jotaf
Journal of Tekirdag Agricultural Faculty
Tekirdağ Ziraat Fakültesi Dergisi

Mayıs/May 2026, 23(3)
Başvuru/Received: 16/10/25
Kabul/Accepted: 06/05/26
DOI: 10.33462/jotaf.1805127

http://dergipark.gov.tr/jotaf
http://jotaf.nku.edu.tr/

ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

The Effect of Direct Current Stimulation on the Growth and Nutrient Uptake of Hot Ornamental Pepper (*Capsicum annuum*)*

Doğru Akım Uyarımının Acı Süs Biberinin (*Capsicum annuum*) Gelişimi ve Besin Alımı Üzerine Etkisi

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Abstract

Pepper (*Capsicum annuum*) is an important horticultural crop cultivated in tropical and subtropical regions worldwide. With increasing consumption demand, pepper has gained attention for its beneficial properties in preventing atherosclerosis, cancer, and cardiovascular diseases, as well as for improving physical resistance. However, pepper has a short shelf life and is highly susceptible to decay and fungal infections. Therefore, various methods such as direct electric current (DC) stimulation are being investigated in plant cultivation. This study aimed to evaluate the effect of direct electric current (DC) stimulation on the development of hot ornamental pepper (*Capsicum annuum*) seeds. Numerous studies in the literature have examined the effects of electrical and DC stimulation on seed development, and it is also known that electric current can improve the quality of food products. In this study, the effects of DC stimulation on hot ornamental pepper seeds from germination to harvest maturity were evaluated through morphological measurements and nutritional analyses. Electrode pots used for DC stimulation were designed and produced specifically for this study. The pots were constructed from 5-mm plywood with copper sheets embedded on the inner surfaces. Hot ornamental pepper seeds were placed in these electrode pots and exposed to DC stimulation at 10 V, 20 V, and 30 V for 15 minutes, three times per week. The experimental setup consisted of three treatment groups and one control group. Throughout the experiment, parameters such as germination rate and time, seedling morphological characteristics, fresh and dry weights of roots and vegetative parts, leaf area, chlorophyll index, color measurements, and nutrient contents (carbohydrate, crude fat, dietary fiber, potassium, calcium, iron) were examined. The results showed that, among the evaluated parameters, number of leaves, leaf width, stem diameter, root length, root dry weight, leaf area, leaf color, carbohydrate, crude fat, and dietary fiber values were significantly affected by DC stimulation. Additionally, the 30 V DC treatment had a positive effect on potassium accumulation.

Keywords: Direct Current (DC) stimulation, Direct current, Pepper development, Food quality, *Capsicum annuum*

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Atıf: Kananizadeh, T., Vardar, A. (2026). Doğru akım uyarımının acı süs biberinin (*Capsicum annuum*) gelişimi ve besin alımı üzerine etkisi**.** *Tekirdağ Ziraat Fakültesi Dergisi*, 23(3): 1043-1058.
Citation: Kananizadeh, T., Vardar, A. (2026). The effect of direct current (DC) stimulation on the growth and nutrient uptake of hot ornamental pepper (*Capsicum annuum*). *Journal of Tekirdag Agricultural Faculty,* 23(3): 1043-1058.

*This study was summarized from the Tuğba Biçen (Kananizadeh) PhD thesis.

Öz

Biber (*Capsicum annuum*), dünya genelinde tropikal ve subtropikal bölgelerde yetiştirilen önemli bir bahçe bitkisidir. Tüketim talebinin artmasıyla birlikte, biberin ateroskleroz, kanser ve kardiyovasküler hastalıkları önlemede faydalı olduğu ve fiziksel direnci artırdığı için de ilgi çekmektedir. Bununla birlikte biber, kısa raf ömrüne sahip olup çürüme ve fungal enfeksiyonlara karşı oldukça hassastır. Bu nedenle, bitki yetiştiriciliğinde doğru akım (DC) uygulaması gibi çeşitli yöntemler araştırılmaktadır. Bu çalışma, doğru akım (DC) uyarımının acı süs biber (*Capsicum annuum*) tohumlarının gelişimi üzerindeki etkisini değerlendirmeyi amaçlamaktadır. Literatürde elektrik ve DC uyarımlarının tohum gelişimi üzerindeki etkilerine ilişkin çok sayıda çalışma bulunmakta olup, elektrik akımının gıda ürünlerinin kalitesini artırabildiği de bilinmektedir. Bu çalışmada, acı süs biberi tohumlarının çimlenmeden hasat olgunluğuna kadar olan gelişimi üzerindeki DC uyarımının etkileri, morfolojik ölçümler ve besin analizleri kapsamında değerlendirilmiştir. Çalışmada kullanılmak üzere özel olarak elektrot saksılar tasarlanmıştır. Elektrot saksılar, 5 mm kalınlığında kontrplaktan üretilmiş ve iç yüzeylerine bakır levhalar yerleştirilmiştir. Acı süs biberi tohumları bu elektrot saksılara yerleştirilmiş ve haftada üç gün, 15 dakika süreyle 10 V, 20 V ve 30 V DC uyarımına maruz bırakılmıştır. Deney düzeneği üç uygulama grubu ve bir kontrol grubundan oluşmuştur. Deney süresince çimlenme hızı ve süresi, fide morfolojik özellikleri, kök ve vejetatif kısımların yaş ve kuru ağırlıkları, yaprak alanı, klorofil indeksi, renk ölçümleri ve besin içerikleri (karbonhidrat, ham yağ, diyet lifi, potasyum, kalsiyum, demir) incelenmiştir. Elde edilen sonuçlara göre, fide döneminde yaprak sayısı, yaprak genişliği, gövde çapı, kök uzunluğu, kök kuru ağırlığı, yaprak alanı, yaprak rengi, karbonhidrat, ham yağ ve diyet lifi değerleri üzerinde DC uyarımının etkileri belirlenmiştir. Ayrıca 30 V DC uygulamasının potasyum birikimi üzerinde olumlu bir etki oluşturduğu tespit edilmiştir.

Anahtar Kelimeler: Doğru akım (DC) uyarımı, Doğru akım, Biber gelişimi, Gıda kalitesi, *Capsicum annuum*

1. Introduction

Pepper is one of the important garden plants grown in tropical and subtropical regions of the world (Tsegay et al., 2013). There is also research on peppers in our country (Azder et al., 2020; Demirel et al., 2012). With the rapidly increasing population, the demand for the use and consumption of pepper has increased. In addition, pepper has recently attracted great attention as it is found to be beneficial in preventing diseases such as atherosclerosis, cancer, cardiovascular diseases and bleeding, and increasing physical resistance (Marin et al., 2004). However, it is a perishable vegetable with a limited shelf life. Due to its short shelf life, it is susceptible to looseness, wilting, wrinkling, fungal infections and spoilage (Ullah et al., 2017; Bayram et al., 2019). These undesirable qualities often affect the fruit's acceptability to the consumer. For this reason, various methods of growing plants are being researched. One of these methods is the direct electric current (DC) stimulation. Various researches are being conducted on the effects of direct electric current (DC) stimulation on plants. Plants have different topological properties physically, chemically and electrically and consist of different cell and tissue types. These properties can affect both their conductivity and their sensitivity to direct electric current (DC) stimulation-induced electroporation (Liu et al., 2019). When the effects of direct electric current (DC) stimulation on plant tissue are examined in the literature, it is seen that the studies are very few.

In many studies conducted in direct electric current (DC) stimulation, plant organs, tissues and fruits have shown different reactions (Fincan and Dejmek, 2002). Some studies on the direct electric current (DC) stimulation effect are given in *Table 1*.

Table 1. Effect of direct electric current (DC) stimulation on plants

DC	Duration	Sort	Conclusion	Source
0.6 kV cm^{-1}, 120 pulses	-	Soybean (Seedling)	Isoflavonoids (+), Reversible permeabilization (+)	Guderjan et al. (2005)
1500 nT, 10Hz	20 day	Soybean (seed)	Yield, plant; length, fresh weight, proteins, polyphenol oxidase, Fe, Cu, Mn, Zn, Mg, K, Na (+), Ca (-)	Radhakrishnan and Kumari (2012)
10 nT	-	Barley (seed)	Fresh and dry weight (-), Root fresh and dry weight (-)	Lebedev et al. (1977)
20 μT, 16 Hz	12 day	Sunflower (seed)	Germination rate (0), Total, stem and root fresh weight (+), total dry weight (-)	Fischer et al. (2004)
0.6 kV cm^{-1}, 120 pulses	-	Corn (seed)	Phytostreol and reversible permeabilization (+)	Guderjan et al. (2005)
7.3 kV cm^{-1}, 120 pulses	-	Corn (seed)	Phytosterol (-)	Guderjan et al. (2005)

In this study, the germination rate and speed of hot ornamental pepper seeds grown in a direct electric current (DC) stimulation, morphological characteristics of pepper seedlings, fresh and dry weights of roots and vegetative parts, root and stem lengths, leaf chlorophyll index and nutrient contents were examined. As a result of the investigations, the effects of the direct electric current (DC) stimulation on hot ornamental pepper were revealed.

2. Materials and Methods

The electrode pots used in this study were constructed from plywood and copper sheets. The equipment included a DC power supply (305D DC 0–30 V, 0–5 A, USA), chlorophyll meter (SPAD-502 Plus, USA), infrared temperature meter (Fluke-62 MAX+ IR), digital lux meter (TT TECHNIC VC 1010A), solar radiation meter (CEM DT-1307), and digital temperature–humidity meter (UNI-T UT-333S). The growth medium consisted of seedling peat, sand–gravel mixture, and worm manure. Hot ornamental pepper seeds (Batem Alpçelik) were used as standard material. Electrode pots were designed to apply Direct Electric Current (DC) stimulation. The pots were made of plywood (100 × 150 × 1350 mm, 5 mm wall thickness), and copper plates (0.8 mm thickness, 164 mm height, 1330 mm length) were mounted on the inner surfaces (*Figure 1*). The experimental setup consisted of three DC treatments (10, 20, and 30 V) and one control group. Voltage was supplied to the copper plates using a DC power source. Because the soil was kept moist throughout the experiment, it behaved as an ionic conductor rather than a dielectric material. Therefore, the system did not function as a capacitor; instead, it acted as an electrochemical cell through which electric current could pass. Under these conditions, DC application may induce electromigration of ions (e.g., K^{+}, Ca^{2+}, Mg^{2+}) and trigger electrochemical reactions at the electrode–soil interface. During the experiment, only constant voltage was applied, and no direct current (mA) measurements were performed. Since soil moisture varied over time, the actual current flowing through the system may have changed during the experiment. This represents an important methodological limitation of the study.

Hot ornamental peppers were exposed to DC stimulation three days per week for 15 minutes (Mosa, 2019). The control group was kept under identical environmental conditions without electrical stimulation. After harvest, morphological and nutrient analyses were performed. Statistical analyses were conducted using JMP software (version 7.0; SAS Institute Inc., Cary, NC, USA).

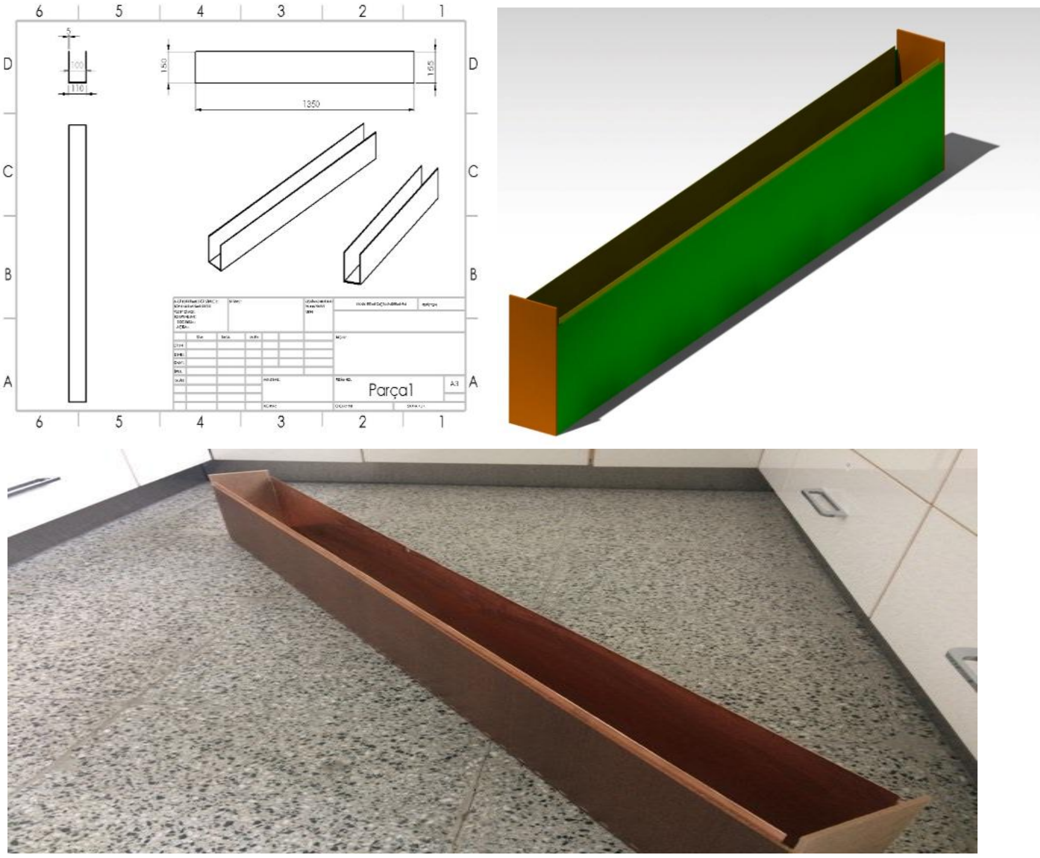

Figure 1. Electrode pot design and prototype

2.1. Trial environment and soil measurements

In experiments conducted in a laboratory environment using only daylight, the light intensity of the environment was measured in Lux and W m^{-2}. Ambient humidity (%) and temperature (°C) were also determined. Soil moisture, subsoil and upper surface temperatures were also recorded during the experiment. Care was taken to ensure that the trial environment was at an average temperature of 25 °C and relative humidity in the range of 50-70%.

2.2. Determination of germination rate and speed of the 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). Seedlings that were healthy and exceeded 2 mm in length on the 14th day of their development were determined and expressed proportionally as a percentage (%). The average germination time (AGT-day) was calculated by counting daily counts throughout the germination period (Ellis and Roberts, 1980).

$$AGT = \frac{(\sum nD)}{\sum n} \quad \text{(Eq. 1)}$$

AGT	Average germination time
n	D number of seeds germinated in days
D	Number of days since the start of the germination test

2.3. Morphological characteristics of hot ornamental pepper seedlings

At the 12th week when hot ornamental peppers became seedlings, three seedlings were selected and morphological measurements were made. In morphological observations, plant height, root length, number of leaves, leaf width and length were measured with the help of a digital caliper (Poşta et al., 2016). It was evaluated statistically.

2.4. Calculation of fresh and dry weights of roots and vegetative parts (g plant^{-1})

After harvest, the plants were divided into vegetative parts (leaves + stem) and roots. Fresh weight was calculated by weighing the vegetative parts of all plants. The roots were washed in deionized water and dried, and their wet weight was determined on a precision scale. The vegetative parts, whose fresh weight was determined, were dried in paper bags in a 70 °C oven until they reached a constant weight. After the samples were dried, they were weighed and their dry weight was determined. The root/stem ratio was found by dividing the dry roots to the dry stem weight (Luo et al., 2021; Ulaş, 2019).

2.5. Calculation of root and stem length (cm plant^{-1}), Number of side branches and leaves in the plant (pcs plant^{-1}), Leaf area (mm^2 plant^{-1}), Total fruit yield (g plant^{-1}), Number of fruits per plant (pcs plant^{-1}), Average fruit weight (g plant^{-1})

Three plants were selected from each treatment. The plant body, starting from the root collar of the plants to the top, was measured with a meter. As a result of the applied treatments, the number of side branches and leaves on the harvested plants was counted and determined as units plant^{-1} (Luo et al., 2021; Ulaş, 2019). From each harvested group, 10 leaves that reached average maturity were taken. The taken leaves were put into the scanner in Ps Adobe Photoshop CS6 Extended program and the total scanned area pixels were calculated by proportioning the leaf area pixels (Dhawi, 2018). Hot ornamental peppers were harvested and measured in g with a precision scale, and the yield values were 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. The total fruit weight obtained from harvested plants was calculated by dividing by the total number of fruits.

2.6. Leaf chlorophyll index and color measurement

Chlorophylls are the pigments that give plants their green color. They can be examined as chlorophyll a and b by various methods. In this study, chlorophyll index was measured using a chlorophyll meter device 5 days a week for 9 months. The color characteristics of the product and the changes in color during the process must be examined. For this reason, 3nh colorimeter was used to measure the color change in hot ornamental peppers growing in direct electric current (DC) stimulation. When each fruit reached maturity, color measurements were made in 10 replicates. L*, a* and b*, C, α°, ΔE* values were evaluated statistically.

L*; It defines a three-dimensional color scale in which brightness (on a lightness-darkness scale) is represented by positive and negative a* values representing redness and greenness, and positive and negative b* values representing yellowness and blueness. Measurements were made on the outer surface of the samples after the initial calibration against standard white and black surface plates. ΔE* refers to the total color difference between two samples. The larger the ΔE* value, the greater the difference between the compared colors. C chroma value indicates color saturation.

The higher the value, the brighter the color, and the lower the value, the duller it is observed. Chroma value C, tone angle α° and ΔE* values were calculated using the following equations (Polat and İzli, 2022):

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

$$\alpha° = tan^{-1}(b^* / a^*) \quad \text{(Eq. 3)}$$

$$\Delta E^* = \sqrt{(\Delta L^*)^2} + \sqrt{(\Delta a^*)^2} + \sqrt{(\Delta b^*)^2} \quad \text{(Eq. 4)}$$

2.7. Nutrient content examination method

Iron (Fe), Calcium (Ca), and Potassium (K) were analyzed on the ICP-MS device with the NMKL 186 analysis method, with service from the Food and Feed Control Central Research Institute of the Ministry of Agriculture and Forestry. Calculation of energy determination in plant foods was made with AOCS official procedure Am 5.04, ANKOM technology method-Version 1/30/09. In addition to determination of total fat amount by AOAC 920.39 method and determination of protein amount by Kjeldahl method, AOAC 968.28; Carbohydrate analysis was carried out using the TS EN ISO 10520 method. Fiber determination was made using the enzymatic technique with the Ankom- Rapid Test method source, and dry matter determination was made using the physical method with the TS 1129 ISO 1026 method source.

3. Results and Discussion

3.1. Trial environment and soil

The trial environment was kept at temperature and humidity values ideal for the growth of pepper. *Figure 2* shows the temperature and humidity values of the trial environment between the planting and harvesting period of peppers.

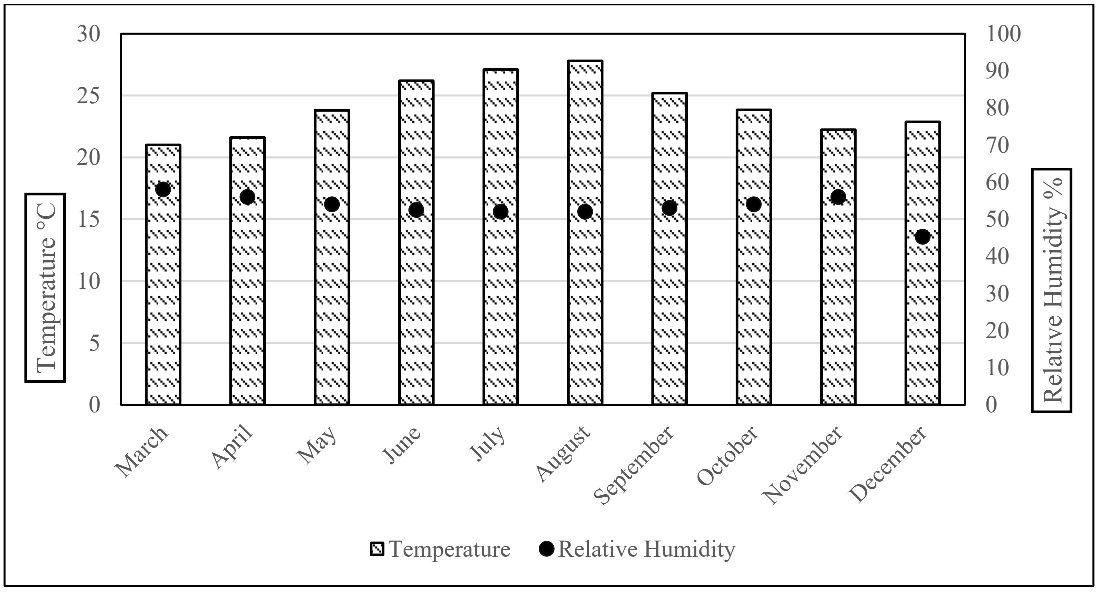

Figure 2. Monthly average temperature and relative humidity values of the trial environment

Here, the highest values in terms of temperature are in June, July and August; The lowest temperatures were observed in March and November. 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 as the temperature dropped. Temperature is directly proportional to the humidity in the air and inversely proportional to relative humidity (Parlak, 2014). In studies conducted under protected open cultivation conditions in a vegetable research farm in India, it was stated that the maximum and minimum values of the temperature throughout the year were 15-37 °C and the relative humidity was 65-93% (Sran and Jindal, 2022). Morphological and physiological characteristics are affected by high radiation (Hoffman et al., 2015). Radiation values falling on hot ornamental peppers were measured in both Lux and W m^{-2} (*Figure 3*).

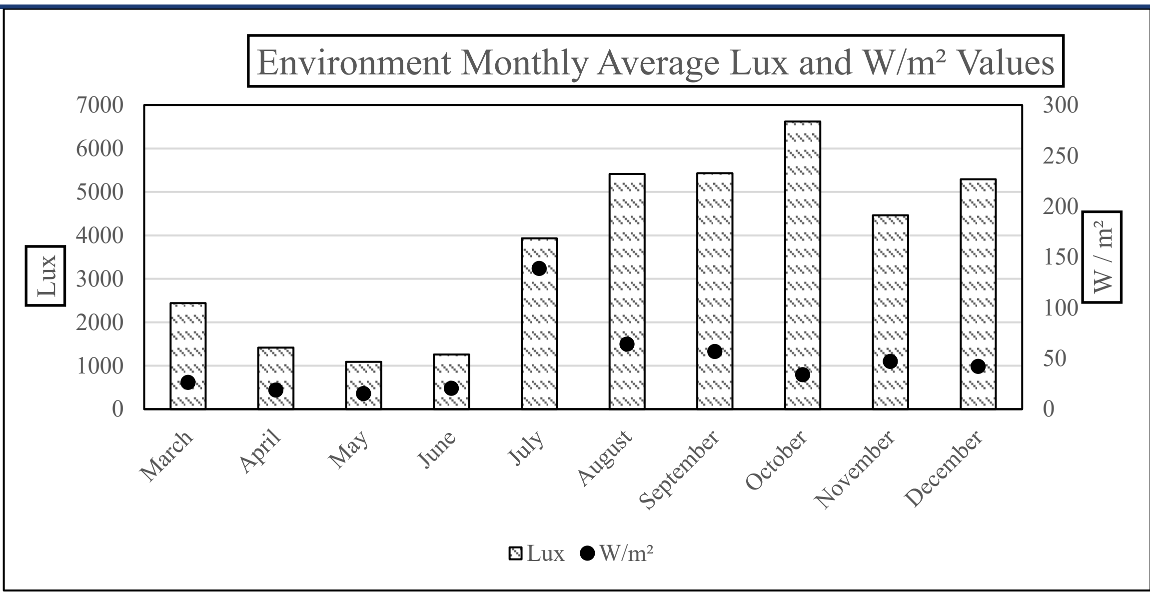

Figure 3. Monthly average light values falling into the environment

As shown in *Figure 3*, both lux and W m⁻² values decreased between March and June. From July onward, lux values increased, while W m^{-2} values decreased. This discrepancy is attributed to the fact that lux and W m^{-2} measure different physical properties. Lux represents visible light perceived by the human eye, whereas W m^{-2} represents total radiant energy. Cloudy weather can reduce total irradiance (W m^{-2}) while increasing diffuse visible light, resulting in higher lux values. Therefore, the divergence between lux and W m^{-2} values is consistent with changes in cloud cover and spectral distribution.

Monthly soil temperature and moisture values are presented in *Figure 4*. Soil temperature was measured both at depth and at the surface, while soil moisture represents volumetric water content.

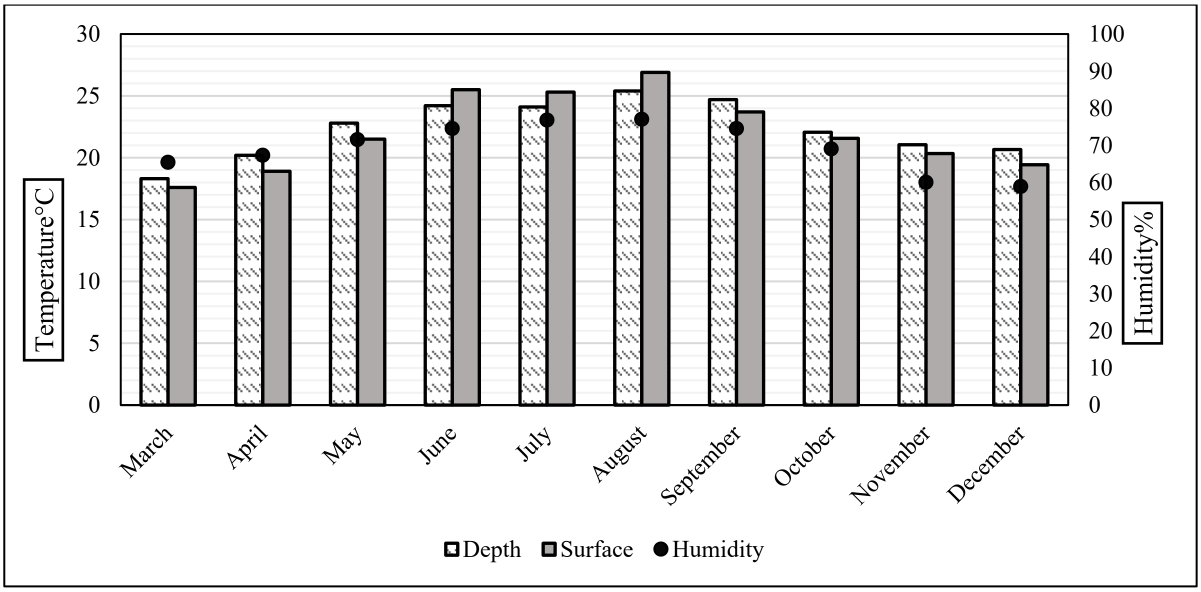

Figure 4. Soil monthly average temperature and moisture change

When soil temperature and moisture changes are examined, it is observed that Direct Electric Current (DC) stimulation increased soil temperature by approximately 1.3 °C. This increase is most likely caused by Joule heating, a phenomenon that occurs when electric current passes through a conductive medium such as wet soil. In conductive environments, electrical energy is partially converted into heat, leading to a measurable rise in temperature. Similar temperature increases have been reported in plant tissues exposed to electrical treatments (Grémiaux et al., 2016). The slight increase in soil temperature may contribute to faster germination by softening seed coats and accelerating metabolic activity (Singh et al., 2021).

The observed temperature increase also highlights the need to distinguish between thermal effects and electrical effects. While DC stimulation can directly influence ion transport, membrane potential, and nutrient uptake, the accompanying thermal rise may also enhance physiological processes. Therefore, both mechanisms may have contributed to the biological responses observed in this study.

Soil depth temperatures were higher between March–June and September–November, while surface temperatures peaked between June–August. Previous studies have shown that the relationship between soil moisture and surface temperature is complex and influenced by environmental conditions (Mahmood et al., 2012). Soil depth temperatures reported in protected cultivation systems range between 13.2–39.7 °C at depths of 5–30 cm (Sran and Jindal, 2022), consistent with the values observed in this study. The soil used in the experiment behaved as an ionic conductor rather than a dielectric material, allowing DC to pass through the medium. Although voltage was controlled, the actual current passing through the soil was not measured, which represents a methodological limitation of the study.

3.2. Determination of germination rate and germination time in seeds used

Statistically evaluated germination rate and germination time values ($p < 0.05$) are presented in *Table 2*. According to the results, Direct Electric Current (DC) stimulation did not produce a statistically significant effect on either germination rate or germination time.

Table 2. Effect of electrode pots on germination rate and germination time

Treatment	Germination time (days)	Germination rate (%)
Control	6.4	84.3
DC 10 V	7.1	81.6
DC 20 V	6.3	86.0
DC 30 V	6.7	83.6

The average germination time ranged from 6.3 to 7.1 days, while germination rates varied between 81.6% and 86.0%. These findings indicate that short-term DC stimulation applied during early growth did not significantly influence germination performance. Similar results were reported by Kobayashi et al. (2004), who observed that DC stimulation enhanced germination in wild parsley seeds; however, the effect appears to be species-dependent and influenced by treatment duration and current intensit.

3.3. Morphological characteristics of hot ornamental pepper seedlings

The effects of DC stimulation on the number of leaves, leaf width and length, stem diameter, and root length of hot ornamental pepper seedlings are presented in *Tables 3* and *4*.

Table 3. Mean squares of DC current treatments

Source of Variance	SD	Number of Leaves	Leaf Width (mm)	Leaf Length (mm)	Stem Diameter (mm)	Root Length (mm)
Treatment	3	9.849*	57.906*	251.054	0.719*	317.375*
Error	8	0.149	1.605	67.376	0.010	33.490

* Significant at $p < 0.05$

Statistical evaluation (*Table 3*) showed that DC stimulation significantly affected number of leaves, leaf width, stem diameter, and root length ($p < 0.05$), while leaf length was not significantly influenced. The mean comparisons in *Table 4* indicate that the highest values for number of leaves, leaf width, leaf length, and stem diameter occurred under the 30 V treatment, suggesting that higher DC intensity promotes shoot development.

In contrast, root length responded differently: the longest roots were observed at 10 V, whereas the shortest roots occurred at 30 V. This indicates a voltage-dependent response in which low-intensity DC stimulation enhances root elongation, while higher intensity favors above-ground growth. This pattern is consistent with hormesis, where mild stimulation promotes growth but stronger stimulation induces stress or shifts biomass allocation. These findings align with previous reports showing that weak DC stimulation can enhance plant growth parameters (Zhang et al., 2023). The reduction in root length observed at 30 V may be partially associated with increased Cu^{2+} release from the copper electrodes, as elevated copper concentrations can inhibit root elongation and impair root tip function.

Table 4. Effect of DC current treatments on morphological characteristics in hot ornamental pepper seedlings

Treatment	Number of leaves*	Leaf Width* (mm)	Leaf Length (mm)	Stem Diameter* (mm)	Root Length* (mm)
Control	3.33^{c}	14.77^{b}	33.26^{a}	1.44^{c}	42.52^{bc}
DC 10 V	5.22^{b}	18.40^{a}	33.60^{a}	1.87^{b}	60.84^{a}
DC 20 V	2.00^{d}	10.55^{c}	16.95^{b}	1.00^{d}	48.35^{b}
DC 30 V	5.99^{a}	20.58^{a}	37.59^{a}	2.11^{a}	36.80^{c}
LSD (0.05)	0.72	2.37	15.40	0.19	10.86

* Significant at $p < 0.05$.
Note: Means followed by the same letter are not significantly different at $p < 0.05$

3.4. 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*.

Table 5. Effect of DC current application on root and vegetative parts

Treatment	Root		Vegetative Part		
	Wet Weight (g plant^{-1})	Dry Weight* (g plant^{-1})	Wet Weight (g plant^{-1})	Dry Weight (g plant^{-1})	Root/Shoot Ratio
Control	7.4	1.1^{ab}	45.0	9.0	0.11^{ab}
DC 10 V	7.0	1.2^{a}	43.3	8.2	0.17^{a}
DC 20 V	4.8	0.7^{bc}	43.1	7.7	0.06^{b}
DC 30 V	5.2	0.6^{c}	41.2	7.2	0.09^{b}

Note: There is no significant difference between the means in the same letter group according to the probability level of $p<0.05$

Statistical analysis showed that only root dry weight was significantly affected by DC stimulation ($p < 0.05$). The effects on root fresh weight, vegetative fresh and dry weights, and the root/shoot ratio were not statistically significant. The treatment closest to the control was DC 10 V, while the most divergent values were observed under DC 30 V.

This indicates that low-intensity DC stimulation may support root biomass stability, whereas higher intensity may slightly reduce root dry matter accumulation. The decline in root dry weight at higher voltage levels may also reflect copper-induced stress, as excessive Cu^{2+} accumulation can reduce root biomass formation.

Fischer et al. (2004) reported that low DC stimulation in sunflower increased total fresh weight and root fresh weight but did not affect total dry weight, which is consistent with the present findings.

3.5. Calculation of root and stem length (cm plant^{-1}), Number of side branches and leaves in the plant (piece plant^{-1}), Total fruit yield (g plant^{-1}), Number of fruits per plant (piece plant^{-1}), Average fruit weight (g plant^{-1})

Root and trunk length, plant side branches and number of plant leaves are given in *Table 6*. DC current does not show statistical significance on the parameters.

Table 6. Effect of DC current on root and trunk length, number of side branches and leaves

Treatment	Root Length (cm)	Trunk Length (cm)	Number of side branches (number)	Number of leaves (number)
Control	39.4	81.4	10.0	201.5
DC 10 V	42.5	80.3	7.8	232.2
DC 20 V	35.8	85.3	9.3	215.0
DC 30 V	38.8	90.0	8.3	162.4

* Significant at 0.05 probability level
Note: There is no significant difference between the averages in the same letter group at the $p<0.05$ probability level

The highest root length was observed under DC 10 V, while the lowest occurred under DC 20 V. Stem length showed the opposite trend, with the lowest value at DC 10 V and the highest at DC 30 V. The number of side branches was similar across treatments. The lowest number of leaves was recorded under DC 30 V.

These results suggest that DC stimulation did not substantially alter architectural traits, and the small variations observed among treatments fall within natural biological variability.

Gogo et al. (2016) similarly reported that DC stimulation did not significantly affect plant height, number of leaves, or root diameter in nightshade. Interpretation of root and shoot responses should consider that the control group did not contain copper electrodes, which introduces a structural limitation when comparing electrode-based treatments with the non-electrode control. The effects of DC stimulation on fruit yield were evaluated. Total fruit yield, number of fruits per plant, and average fruit weight are presented in *Table 7*.

Table 7. Effect of DC stimulation on pepper yield

Treatment	Total Fruit Yield (g plant^{-1})	Number of fruits per plant (number plant^{-1})	Average fruit weight (g fruit^{-1})
Control	4.50	5.90	1.08
DC 10 V	4.65	3.60	1.30
DC 20 V	5.61	4.80	1.20
DC 30 V	3.02	5.78	1.43

DC stimulation had no statistically significant effect on fruit yield parameters. The absence of yield response suggests that short-term DC stimulation influences early vegetative traits more strongly than reproductive development. Pietruszewski (1996) similarly reported that magnetic or electrical pre-sowing treatments did not significantly affect crop yield in wheat.

3.6 Leaf area, leaf chlorophyll index and color measurement

The effects of direct electric current (DC) stimulation on leaf area are presented in *Table 8*.

Table 8. Effects of DC stimulation on leaf area

Treatment	Leaf area (mm^2)*
Control	8.18^a
DC 10 V	5.04^c
DC 20 V	6.61^b
DC 30 V	8.89^a

* Significant at $p < 0.05$

DC stimulation had a statistically significant effect on leaf area. Leaf area was smaller under DC 10 V and DC 20 V compared to the control, while DC 30 V produced values similar to the control. These results indicate that low-intensity DC stimulation may temporarily suppress leaf expansion, whereas higher intensity (30 V) does not negatively affect leaf area.

Figure 5 shows the monthly chlorophyll index values of the control, DC 10 V, DC 20 V, and DC 30 V treatments.

The highest chlorophyll index was recorded in October, while the lowest values occurred in May, corresponding to the seedling stage. DC 10 V and DC 20 V treatments showed similar seasonal patterns, with low chlorophyll values in May and peak values in October. DC 30 V consistently showed lower chlorophyll index values than the other treatments. Overall, DC 10 V produced the highest chlorophyll index values, suggesting that mild DC stimulation may enhance chlorophyll accumulation during later growth stages.

Total chlorophyll, chlorophyll a and b and carotenoid values measured in the leaf in the absorbance values A470, A645, A652 and A663 nm ranges are given in *Table 9*.

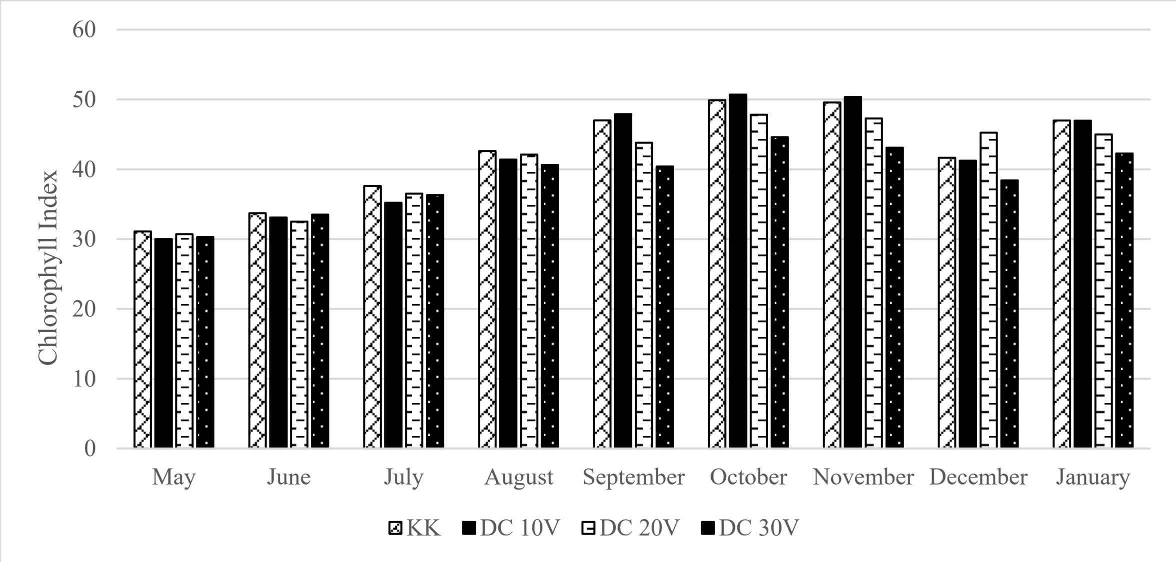

Figure 5. Effect of DC stimulation on monthly chlorophyll index

Table 9. Total chlorophyll, chlorophyll a and b and carotenoid values in the leaf

Treatment	Total Chlorophyll	Chl-a	Chl-b	Carotenoid
Control	0.19	1.26	1.69	0.45
DC 10 V	0.28	2.13	2.03	0.73
DC 20 V	0.25	2.01	1.80	0.72
DC 30 V	0.21	1.42	1.80	0.51

Statistical analysis showed that DC stimulation did not significantly affect total chlorophyll, chlorophyll a, chlorophyll b, or carotenoid contents (*Table 9*), indicating that final pigment concentrations were not altered by DC application. This suggests that DC stimulation influences chlorophyll index dynamics over time (*Figure 5*) without altering final pigment concentrations. Gogo et al. (2016) similarly reported that DC stimulation did not significantly affect chlorophyll a, chlorophyll b, or total carotenoid levels in leaves.

They observed that direct current had no effect on chlorophyll a, b and total carotenoid values in the leaves. In addition, Chl-a in the root and chlorophyll b and total carotenoid values in the stem showed a positive effect (*Table 10*).

Table 10. Average effect of direct electric current (DC) stimulation applications on leaf color of hot ornamental pepper seedlings

Treatment	L*	a*	b*	C^*	α°	ΔE^*
Control	39.59^{c}	-9.08^{a}	15.48^{b}	17.95^{c}	-59.57	-
DC 10V	40.51^{bc}	-10.22^{ab}	16.88^{b}	19.73^{bc}	-58.47	41.16^{b}
DC 20V	41.57^{b}	-11.29^{b}	17.89^{b}	21.15^{b}	-57.65	46.67^{ab}
DC 30V	44.07^{a}	-13.19^{c}	21.97^{a}	25.63^{a}	-58.80	51.07^{a}

DC stimulation significantly affected L*, a*, b*, C*, and ΔE*, while α° was not significant. DC 30 V produced the highest brightness (L*) and the most intense greenness (more negative a*). The b* (yellow–blue) and C* (color saturation) values were also highest under DC 30 V.

These results indicate that higher DC intensity enhances leaf brightness and color saturation, producing visually more vivid foliage.

Dannehl (2018) reported that electric and magnetic fields can enhance leaf area, photosynthesis, stomatal conductance, ion accumulation, and chlorophyll content, supporting the potential of electrical stimulation to influence leaf physiology. The effect of DC stimulation on pepper fruit color was statistically insignificant.

Average values are given in *Table 11*.

Table 11. Effect of DC stimulation on pepper fruit color

Treatment	L	a	b	C	α°	ΔE
Control	56.21	-3.61	32.75	32.96	-83.87	-
DC 10 V	55.06	-3.50	33.16	33.44	-65.56	53.60
DC 20 V	54.99	-5.19	32.79	33.20	-81.32	58.11
DC 30 V	55.30	-4.21	27.48	27.83	-81.80	56.00

Values among treatments were similar. The control group showed slightly higher brightness, while DC 20 V produced the most intense greenness. The highest b* (yellowness) value was observed under DC 10 V.

These results confirm that DC stimulation does not significantly alter fruit color characteristics.

3.7. Nutrient Content Analyzes

The nutrient contents of hot ornamental pepper grown under DC stimulation treatments are presented in *Table 12*.

Table 12. Effect of DC stimulation on nutrient composition

Analytics	**Control**	**DC 10 V**	**DC 20 V**	**DC 30 V**
Carbohydrate, (%)	1.12	0.83	0.57	5.26
Protein, (%)	4.74	4.70	4.55	4.79
Raw oil, (%)	1.45	1.34	1.05	3.36
Dietary Fiber, (%)	12.6	14.70	14.5	13.11
Dry Matter, (%)	70.68	73.56	73.73	82.55
Iron (Fe), mg kg^{-1}	7.0	6.0	7.5	6.0
Calcium (Ca), mg kg^{-1}	203	173	184	227
Potassium (K), mg kg^{-1}	6701	5881	6946	10290

Among the treatments, DC 30 V produced the highest values for carbohydrates, protein, crude fat, and dry matter. Dietary fiber content was highest under DC 10 V. Iron content ranged from 6.0 to 7.5 mg kg^{-1}, with the highest value observed under DC 20 V. Calcium content increased from 203 mg kg^{-1} in the control to 227 mg kg^{-1} under DC 30 V. Potassium content showed the most pronounced response, with DC 30 V reaching 10,290 mg kg^{-1}. These results suggest that higher DC intensity (30 V) may enhance the accumulation of certain macronutrients and minerals, particularly potassium and calcium. The increase in mineral content under higher voltage may be associated with enhanced ion mobility and uptake efficiency induced by DC stimulation. The pronounced increase in potassium content at 30 V is consistent with electromigration, in which DC enhances the directional movement of K^+ ions toward the root zone, facilitating greater uptake.

Ward (1996) similarly reported that DC stimulation increased Ca (16.6%), K (3.4%), and Mg (12.4%) contents in tomato plants, supporting the potential of electrical treatments to influence nutrient accumulation.

4. Conclusions

This study evaluated the development of hot ornamental pepper from germination to harvest under direct electric current (DC) stimulation at 10 V, 20 V, and 30 V. Short-term exposure to low-intensity DC stimulation influenced several morphological and physiological traits.

DC stimulation at 10 V, 20 V, and 30 V affected the number of leaves, leaf width, stem diameter, root length, root dry weight, leaf area, leaf color parameters, carbohydrate content, crude fat, dietary fiber, and potassium accumulation.

Higher DC intensity (30 V) generally enhanced shoot-related traits and mineral accumulation, particularly potassium, whereas lower intensities (10–20 V) showed more variable effects on root and leaf characteristics.

Statistical impact evaluations and treatment effects of DC stimulation are summarized in *Table 13*.

Table 13. Statistical impact evaluation of DC current treatments

Examined parameters	DC 10V		DC 20V		DC 30V	
	Statistical Evaluation	Treatment Effects	Statistical Evaluation	Treatment Effects	Statistical Evaluation	Treatment Effects
Germination Rate and Germination Time	-	0	-	0	-	0
Number of Leaves, Leaf Width, Stem Diameter, Root Length of Peppers in Seedling Form	+	+	+	-	+	+
Root Fresh Weight and Root/Stem	-	0	-	0	-	0
Root Dry Weight	+	+	+	-	+	-
Root and Stem Length	-	0	-	0	-	0
Number of Side Branches and Number of Leaves	-	0	-	0	-	0
Leaf Area	+	-	+	-	+	+
Chl-a, Chl-b and Carotenoid	-	0	-	0	-	0
Leaf Color Measurement	+	+	+	+	+	+
Total Fruit Yield, Number of Fruits per Plant, Average Fruit Weight	-	0	-	0	-	0
Carbohydrate		-		-		+
Raw oil		-		-		+
Dietary fiber		+		+		+
Potassium		0		0		+

Note: In statistical evaluation, "-" is unimportant and "+" is important. In the impact assessment, "-" is expressed as negative, "+" as positive and "0" as ineffective

Acknowledgment

This work supported by the Bursa Uludağ University Research Project (Project No: FGA-2021-375), Türkiye. We would like to thank Bursa Uludağ University Scientific Research Project Unit (BAP) for their financial support.

Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Kananizadeh, T., Vardar, A.; Design: Kananizadeh, T., Vardar, A.; Data Collection or Processing: Kananizadeh, T.; Statistical Analyses: Kananizadeh, T.; Literature Search: Kananizadeh, T.; Writing: Kananizadeh, T., Vardar, A.; Review and Editing: Vardar, A.

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