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Research Article

Khoury, Bryan-Eli[1]

[1] Faculty of Science, McGill University, Montréal, QC, Canada

Effects of Electrical Stimulation on Germination and Early Seedling Growth in Corn

Keywords

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Email Correspondence

bryan-eli.khoury@mail.mcgill.ca

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Abstract

Early seedling establishment is increasingly important for agricultural resilience[1]. Electrical stimulation has been proposed as a low-cost approach to modulate plant signalling pathways and potentially improve germination and early growth[2]. This study tested whether brief daily electrical stimulation affects germination success and early seedling growth in corn (*Zea mays* subsp. *mays)*.

Pre-soaked corn seeds were distributed into five groups (0 V, 3 V, 6 V, 9 V, 12 V; 35 seeds per group; total n=175). Electrical stimulation was applied for 10 min daily over 5 consecutive days using battery power sources and alligator clip electrodes placed diagonally across each tray on a moistened paper substrate. Germination was defined by visible root emergence (with or without shoot emergence). After 5 days, shoot and root lengths were measured, and group means were compared using one-way ANOVA.

Germination percentages were similar across treatments (45.7-54.3%), with no clear voltage-dependent trend. Mean shoot length was highest at 6 V (1.20 cm; standard deviation (SD)=0.97) but did not differ significantly across voltages (ANOVA p=0.410). Mean root length peaked at 6 V (2.00 cm; SD=1.34) and decreased at higher voltages (e.g., 12 V: 1.10 cm; SD=0.85), with voltage producing a significant effect on root length (ANOVA p=0.014).

Interpretation is limited by the short duration (5 days) and substantial non-germination, which reduced the effective sample size and statistical power. Growth on a nutrient-free paper substrate may limit generalizing to soil conditions. In addition, results may be influenced by variability in delivered voltage (battery drift/electrode placement) and by measurement error from bent or branching roots.

Electrical stimulation did not improve germination, but moderate stimulation (6 V) was associated with enhanced early root elongation, while shoot growth differences were not significant. These findings suggest that appropriately tuned electrical stimulation may selectively enhance early root development in maize seedlings, warranting longer-term studies assessing downstream effects on plant performance and yield.

Introduction

The challenge of enhancing seed germination and early seedling growth is critical in the field of agriculture, especially given the global issue of climate change, which poses significant challenges to seed germination and plant life[3]. Because establishment depends on multiple interacting conditions, a myriad of factors can affect germination and growth rates, such as temperature, water availability, light exposure, and electric stimulation. Therefore, this investigation aims to assess the influence of varying voltages of electrical stimulation (0 V, 3 V, 6 V, 9 V, 12 V) on the germination and growth of corn (*Zea mays* subsp. *mays)* seeds, with a focus on measuring changes in shoot and root length. Specifically, the study evaluates whether an intermediate voltage enhances early growth relative to both no stimulation and higher-voltage exposure.

Seed germination is a crucial stage in a plant's life cycle that follows a period of dormancy and is influenced by many internal and external factors. Because germination is highly sensitive to abiotic conditions, other factors such as water availability, oxygen exposure, and temperature were kept consistent across treatments. A dormant seed contains approximately 6-15% water in its cells, whereas metabolically active cells require about 75-95% water to sustain enzymatic and respiratory activity[4]. Therefore, the absorption of water by the embryo triggers cell rehydration and reactivates the seed's metabolism[5]. This rehydration also softens the seed coat, enhances permeability, and transforms food from an insoluble form to a soluble one while facilitating gas exchange. As metabolism resumes, adequate oxygen is required, as it is crucial for aerobic respiration to release the energy needed for early growth. Because respiration and other enzyme-mediated metabolic processes are temperature-sensitive, temperature also plays an important role in germination. Optimal temperatures around 30°C facilitate efficient enzymatic processes for most seeds (including *Zea mays* subsp. *mays)*, while cooler temperatures slow these reactions, and higher temperatures can denature enzymes, thus affecting and even preventing germination from occurring[6, 7].

Electrical signalling naturally occurs internally in both plants and animals. Similar to internal signalling, external electrical stimulation can regulate many plant biological processes at the cellular level by modifying cellular metabolism through interaction with chemical, hydraulic, and hormone signalling; at the biochemical level by controlling protein synthesis, secondary metabolites, hormones (jasmonic acid and abscisic acid), and protein kinase inhibitors; at the molecular level by regulating gene expression of enzymes related to ribosome proteins and carbon metabolism; and at the physiological level by adjusting stem growth, leaf movement, stomatal opening, transpiration, and respiration[8]. In addition, electrical stimulation can significantly improve the plant's tolerance to freezing and salt stress[9].

Electrical stimulation can enhance seed germination by first activating ion channels, which then trigger Ca^{2+} and ROS (reactive oxygen species) signalling. This signalling cascade increases the activities of catalase, peroxidase, and other enzymes related to carbon metabolism, and can enhance the uptake of nutrients like potassium (K), calcium (Ca), magnesium (Mg), etc. Beyond germination, external electrical stimulation may influence early seedling growth and post-germination physiology by promoting photosynthetic thermotolerance, defined here as the ability of the photosynthetic apparatus (particularly photosystem I) to maintain function under heat stress[9]. Following electrical stimulation, signalling molecules such as Ca^{ref2+}, ROS, and plant hormones can be mobilized, with changes in gene expression (e.g., calmodulin, proteinase inhibitors, and Rubisco) and phloem mass flow. Downstream, this response has been linked to decreased carbon dioxide (CO_2) assimilation and activation of photoprotective mechanisms, including non-photochemical quenching and cyclic electron flow, increased ATP content, and changes in transpiration, leaf heating, and state transitions. However, high-voltage electrical stimulation can inhibit seed germination by disrupting cell membrane integrity, which can impair water balance and lead to reduced relative water content, i.e., dehydration. This dehydration-associated stress can trigger a broad stress response, including the accumulation of secondary metabolites, and can increase oxidative damage; consequently, lipid peroxidation rises and malondialdehyde (MDA) accumulates as an indicator of stress-related cellular damage[10]. Antioxidant enzyme activity can decrease under high-voltage electrical stimulation, promoting H_2O_2 buildup and oxidative stress[11]. In shoots, a reduction in Superoxide dismutase (SOD) activity occurs, an important antioxidant enzyme that catalyzes the disproportionation of the superoxide anion to hydrogen peroxide, which can allow reactive oxygen species to accumulate and damage cellular components. However, catalase activity decreases, reducing H_2O_2 detoxification and increasing oxidative damage to membranes, proteins, and DNA. In roots, a decrease in ascorbate peroxidase (APX) activity occurs, further limiting hydrogen peroxide detoxification and antioxidant defence[9, 12].

While the concept of using electricity for seed germination is a promising and low-cost approach, it remains relatively underutilized and uninvestigated in the field of agricultural research. This paper aims to expand our understanding of how external electrical stimulation interacts with seeds to promote their germination and growth. Because electrical stimulation can influence ion-channel activity, Ca^{2+}/ROS signalling, enzymatic function, nutrient uptake, and stress responses, its effects are expected to depend on stimulus intensity. This experiment varied the applied voltage (0 V, 3 V, 6 V, 9 V, 12 V) and stimulated seeds for 10 minutes daily over five days to test how voltage influences early seedling performance. Germination and growth were evaluated using shoot and root lengths as primary outcomes. It was hypothesized that an intermediate treatment (9 V) would produce the greatest positive effect on germination and growth by providing sufficient stimulation without causing injury, whereas 12 V may inhibit growth or progress and lower voltages may be insufficient to elicit measurable improvement[13].

Methods

Approximately 200 *Zea mays* subsp. *mays* (corn) seeds were first imbibed by soaking in bottled mineral water for 24 hours; floating seeds were removed due to their low likelihood of germination. For each treatment, plastic trays were prepared by lining the base with five layers of thick tissue paper and overlaying a single sheet of filter paper. Each tray was then hydrated with 20 cm³ of water to fully saturate the substrate. Following soaking, 35 seeds were evenly spaced on the moistened filter paper in each tray, and trays were labelled according to the assigned electrical stimulation to avoid cross-contamination between treatments. A 3 V power source was assembled by connecting two 1.5 V batteries in series, and separate 6 V, 9 V, and 12 V batteries were each connected to alligator clip leads. The clips were positioned diagonally opposite one another within each tray, with the positive and negative terminals kept consistently oriented on the same side across all setups. Because electrical exposure parameters are not yet well established for this setup, we used a brief, repeated stimulation schedule of 10 minutes per day over five consecutive days as a practical and low-cost exploratory protocol spanning early germination and initial seedling establishment. To maintain consistent moisture conditions, 10 cm³ of water was added to each tray once per day throughout the stimulation period. After the 5-day treatment, seedling shoot and root lengths were measured using a ruler.

Data processing

First, germinated seeds were identified from seeds that did not germinate based on the growth of the root and shoot. Presence of either a shoot and root or root only was considered germinated, while the absence of both shoot and root was categorized as ungerminated. To find the percentage germination, the number of germinated seeds was divided by the total seed number and multiplied by one hundred.

$$\text{percentage germination } \% = \frac{\text{number of germinated seeds}}{\text{total number of seeds } (n = 35)} \times 100$$

Next, Microsoft Excel was used to calculate the mean and standard deviation (σ) of the shoot and root lengths of germinated seeds independently.

Then, the germination rate was calculated by dividing the average lengths (i.e. length) by the time given for the seeds to grow in *n* days (n = 5 days).

$$\text{rate of germination} = \frac{\text{length}}{5} = \text{cm/day}$$

Statistical analysis

Descriptive statistics (mean (μ) and standard deviation (σ)) were calculated in Microsoft Excel, and the error bars in Figure 1 represent ±1 SD. In addition, a chi-square test of independence was used to compare germination outcome (germinated versus ungerminated) across voltage treatments (α=0.05).

Finally, to analyze both the root lengths and shoot lengths among the different voltage strengths, a one-way ANOVA test was performed using IBM SPSS Statistics software. The test was utilized to determine whether there were statistically significant differences in the means of root and shoot lengths among the various voltage levels or if it was merely due to random variation. The raw data for root and shoot lengths across different voltage strengths were inputted into the software, and the one-way ANOVA test was conducted assuming equal variance.

Statistical hypotheses

Shoots:

(H_{s0}): No significant difference in the mean shoot lengths of Zea mays subsp. *mays* seeds is present when subjected to different voltages of electrical stimulation.

(H_{s1}): A significant difference in the mean shoot lengths of Zea mays subsp. *mays* seeds is present when subjected to different voltages of electrical stimulation.

Roots:

(H_{r0}): No significant difference in the mean root lengths of Zea mays subsp. *mays* seeds is present when subjected to different voltages of electrical stimulation.

(H_{r1}): A significant difference in the mean root lengths of Zea mays subsp. *mays* seeds is present when subjected to different voltages of electrical stimulation.

Results

Table 1. Germination outcomes by voltage treatment. Number of germinated and ungerminated seeds, and the resulting germination percentage (%), for seeds exposed to 0 V, 3 V, 6 V, 9 V, and 12 V.

Voltage (V)	0	3	6	9	12
Number of Ungerminated Seeds	16	19	16	18	16
Number of Germinated Seeds	19	16	19	17	19
Percentage Germination (%)	54.3	45.7	54.3	48.6	54.3

Shoot and root growth rates across voltage treatments. Mean shoot and root growth rates (cm/day) of germinated corn (*Zea mays* subsp. mays) seeds exposed to electrical stimulation at 0 V, 3 V, 6 V, 9 V, and 12 V. Growth rate was calculated by dividing the mean shoot/root length by the growth period (days). Error bars indicate variability in the underlying length measurements (standard deviation, σ, calculated in Excel).

In Figure 1, mean root growth rate increased from 0 V to 6 V and decreased from 6 V to 12 V. Mean shoot growth rate increased from 3 V to 6 V and decreased from 6 V to 12 V (Figure 1).

The standard deviation of the length values is low for all voltage treatments, with a maximum of 1.34 for the 6 V root sample, indicating that measurements were relatively consistent within each voltage treatment. However, variability was highest for the 6 V roots, thus a less uniform response is present at this voltage.

The root lengths in all of the voltage treatments were greater than those of the shoots. This pattern is consistent with the normal germination sequence, where early root elongation precedes shoot emergence, as reflected by higher growth rates in roots compared to shoots (Table 3). At 6 V, the highest growth rates were observed: the shoot growth rate is 0.24 cm/day, while the root growth rate is 0.4 cm/day (Table 3). However, we can see that the difference between the root and shoot lengths and growth rate is larger around the optimum voltage of 6 V, indicating that electrical stimulation might have a greater effect on the seeds' roots rather than shoots.

Due to the large difference between the roots and shoots results, the ANOVA statistical test was used to determine if the effect of electrical stimulation is significant. Despite observing a difference in the mean lengths of the shoots at the different voltages, the p-value = 0.410 showed no significance (Table 4). This indicates that H_{s0}, suggesting that the observed difference between the voltage strengths for shoots, is not statistically significant. The p-value = 0.014 for the root lengths was significant (Table 4). This suggests that electrical stimulation does not have a significant effect on the growth rate of the shoots, but can positively impact the growth rate of roots at an intermediate voltage of ~6 V**.**

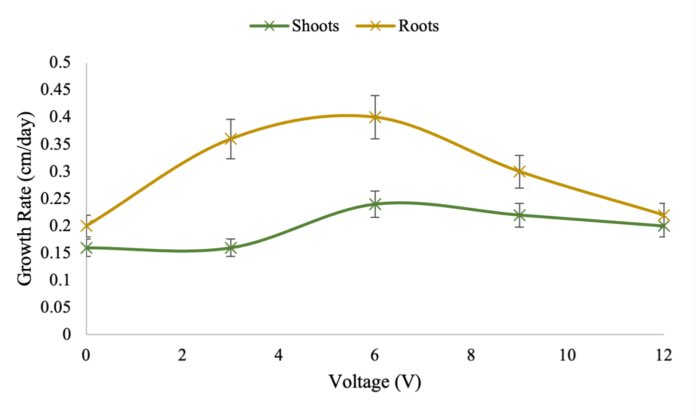

Figure 1. Shoot and root growth rates across voltage treatments. Mean shoot and root growth rates (cm/day) of germinated corn (Zea mays subsp. mays) seeds exposed to electrical stimulation at 0 V, 3 V, 6 V, 9 V, and 12 V. Growth rate was calculated by dividing the mean shoot/root length by the growth period (days). Error bars indicate variability in the underlying length measurements (standard deviation, σ, calculated in Excel).

As observed in Table 1, which details the percentage of germinated seeds (i.e. successful germination), electrical stimulation did not affect percentage germination. This is because the values vary slightly among the voltage levels, with the highest percentage of 54.3% observed at each 0 V, 6 V, and 12 V, and the lowest percentage of 45.7% observed at 3 V (difference of 8.6%). Consistent with this, a chi-square test of independence detected no significant association between voltage treatment and germination outcome (χ^2=0.915, p=0.922, d.f.=4, n=175).

Discussion

Overall, this experiment indicates that brief electrical stimulation can influence early seedling elongation in corn, with effects that are more apparent for roots than for shoots.

The hypothesis that 9 V would produce the greatest improvement in germination and early growth was not supported. This is shown in Figure 1, where the optimal voltage for both shoot and root growth was 6 V. Compared with 0 V (shoot: 0.80 cm; root: 1.00 cm), the 6 V treatment produced higher mean lengths (shoot: 1.20 cm; root: 2.00 cm), indicating a ~50.0% increase in shoot length and 100.0% increase in root length. The hypothesized optimal condition of 9 V showed smaller increases relative to 0 V (shoot: 1.10 cm, +37.5%; root: 1.5 cm, +50.0%). Across treatments, growth followed a non-linear pattern: elongation increased from 0-6 V and declined at higher voltages of 9 and 12 V, consistent with an "optimal stimulation window" rather than a strictly linear dose-response. Overall, the trend resembles a downward-opening parabola, and it suggests a relatively symmetric pattern around the vertex at 6 V (more pronounced in roots than in shoots). However, given the variability within groups (Table 2), this pattern should be interpreted cautiously and confirmed with additional replication and longer growth periods. Standard deviations were generally low, suggesting the pattern is not driven by a small number of extreme values.

Analysis of the growth rates reveals that electrical stimulation has a more

Table 2. Mean shoot and root lengths of germinated seeds by voltage treatment. Mean shoot and root lengths (cm) for germinated seeds at 0 V, 3 V, 6 V, 9 V, and 12 V, with corresponding standard deviations (σ). Mean lengths are reported with a measurement precision of ±0.1 cm.

Voltage (V)	0		3		6		9		12	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Mean Length (±0.1cm)	0.8	1.0	0.8	1.8	1.2	2.0	1.1	1.5	1.0	1.1
Standard Deviation (σ)	0.81	0.85	0.86	0.84	0.97	1.34	0.72	0.80	0.68	0.85

Table 3. Shoot and root growth rates by voltage treatment. Shoot and root growth rates (cm/day) for germinated seeds at 0 V, 3 V, 6 V, 9 V, and 12 V. Growth rate was calculated by dividing the mean shoot/root length by the growth period (days).

Voltage (V)	0		3		6		9		12	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Growth rate (cm/day)	0.16	0.20	0.16	0.36	0.24	0.40	0.22	0.30	0.20	0.22

prominent effect on root growth compared to shoots. Statistical analysis also shows that differences in root lengths are significant, whereas those of the shoots are not. Specifically, one-way ANOVA indicated a significant effect of voltage on root length (p=0.014) but not on shoot length (p=0.410) (Table 4), implying that electrical stimulation selectively impacted early root elongation under the conditions tested. The root–shoot difference was largest around 6 V, suggesting stimulation may have a stronger effect on roots than shoots near the apparent optimum. The percentage of germinated seeds is relatively consistent across different voltage levels (45.7-54.3%), suggesting that electrical stimulation did not have a meaningful change in germination success in this experimental setup.

This study addressed how varying the applied voltage (0-12 V) affected germination and early growth, measured by shoot and root length. The results support an effect on root growth: root length differed across voltage treatments (one-way ANOVA, p = 0.014), with the highest mean observed at 6 V (2.00 cm). The effect on germination success rate and shoots was, however, not statistically significant in this dataset.

Insights into the effect of electrical stimulation on corn seeds have potential implications in the field of agriculture. The observed improvement in root growth under specific electrical voltages suggests an innovative approach to improving crop development, particularly in the early stages that are crucial for yield. Notably, this outcome is partially consistent with prior work showing that electrical stimulation can enhance maize seedling growth, while higher-intensity exposure may become inhibitory depending on stimulation parameters and stress responses[9]. However, further research is essential to understand the long-term impacts on mature plants and overall yield, especially for vital crops like corn. In natural or *in situ* settings, crops may also experience electrical or mechanical stimuli (e.g., ambient electric fields near infrastructure, wind, vibration, etc.) and determining whether these exposures produce comparable effects remains an important direction for future work.

Limitations

The effective sample size per treatment was limited by substantial non-germination. Although 35 seeds per voltage were used, approximately half did not germinate, reducing statistical power and the robustness of between-group comparisons; additionally, the five-day duration may not have provided sufficient time for all seeds to complete the germination process. Only one experimental run was completed, eliminating statistical inferences over replicates. The seeds used were not of the same size, meaning nutrient reserves likely differed between seeds, which can affect the germination rate and process. In addition, the use of tissue and filter paper as a substrate did not provide the seed with the essential nutrients to grow. The measuring instrument had limited precision (reported as ±0.01 cm), which might not have correctly identified more subtle differences. Additionally, the shoot and root of the corn seeds were usually bent, which made measuring their lengths difficult (consequently, measurements were taken from the tip to the bend and from the bend to the end). Roots were sometimes branched; thus, the longest branch was measured. Together, these issues limit construct validity because one-dimensional length measurements do not capture traits such as branching architecture, total root surface area, or biomass, which may respond differently to stimulation. In terms of statistics, only an omnibus one-way ANOVA was performed, and post-hoc tests (e.g., Tukey HSD) would be needed to determine which voltage treatments differ from each other.

Even though seeds were acquired from the same source, confounding variables such as seed size can still exist and affect the results. To prevent this, seed sizes can be controlled using either a balance or a ruler. Providing the corn seeds with nutrients (soil or ½-strength Murashige and Skoog nutrient medium) would improve ecological relevance and may reduce nutrient-limitation effects on growth[14]. A climate chamber can be used to control factors like temperature, moisture and air quality. Regular checks and recalibrations of the batteries would be crucial for maintaining the accuracy of voltage delivery. More importantly, recording the delivered current (mA) and electrode spacing would better standardize exposure across trays.

Table 4. One-way ANOVA results for shoot and root lengths across voltage treatments. One-way ANOVA summary statistics for shoot and root length measurements across five voltage conditions at 0 V, 3 V, 6 V, 9 V, and 12 V, including reporting sum of squares, degrees of freedom (df), mean square, F-statistic (F), and significance (Sig.). For shoots, the ANOVA returned F=1.004 with p-value =0.410; for roots, F=3.328 with p-value =0.014.

Shoots					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.663	4	.666	1.004	.410
Within Groups	56.353	85	.663	-	-
Total	59.016	89	-	-	-
		Roots			
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	12.571	4	3.143	3.328	.014
Within Groups	80.274	85	.944	-	-
Total	92.845	89	-	-	-

The effect of varying electric voltages can be evaluated more accurately by measuring the dry mass of the germinated seeds. This would overcome the issue of root branching. Ensuring consistent seed spacing is essential and verifying that the electrical field experienced by seeds is comparable within and across trays (rather than relying only on nominal battery voltage) would strengthen internal validity.

Future directions

Future directions include investigating the long-term effects of electrical stimulation on mature corn plants, because this experiment does not elucidate the effect of electrical stimulation on the crop yield of the maize plant. A longer study should track plants through vegetative growth and reproduction while testing whether early root elongation at 6 V translates into measurable agronomic outcomes. Since maize is a major food crop, it is essential to determine whether electrical stimulation improves productivity under realistic conditions. Therefore, assessing outcomes such as cob size, kernels per cob, and total biomass (with appropriate replication and field- or greenhouse-relevant substrates) would clarify whether electrical stimulation produces durable benefits or only short-term changes in early development.

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