, %	5.17 ± 0.10^{a}	4.98 ± 0.09^{a}	4.85 ± 0.08^{a}
Crude fat, %	3.34 ± 0.07^{b}	4.25 ± 0.09^{a}	2.64 ± 0.06^{c}
Dietary Fiber, %	13.6 ± 0.5^{b}	15.8 ± 0.6^{a}	14.9 ± 0.5^{a}
Dry Matter, %	75.5 ± 1.2^{a}	72.0 ± 1.1^{b}	72.9 ± 1.0^{b}
Iron (Fe), mg.kg^{-1}	7.3 ± 0.3^{a}	5.0 ± 0.2^{b}	6.5 ± 0.3^{a}
Calcium (Ca), mg.kg^{-1}	167 ± 5^{b}	284 ± 6^{a}	266 ± 5^{a}
Potassium (K), mg.kg^{-1}	6726 ± 150^{b}	8575 ± 180^{a}	8696 ± 170^{a}

Values with different letters within a column indicate statistically significant differences ($p<0.05$) (Tukey's test). SD: Standard deviation.

As a result of the analysis, 10V AC had the highest percentage value in terms of *carbohydrates* among the treatments, while the value of the control group was found to be higher in protein analysis.

While 10V AC had a high value in *crude oil* and *dietary fiber* value, it was seen that the high value in *dry matter* belonged to the control group. As seen in Table 12, while the *iron* element was 7.3 mg.kg^{-1} in the control group, 10V AC 5 mg.kg^{-1} and 20V AC 6.5 mg.kg^{-1}. *Ca* element values were determined as 167 mg.kg^{-1}, 284 mg.kg^{-1} and 266 mg.kg^{-1} at control, 10V AC and 20V AC, respectively. *Potassium* values are listed as 6726 mg.kg^{-1}, 8575 mg.kg^{-1} and 8696 mg.kg^{-1}. On the *potassium* element, although there is not much difference between 10V AC and 20V AC, 20V AC has the highest value. Mi et al. (2020) based on multi-element analysis, the value of Fe element in the range of 6.81-8.2 mg.kg^{-1}, the element Ca 86.32-111.12 mg.kg^{-1} and the element K 3208.82-3389.32 in the characterization and separation of hot peppers. They are expressed in mg.kg^{-1}. In addition, studies on soil fertilization have shown that the potassium value in pepper is 112.78 kg.ha^{-1} (Mali et al., 2019). It has been noted that charges with water undergoing electromagnetic treatment significantly increase the P, N and K content in all tissues of the potato (Hachicha et al., 2018). Compared to standard data, the results obtained are close to each other between groups, but have higher values compared to standard data.

The statistical effects of EMF treatments (10V AC and 20V AC) on all measured parameters were evaluated and are summarized in Table 13.

Table 13. Summary of statistical significance of electromagnetic field (EMF) treatments on measured parameters

Examined Parameters*	10V AC		20V AC	
	Statistical Evaluation	Treatment Effects	Statistical Evaluation	Treatment Effects
Germination rate and Germination time	-	**0**	-	**0**
Number of leaves, Leaf width and length, Stem diameter, Root length of seedling peppers	+	+	+	+
Wet and dry weights at root, root/stem	-	**0**	-	**0**
Vegetative part; Wet and dry weight	+	-	+	-
Root and trunk length	+	+	+	+
Number of side branches and Number of leaves	-	**0**	-	**0**
Leaf area	+	-	+	-
Leaf chlorophyll index, Chl-a, Chl-b and Carotenoid	-	**0**	-	**0**
Leaf and Fruit color measurement	+	-	+	-
Total fruit yield, Number of fruits per plant, Average fruit weight	-	**0**	-	**0**
Carbohydrate		+		+
Crude fat		+		-

Dietary fiber	+	+
Calcium	+	+

*: "-" sign means unimportant, "+" sign means important in statistical evaluation. In the impact assessment, "-" sign was expressed as negative, "+" sign as positive and "0" as ineffective.

According to the results, the responses of the parameters to EMF application varied depending on the treatment intensity. While some parameters such as leaf number, root length, and nutrient content showed statistically significant differences, others, including total fruit yield, did not exhibit significant changes. These findings indicate that EMF treatments had selective effects on plant growth and development.

Conclusion

Electromagnetic field (EMF) application with 10V AC voltage values corresponded to 0.70-0.90 mT (y-x) while the application with 20V AC voltage values corresponded to 1.53–1.77 mT (y–x). It was concluded that the EMF application at 10V AC under short-term and low-intensity conditions was effective in improving the number of leaves, root length, carbohydrate content, crude fat, dietary fiber, and calcium levels in hot ornamental pepper plants. Similarly, the EMF application at 20V AC was found to be effective on the number of leaves, leaf width and length, stem diameter, root and stem length, as well as pepper and leaf color and potassium content. However, no statistically significant increase was observed in total fruit yield compared to the control group. Although the EMF positively affected several growth and nutritional parameters, the absence of a significant increase in total fruit yield was attributed to the short duration and low intensity of the treatments. It was suggested that longer durations or higher intensities might be required to achieve a significant improvement in yield. The statistical effects of 10V AC and 20V AC treatments were evaluated.

Furthermore, it was suggested that additional physiological parameters such as photosynthesis, transpiration, stomatal conductance, and leaf temperature should be evaluated in future studies to better understand plant responses during EMF applications. In conclusion, short-term low-voltage EMF treatments can be considered a promising approach to enhance certain growth and nutritional parameters; however, further studies were required to optimize the treatment conditions for improving total fruit yield.

Acknowledgement

This article has been prepared by using the data of the doctoral thesis named "Effects of Electromagnetic Field on the Development and Food Quality of Hot Ornamental Pepper (*Capsicum annuum*)" produced from Bursa Uludağ University Scientific Research Project Unit (BAP), the project numbered "FGA-2021-375". We thank BAP for their support.

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