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# Effect of a Directional Electromagnetic Field on the Early Stages of Plant (*Raphanus sativus* and *Saccharum officinarum*) Growth

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**Abstract:** In this study, we aimed to develop a novel directional electromagnetic field (EMF) application method for promoting plant growth using a solenoid coil-based cultivation system. The emergence of plant shoots from seeds, shoot elongation, root proliferation, and plant growth hormones were monitored in the presence of a directional EMF using our solenoid coil system. To observe the effect of the directional EMF on seed germination, radish and sugarcane seedlings were cultivated in the system. At the seed germination stage, the EMF applied had no significant effect on germination or growth. However, after germination, shoot growth was sensitive to a directional EMF, as it was promoted by different conditions in a plant-species-dependent manner. The maximum growth promotion rates were 25.65% ± 4.21% and 38.57% ± 12.81% for radish and sugarcane, respectively. Similarly, plant root proliferation and indole-3-acetic acid (IAA) analyses indicated that directional EMF application was associated with root proliferation and hormone synthesis. Plant growth in the experimental system proved controllable; either growth stimulation or reduction were possible as the system operating conditions were made to vary. Our findings indicate that the application of a specific directional EMF could serve as an electrical plant stimulant (or electrical fertilizer).

**Keywords:** plant growth; electromagnetic field; solenoid coil; *Raphanus sativus*; *Saccharum officinarum*; electrical fertilizer; electrical plant stimulant; plant hormones; shoot elongation; root proliferation; water availability

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## 1. Introduction

Plant growth is affected by numerous environmental factors, such as light intensity, ambient $CO_2$ concentration, soil physical conditions, and nutrient and water availability. Further, previous studies have indicated that the natural electromagnetic field (EMF) inevitably affects plant growth on Earth [1,2]. In this context, several related techniques, such as the application of a pulsed magnetic field [3], direct exposure of seeds to an EMF [4–7], and electrical ground connections [8], have been tested for their ability to enhance plant activity. Specifically, the application of an EMF to plants has an extended research history and remains an attractive research area for the development of strategies to control plant growth. The related methods are well documented in the literature [5,9–12].

Previous experimental results have suggested that the application of an EMF to plants is closely related to variations in root proliferation, gene expression, metabolic and physiological activity, and ion transport in plant cells [4]. Moreover, several studies have shown that when plants are grown in the absence of an EMF (e.g., when grown in a Faraday cage), their growth is inhibited [13]. These observations suggest that EMF application may be a useful tool for controlling plant growth and productivity. However, the mechanisms responsible for EMF-induced changes in plant metabolism and physiology are not yet fully understood, owing to the great number of factors involved in plant responses to an EMF in different species.

We previously used a simple electrical ground connection to demonstrate that controlling the EMF surrounding the pots in which plants were grown effectively stimulated plant growth [7] and induced the adsorption of influenza virus particles on the surface of plant leaves [14]. Further, measurement of the EMF surrounding the pots based on inductance or the standing wave ratio (SWR) using a simple solenoid-type sensor was found to be a useful tool for monitoring plant water content [15] or plant vital activity [16]. In particular, in the case of inductance and SWR measurements using the solenoid-type sensor surrounding the plant, the water flow in the experimental plant was used as the basis for the measuring system [16]. Therefore, we hypothesized that the induction of internal water and/or nutrient flow in plant stems can be conveniently achieved by applying an active directional EMF to a live plant using a simple solenoid-type device with a suitable direct electrical current (DC).

A solenoid is an electromagnet formed by a helical coil of wires that generates a controlled magnetic field. This coil can produce a uniform and stable magnetic field in space when an electric current passes through it. Therefore, in the presence of a suitable electric current, the interior of the current-carrying solenoid generates a magnetic field with uniform direction and magnitude. A well-known example of a solenoid is a valve used as a fluid controller. The main advantage of a solenoid is its rapid mechanical reaction when electricity is applied. Therefore, when a plant stem is placed at the center of a solenoid, the EMF generated by the solenoid may physically affect the fluid moving inside the stem [16]. Further, a directional magnetic field based on Ampere's law can be easily generated using a current-carrying solenoid [17]. This phenomenon may induce further plant-growth differences based on the resulting water and nutrient flow-rate variations [18].

In this study, we aimed to monitor the effects of a directional EMF generated by a solenoid on seed germination and plant growth in two plant species: common radish (*Raphanus sativus*) and sugarcane (*Saccharum officinarum*). Experiments were performed with seeds placed at the center of the solenoid in the presence of a current. Shoot elongation, root proliferation, and plant hormone levels were then analyzed to determine the effect of the applied EMF on plant growth. Our findings help to better understand plant responses to the application of a directional EMF and provide a solid theoretical framework for the design and development of control systems for plant growth rate using a directional EMF based on a simple solenoid.

## 2. Materials and Methods

### *2.1. Plant Material*

In this study, we examined the effect of applying a directional EMF on the seed germination and growth of two different plant species, common radish (*Raphanus sativus*) and sugarcane (*Saccharum officinarum*), which were selected because of their rapid germination and easy cultivation characteristics [19,20]. Seeds were purchased from the Yangjae Flower Market, Seoul, Republic of Korea. Seeds were not surface-sterilized in order to avoid any influence of this process on seed germination kinetics [21]. Seed imbibition was achieved by placing the seeds in test tubes containing 200 mL of tap water at 22–25 °C for 24 h.

### *2.2. Solenoid-Type EMF Generator*

Figure 1 illustrates the solenoid-type EMF-generation system used in this study. The solenoid was constructed using a 0.3 mm copper wire wound approximately 2000 times around an acrylic bobbin (diameter: 32 mm, height: 200 mm), and the ends of the wire were tabbed for connection to a DC power supply (SDP30-5D, SMtechno, Seoul, Republic of Korea). The current and EMF were measured using a multimeter (Fluke 189, Fluke, Everett, WA, USA) and a Tesla meter (TM-601, Kanetec, Tokyo, Japan), respectively. The bobbin was then placed in a 50 mL conical tube used as a pot containing 17 g of organic soil (Jeil Co., Seoul, Republic of Korea). Seeds were placed in a pot (diameter: 30 mm, height: 115 mm) at a depth of 10 mm from the soil surface. When the system was initially set up with the seeds in it, 10 mL of tap water was added to the pot with a 10 mL serological pipette (91010; SPL Life Science, Pocheon, Republic of Korea), and both solenoid taps were connected to a DC power supply (5.0 V) to generate a directional EMF inside the pot. When the experiment was initiated, no additional watering was carried out. When a DC voltage of 5.0 V was applied to the constructed solenoid, an 0.8 mT EMF was observed at a 120 mA current. The direction of the current that provided a directional EMF to the pot was maintained for a given time in continuous mode (0, 24, 48, and 72 h). When a direction change in the EMF around the pot was required, the direction of the current connected to the solenoid from the power supply was changed based on Ampere's law [22]. This experimental system was maintained under a light (PAR38; Philips, Eindhoven, Holland) intensity of 90 μmol/m$^2$/s (distance from the surface of the soil to the light: 450 mm), and a temperature of 25 ± 1 °C with 45–50% relative humidity (Figure S1).

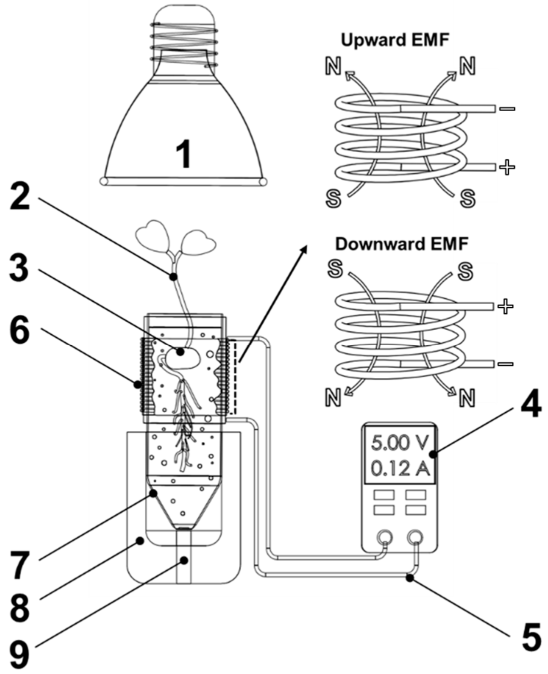


**Figure 1.** Schematic representation of the EMF application system for plant-growth control: (1) light source, (2) plant shoots, (3) seeds and roots, (4) power supply, (5) electric wires, (6) solenoid coil, (7) cultivation pot, (8) pot holder, and (9) water drain. "N" and "S" in the figure indicate the direction of EMF application in the system: the direction can be altered by reversing the connection of the electric wire to the power supply.

### *2.3. Measurement of Plant Growth*

Freshly imbibed radish and sugarcane seeds were planted at a rate of three seeds per pot in the experimental system to evaluate the effect of an applied EMF on the seed germination rate and initial plant growth. Each experimental pot was subjected to different durations of EMF application (0, 24, 48, and 72 h) from the start of the experiments (i.e., just after planting). The magnetic field flow produced by the DC (0.12 Ampere at 5.0 Volt) connected to the solenoid coil was set in an upward direction (Figure 1). During cultivation, the germination rate was monitored visually and shoot elongation was measured using a caliper (Model Inoxyd, Helios, Gammertingen, Germany) [23]. Seed germination rate and shoot length data were collected at 24 h intervals during the 7-day experimental period. For the control treatment, pots were set up without electrical power supplied to the solenoid.

To estimate the effect of an EMF on plant growth and root proliferation, a new set of freshly imbibed seeds were planted in the experimental pots and grown for approximately 72 h in the absence of an applied EMF. Following this, an EMF with a certain intensity was applied to the seedlings either in an upward or a downward direction. When the shoots had reached a specific length (radish: 5 ± 0.5 mm, sugarcane: 10 ± 1 mm above the soil surface), an EMF (in an upward direction) was applied to the growing shoots for different periods (0 (control), 24, 48, and 72 h). Additionally, identical experimental conditions with a reversed electrical current connection from the power supply were performed to observe the effect of applying an EMF in the reverse direction (i.e., downwards). Shoot growth under different EMF exposure times and different EMF directions was monitored for 96 h using a caliper. Plants were removed from the pots after 96 h of cultivation. The roots were then washed with tap water and the length of the main root was recorded using a digital camera with a scale bar. Subsequently, whole-plant samples were used for indole-3-acetic acid (IAA) analysis. All experiments were performed in triplicate and mean values were plotted.

### 2.4. IAA Analysis

The effects of various plant hormones on plant growth and metabolism have been extensively documented, and many such effects are well established [24,25]. We selected IAA for analysis in this study because it reportedly plays a critical role in regulating plant growth and influences root and shoot elongation and development [26,27]. Whole plants were used for plant growth and endogenous IAA determination. Plants were washed thoroughly with tap water to remove soil particles and dust; then, they were allowed to dry at room temperature for 3 h. Dried samples were homogenized using a stainless-steel pestle. For IAA extraction, 0.4 g of tissue sample was collected using a pestle and suspended in 3 mL of 80% methanol. The extraction was then performed over 24 h using a shaking incubator at 150 rpm and 20 °C [28,29]. The obtained extracts were centrifuged at 2000 × $g$ for 8 min, and 2 mL of each supernatant was collected [30]. The collected samples were then applied to 0.2 μm syringe filters (6779-1302, Whatman Co., Ltd., Maidstone, UK) [31]. The filtrates were analyzed by a high-performance liquid chromatography (HPLC) instrument (YL9100 HPLC System, Youngin Chromass, Anyang, Republic of Korea) equipped with a Hypersil ODS C18 column (250 × 4.6 mm, 5 μm) and a UV/Vis detector (280 nm). The column temperature was set at 30 °C, and a gradient elution process for the mobile phase was applied based on previous studies [32–34].

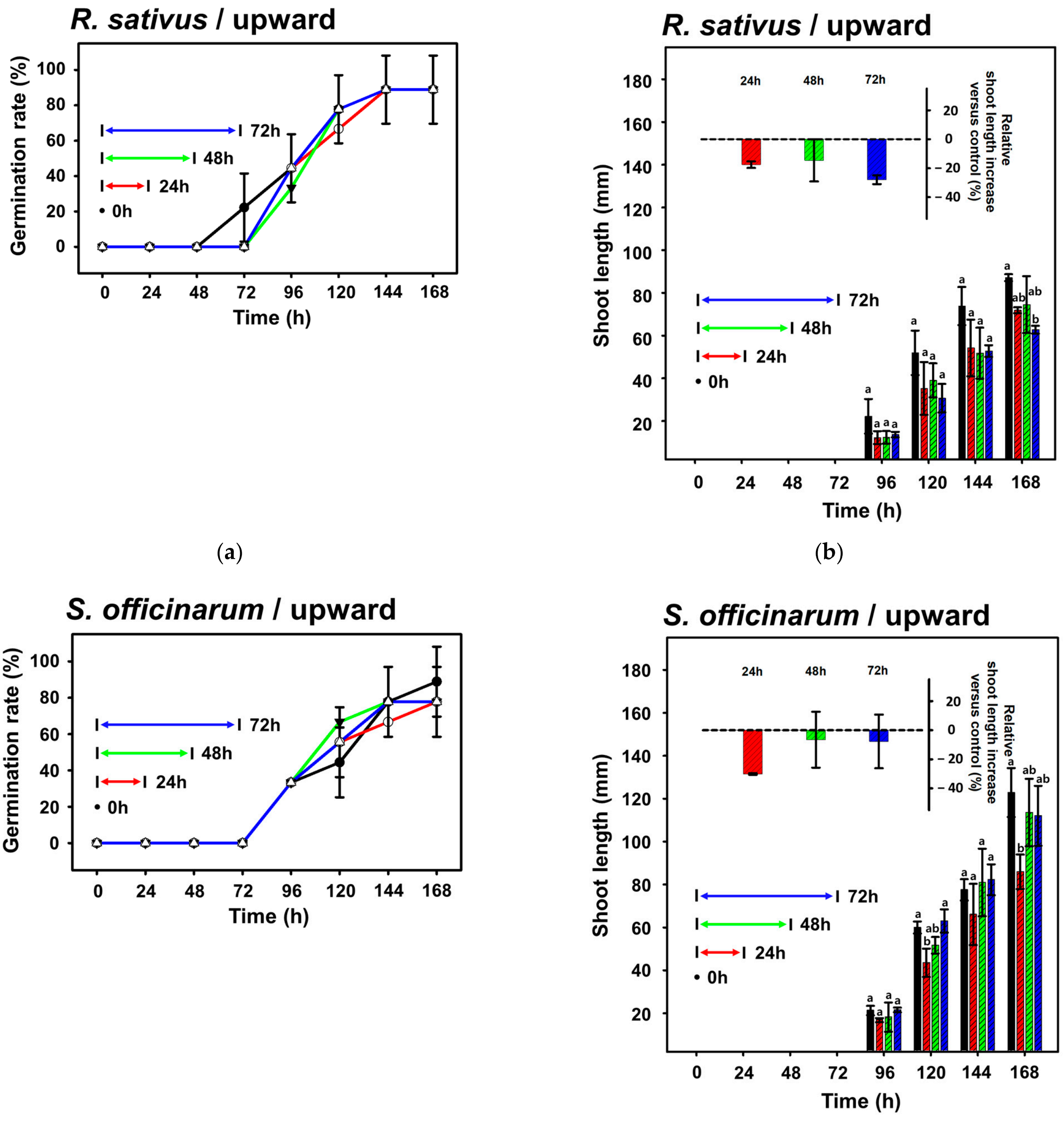
### 2.5. Statistical Analysis

The experimental data were analyzed using SPSS 22.0 software. ANOVA and Tukey's post-test were performed to evaluate treatment differences at a significance level of $p < 0.05$. Data shown in the figures are means ± standard deviation (SD). Figures were plotted using SigmaPlot (V14.5, Systat Software, Chicago, IL, USA).

## 3. Results and Discussion

### 3.1. Effect of an Applied EMF on Seed Germination

The application of an EMF during the experimental period (i.e., from seeding to shoot emergence from the soil surface) had no significant effect on the germination rate and rather had a negative effect on shoot elongation. Germination was first observed in pots containing radish seeds (Figure 2a) without EMF application (i.e., control treatment), and shoot length measurements showed that EMF application during the seed germination period had a negative effect on the ensuing shoot elongation. A comparison of shoot length data showed that the greatest negative effect was observed in the EMF-treated pots subjected to the longest period of application (i.e., 72 h, Figure 2b).



(**a**) (**b**)

(**c**) (**d**)

**Figure 2.** Effects of an upwardly directed EMF application on plant (*R. sativus* and *S. officinarum*) seed germination rate (**a**,**c**) and shoot elongation (**b**,**d**). The colored arrows in the figures indicate the effective EMF application periods from the initial stage of the experiment. The color codes in the plots indicate the measurement results with different EMF application periods (black dot: 0 h, red: 24 h, green: 48 h, blue: 72 h). The inner (upper) graphs in (**b**,**d**) indicate that the relative shoot length increased after 168 h of cultivation with different EMF application times during the early shoot growth. Different lowercase letters indicate significant differences ($p < 0.05$).

As for sugarcane seed germination and seedling growth, the results showed that EMF application to the seeds had minor or negative effects on germination and early shoot elongation, with most seeds germinating within 6 d of cultivation (Figure 2c,d).

Overall, the results indicate that early seed germination was barely affected by EMF application; furthermore, seed sensitivity to the applied EMF varied slightly with the plant species. Another paired set of experiments conducted under identical conditions but under a downwardly directed EMF showed no detectable effect, similar to the results with the upwardly directed EMF (Figure S2). Based on these observations, further experiments were conducted to evaluate the effect of EMF on plant growth, especially after the completion of seed germination.

### 3.2. Effect of Different Directional EMFs on Plant Shoot Growth

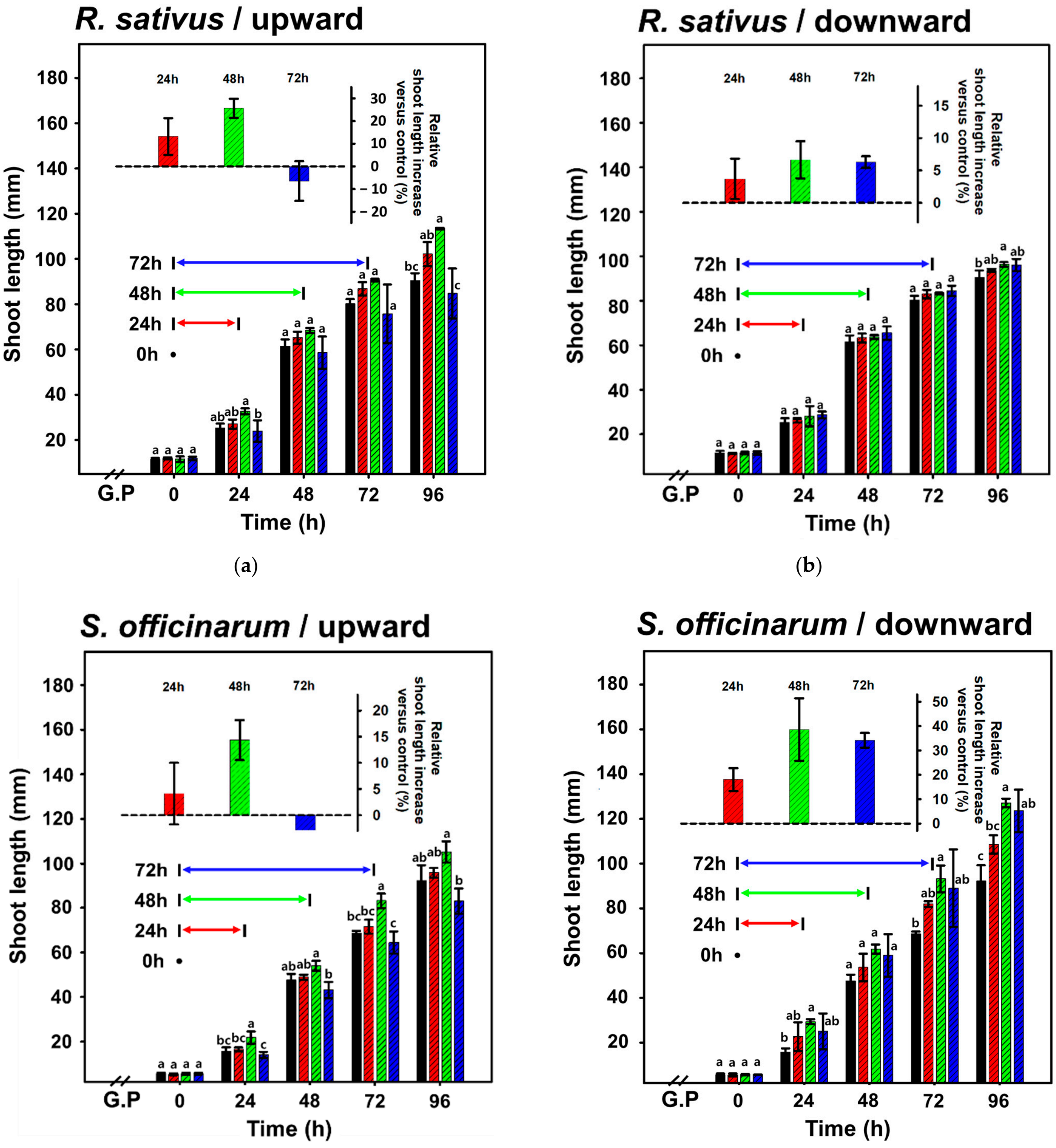
Newly imbibed radish and sugarcane seeds were planted at a rate of three seeds per pot in the experimental system and grown for approximately 72 h in the absence of an applied EMF to evaluate its effect on shoot growth. Subsequently, an EMF with a certain intensity was applied to the germinated seedlings either in an upward or a downward direction. EMF application had varying effects on shoot elongation rate (Figure 3). Thus, in the case of radish seedlings cultivated for 96 h after germination under an upwardly directed EMF, the 48 h treatment had the greatest effect on shoot growth (113.43 ± 0.35 mm). This finding indicated a 25.65% ± 4.21% growth increase compared with that in the control group (i.e., no EMF application). However, the 72 h EMF treatment had a negative effect on shoot growth (−6.45% ± 8.76%), compared with that in the control treatment (Figure 3a). Conversely, EMF application promoted growth when a reversed EMF (i.e., in a downward direction) was applied to the same species (Figure 3b), but shoot growth was slightly less than that of the plants subjected to the 48 h EMF treatment in the upward direction. Notably, 72 h of EMF application in the downward direction produced a positive effect on the growth of shoot length compared to the negative result produced by the EMF application in the upward direction.

An almost identical trend was observed in sugarcane seedlings grown under the two different EMF application directions (Figure 3c). Thus, in the case of upward EMF application, the highest growth rate was observed in the 48 h treatment (105.19 ± 4.71 mm). Similarly, the seedlings treated with the EMF for 72 h showed a lower growth rate compared to that of the control group. In contrast, when the EMF direction was reversed (Figure 3d), the results showed an increase in growth induced by all the EMF treatment durations tested, compared to that in the controls. In particular, the 48 h EMF treatment resulted in the greatest growth (127.09 ± 1.95 mm), indicating a 38.57% ± 12.81% increase compared with that in the control group, whose final length was 92.15 ± 1.95 mm. As inferred, directional variation of EMF application with different application times influenced this growth promotion/inhibition. The possible reasons for these effects of directional EMF application may be closely related to water and nutrient transport through the xylem and/or phloem [35,36].

During germination and early shoot elongation (Figure 2), relatively less organized and developed water and nutrient transport systems are at work moving sap through the young plant body. In our experiments, the initial length of the shoots was generally less than 10 mm. Therefore, a possible reason for the negative or lack of an effect of EMF application on early plant growth might have been the undeveloped condition of EMF-responsive organs or tissues (i.e., xylem and/or phloem) in the plant body. However, once shoot length reached a minimum threshold (generally over 20 mm), EMF application effectively promoted growth. After germination, the seedlings had more organized and longer pathways for water and nutrient transport. This increase in water and nutrient transport pathways in the plant body may also increase their responsiveness to an applied EMF.

Therefore, the observed growth promotion by EMF application in plants after germination was probably because of the more developed condition of the vascular tissues, which allowed for increased water and nutrient transport through the plant body. Currently, the reason for the observed reduction in plant growth in the seedlings subjected to longer-duration EMF treatments (e.g., 72 h in Figure 3a,c) is not clear; however, it may be attributed to differences in the sensitivity of nutrient and water pathways to EMF treatment between the species under study.

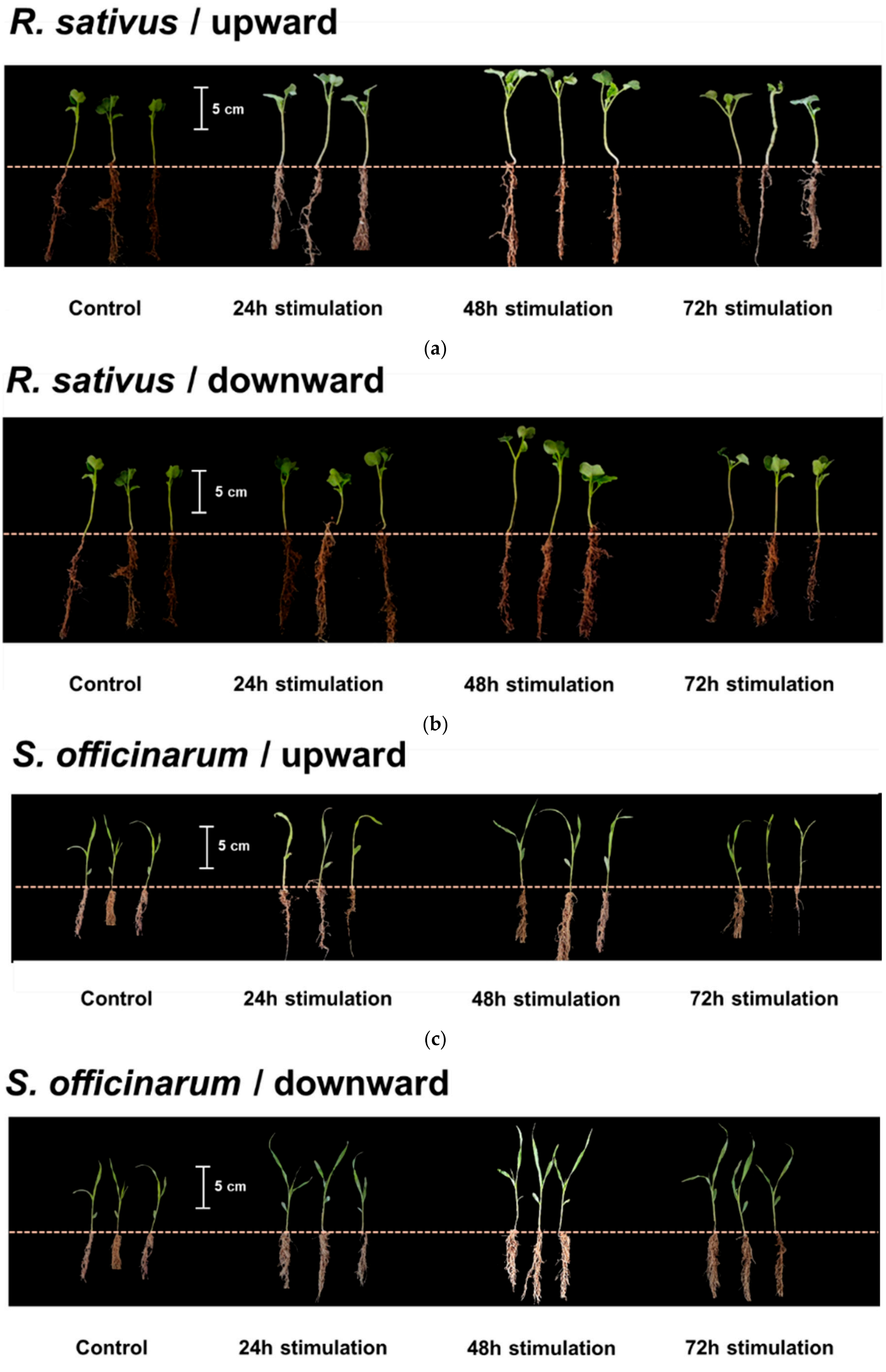
To determine the effect of EMF on root proliferation, plants (Figure 3) were harvested after cultivation for 7 days. Figure 4 shows a comparison of root proliferation at various EMF application times. Highly extended roots were observed after 48 h application of upward EMF (in radish) and downward EMF (in sugarcane). These results indicate that root proliferation was closely related to plant shoot growth, and that EMF applied under specific conditions promoted shoot growth and root proliferation. Based on these observations, further experiments were performed to elucidate additional reasons for the growth-promoting effects of EMF on plants.



(**a**) (**b**)

(**c**) (**d**)

**Figure 3.** Effects of different EMF application directions (EMF upward (**a**,**c**) and EMF downward (**b**,**d**)) on shoot growth (*R. sativus* and *S. officinarum*). The colored arrows in the figures indicate the effective EMF application periods after the seed germinations. The color codes in the plots indicate the measurement results with different EMF application periods (black dot: 0 h, red: 24 h, green: 48 h, blue: 72 h). The inner (upper) graphs indicate that the relative shoot length increased after 96 h of cultivation with different EMF application times and directions from early shoot growth (after germination). Different lowercase letters indicate significant differences ($p < 0.05$).



(**a**)

(**b**)

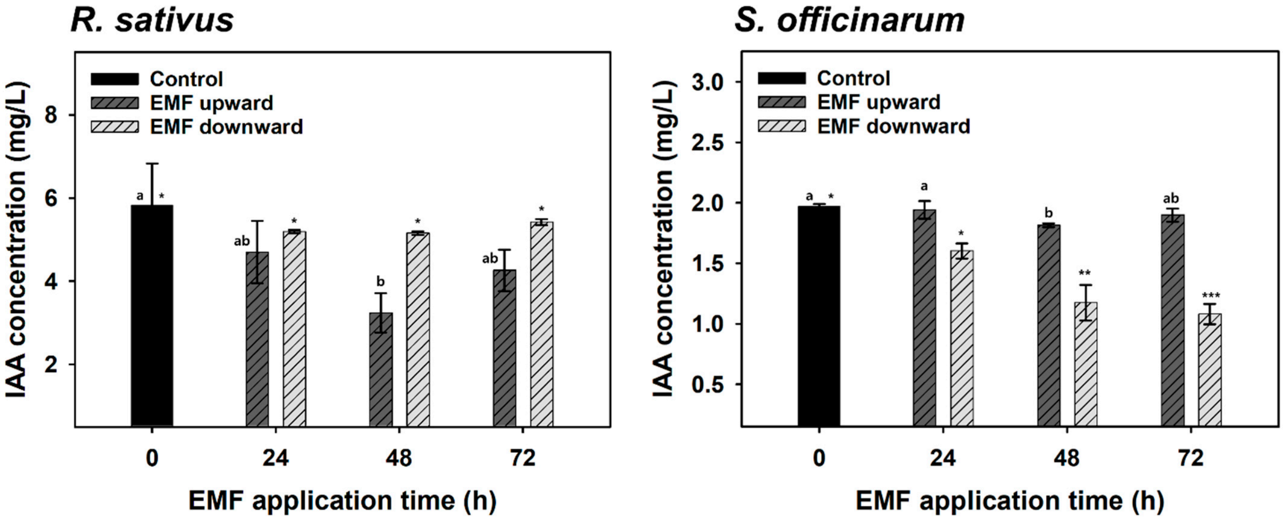
(**c**)

(**d**)

**Figure 4.** Comparison of shoot growth and root proliferation (*R. sativus* and *S. officinarum*) under various EMF application conditions (EMF upward (**a**,**c**) and EMF downward (**b**,**d**)). The dotted line indicates the growth measurement level. Data were obtained after 96 h of cultivation.

### *3.3. Effect of Different Directional EMFs on Endogenous IAA Concentration*

To verify the relationship between EMF application and endogenous IAA levels, whole plants under different EMF application times were prepared for the analysis. In the case of radish cultivated under an upwardly applied EMF, the endogenous IAA concentrations in all experimental groups were lower than those in the control groups (5.82 ± 1.01 mg/g; Figure 5a). Furthermore, IAA concentrations were the lowest for the 48 h EMF application treatment (3.24 ± 0.47 mg/g). After 48 h of EMF application, this was visually evident when the results on length were compared (Figure 3a). When radish seedlings were cultivated under a downwardly oriented EMF, the IAA concentrations of all experimental groups were slightly lower than those of the control groups. However, the reduction of IAA concentration in the downward-EMF-treated plants was not greater than that observed in the upward-EMF-treated ones.



(**a**) (**b**)

**Figure 5.** Effects of EMF application on IAA concentration in plants (*R. sativus* (**a**) and *S. officinarum* (**b**)). Results were obtained after 96 h of cultivation. Whole plants were used for IAA analysis. Different lowercase letters indicate significant differences ($p < 0.05$).

As for sugarcane seedlings cultivated under the application of an upward EMF, a slightly lower IAA concentration was observed in all experimental groups than in the control groups (1.97 ± 0.02 mg/g; Figure 5b). However, significant differences in IAA concentrations were observed under different EMF application times compared with those in the control groups in the case of the downward EMF treatment.

Altogether, our findings indicate that EMF application to growing seedlings effectively induced IAA accumulation in a manner dependent on EMF treatment duration and intensity. A comparison of endogenous IAA concentrations with measurements of shoot length (Figure 3) revealed an inverse correlation ($r^2$: 0.387868 in upwardly directed EMF for radish, $r^2$: 0.963257 in downwardly directed EMF for sugarcane). For example, maximum growth was observed under the 48 h upward EMF application in radish and the 48 h downward EMF application in sugarcane (Figure 3). Concomitantly, relatively low concentrations of IAA were measured in these treatment groups (Figure 5). A previous study showed that high concentrations of endogenous IAA inhibited plant growth and root proliferation [37,38], owing to the induction of ethylene synthesis [39]. Therefore, the differences in shoot length observed in Figure 3 were closely related to variations in endogenous IAA concentration induced in a manner dependent on EMF treatment duration. However, it is worth noting that the applicability of EMF for growth control may vary significantly with species. Further, more research is required to improve the performance of the solenoid-type plant-growth-control system and to verify the control mechanisms and overall applicability of our system to diverse plant species, plant physiological conditions, plant sizes, and experimental conditions, including application intervals. In particular, our study was only related to the early stages of plant growth, while grown plants may show very different sensitivity to EMF application. Therefore, the effects of longer durations of EMF application to various plant species at different cultivation stages need to be verified in order to interpret the EMF–plant interactions. Further, conducting future studies on other growth-related physiological indicators such as photosynthetic efficiency measurements, plant exudates and rhizobacteria analysis could help to clarify the mechanisms by which the EMF system affects plants. Future research prospects include the assessment of all these possibilities and the applicability of our method to the investigation of other plant species under different cultivation environments.

## 4. Conclusions

Immediate EMF application to radish and sugarcane seeds had no significant effects on germination. However, the application of EMF to young shoots had significant effects. Both EMF direction and application time were crucial factors in promoting shoot growth and root proliferation. EMF application also affected endogenous IAA concentrations, which were inversely proportional to shoot length, suggesting a regulatory role of EMF in plant-hormone-mediated processes. The effects of the EMF direction and treatment duration varied depending on plant species. By optimizing EMF application conditions (e.g., intensity, duration, and interval), plant growth could be either promoted or inhibited, highlighting the possibility of EMF application as an electrical plant stimulant (or electrical fertilizer) in the agriculture industry.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae10090973/s1, Figure S1: Photograph of the experimental plant-growth-control system used in this study; Figure S2: Effect of downward EMF application on seed germination rate and shoot growth.

**Author Contributions:** Conceptualization, J.W.J. and H.J.K.; methodology, J.W.J.; software, S.W.Y.; validation, J.W.J., S.W.Y. and H.J.K.; formal analysis, J.W.J.; investigation, J.W.J. and S.W.Y.; resources, G.W.L., J.H.K. and Y.J.K.; data curation, Y.-K.C.; writing—original draft preparation, J.W.J. and S.W.Y.; writing—review and editing, G.W.L., J.H.K., Y.J.K. and Y.-K.C.; visualization, J.W.J. and S.W.Y.; supervision, K.J.K., H.-S.L., S.W.B. and H.J.K.; project administration, H.J.K. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

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**Conflicts of Interest:** Author Yong-Keun Choi was employed by the company R&D Center, Choilab Inc. Author Sung Won Bang was employed by the company GARDEN4U Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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