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# Utilizing electromagnetic fields for enhancing root germination of cassava Kasetsart 50 varieties

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**Abstract:** This study aimed to investigate the optimal duration and intensity of electromagnetic field exposure for enhancing root development in cassava (Kasetsart 50). A 5 x 5 factorial experiment with four replications was conducted in a greenhouse over a 30-day period. Two factors were examined: stimulation duration (0, 15, 30, 45, and 60 minutes) and electromagnetic field intensity (10, 20, 30, 40, and 50 mT). Various root morphological parameters were measured, including total root length, total surface area, root length/volume ratio, root volume, number of root tips, mean root diameter, root width, and surface area. Results indicated that both stimulation duration and electromagnetic field intensity significantly influenced root development. Notably, the combination of 45 minutes and 40 mT, as well as 60 minutes and 10 mT, yielded the most favorable outcomes, including increased root tips, total surface area, root volume, and mean root diameter. Additionally, total root length exhibited a strong positive correlation with total surface area (r = 0.9847**), root length/volume ratio (r = 0.602**), and root volume (r = 0.4328*). Conversely, a negative correlation was observed between the number of root tips and root diameter (r = -0.2427), as well as between root diameter and root width (r = -0.0586).

**Keywords:** Electromagnetic field, *Manihot esculenta* Crantz, root cassava, greenhouse conditions.

## Introduction

Numerous studies have investigated the effects of various physical treatments on plant growth and germination. Magnetic fields, in particular, have been shown to positively influence plant growth by altering water properties and enhancing seed germination and growth performance (Zaidan et al., 2023). Exposure to weak magnetic fields can induce changes in plant chemical composition, affecting essential, beneficial, and non-useful elements, as well as metabolite synthesis and litter decomposability traits (Bellino et al., 2023). Moreover, magnetic treatments have been found to reduce germination time and improve germination rates, fresh weight, and mean germination time in various plant species. This suggests potential for enhancing yields and optimizing agricultural practices (Tapia-Belmonte et al., 2023; Carbonell et al., 2022). The application of magnetic fields in agriculture holds promise for sustainable plant growth enhancement, although the effects vary depending on the intensity and duration of exposure. Further research is needed to elucidate the underlying biophysical mechanisms and optimize agricultural practices (Qoni' et al., 2022).

Cassava (*Manihot esculenta* Crantz) is a globally significant commercial food crop cultivated extensively in tropical and subtropical regions. It serves as a vital source of food, feed, starch, and starch-derived products worldwide (Li et al., 2017; Parmar et al., 2017). In Thailand, promoting locally sourced cassava chips can enhance the sustainability of the cassava value chain by considering factors such as consumer preferences, education levels, and regional differences.

Previous research has demonstrated that exposure to magnetic fields can stimulate seed germination and accelerate plant growth. This can be achieved through direct stimulation of seeds or by using magnetically treated water in irrigation systems (Ling and Hai-long, 2011; Martinez et al., 2000; Maffei, 2014). Several studies suggest that treatment with magnetic fields (MFs) of higher intensity than the geomagnetic field (GMF) can stimulate the growth and yield of various agronomically important plant species. However, the effects are dependent on the flux density and duration of exposure to MFs (Podleśny et al., 2021; Maffei, 2014). MFs have also been shown to modify seed germination and affect seedling growth and development in a wide range of plants, including field crops, fodder, industrial crops, cereals, and pseudo-cereals (Bhardwaj et al., 2012a; Araujo et al., 2016).

While magnetic field applications offer potential benefits for plant growth, it is essential to consider potential adverse effects and ensure the safety and acceptance of these new technologies. Important considerations for the use of magnetic fields in seed cultivation include optimizing watering practices, seedling preparation, and the selection of appropriate magnetic field intensities and durations. These parameters should be tailored to the specific type and age of the experimental plants (Dhawi, 2014).

Rezaei-Zarchi et al. (2012) demonstrated that the application of electric and magnetic fields can improve plant germination by enhancing the movement of ions and electrons, cell division, and plant growth. MFs, a form of non-ionizing radiation, can positively influence plant morphogenesis by providing an environmentally friendly and non-toxic stimulus for seed germination and plant growth. Research indicates that MFs and electromagnetic fields (EMFs) ranging from 1.5 to 250 millitesla (mT) can have beneficial effects on seed germination and seedling growth in various plant species, leading to increased biomass and yield (Vashisth and Nagarajan, 2010).

The use of magnetic fields to enhance germination represents a novel technology with potential applications in Cassava cultivation. This approach can stimulate root growth, strengthen root systems, and accelerate overall cassava development. Despite the potential benefits, there is currently a lack of research on the effects of magnetic fields on cassava root development. Investigating the impact of permanent magnetic fields on the formation of food storage roots in cassava is a compelling area for future research. This study distinguishes itself from most of the research, which concentrates on the effects of electromagnetism on seed germination. Instead, this investigation focuses on cassava, a plant that is propagated vegetatively through stem cuttings (breeding pipe) rather than through seeds.

## Results and discussion

The results of this study will be divided into two main parts: 1. Statistical description (Growth of Cassava Obtained from Experiments), and 2. Correlational description (Interaction Effects and Correlation Analysis). The discussion of the results will primarily focus on the second part, which pertains to the correlational analysis.

Growth of Cassava Obtained from Experiments

This section presents the results of the study on the effects of electromagnetic field (EMF) stimulation on various root growth parameters of cassava (Table 1).

### *Total root length*

EMF stimulation significantly influenced total root length. Stimulation durations of 15, 45, and 30 minutes resulted in the longest root lengths (447.38 cm, 444.95 cm, and 443.77 cm, respectively). Similarly, EMF strength played a crucial role, with 50 mT and 40 mT inducing the greatest root lengths (445.70 cm and 444.41 cm, respectively). The above results are consistent with several previous studies. For example, Vashisth and Nagarajan (2010) found that static magnetic fields affect the germination and early growth of sunflower seeds, increasing root length and seedling dry weight. Similarly, Radhakrishnan and Kumari (2012) studied the effect of magnetic fields on the growth, development, and yield of soybeans and found that magnetic fields increased root length, root number, and root dry weight. Mahajan and Pandey (2014) also found that static magnetic fields increased root length, root number, and root dry weight in chickpeas. Shine et al. (2011) studied the effect of magnetic fields on the growth and biochemical parameters of maize and found that magnetic fields affected root length, dry weight, and chlorophyll content.

### *Total root surface area (cm$^2$)*

Stimulation duration significantly affected total root surface area. Stimulation periods of 0, 15, 30, and 45 minutes yielded the largest surface areas, while 60 minutes resulted in the smallest (21.287 cm$^2$). EMF strengths of 10, 30, 40, and 50 mT produced the largest surface areas, with 20 mT resulting in the smallest (21.427 cm$^2$). The study indicates that the duration and intensity of electromagnetic field (EMF) stimulation affect root surface area, a crucial factor in water and nutrient uptake in plants. However, research directly investigating the effects of EMF on root surface area is limited. Most studies tend to focus on the effects of EMF on root length, dry weight, or germination. Despite these limitations, some studies may provide insights into the relationship between EMF and root surface area. For instance: Yildiz et al. (2007) studied the effects of magnetic fields on yield and nutrient content in barley seeds. They found that magnetic fields influenced the absorption of certain nutrients, which may indicate changes in root surface area, although the study did not directly measure this parameter. De Souza et al. (2006) investigated the effects of pre-sowing magnetic field treatment on tomato seeds. They observed that magnetic fields enhanced tomato growth and yield, potentially due to increased root surface area, although this was not directly measured. Florez et al. (2004) studied the effects of magnetic fields on germination and early growth of barley seeds. They found that magnetic fields influenced root development, which could potentially affect root surface area in the long term, although the study did not measure long-term root surface area changes. While these studies did not directly examine the effects of EMF on root surface area, they demonstrate that EMF influences various root processes, potentially indirectly affecting root surface area. This highlights a promising area for future research.

### *Root length/volume (cm/m$^3$)*

Significant differences in root length per volume were observed across stimulation durations. A 45-minute stimulation yielded the highest ratio (1778.0 cm/m$^3$), while 60 minutes produced the lowest (1425.9 cm/m$^3$). EMF strength also impacted this ratio, with 40 mT inducing the highest value (1838.6 cm/m$^3$) and 10 mT the lowest (1491.2 cm/m$^3$). The study shows that EMF stimulation affects the root length to volume ratio, indicating the space-use efficiency of root growth. However, finding research that directly investigates the effect of EMF on this ratio is challenging. Most studies focus on the effects of EMF on root length, dry weight, or root quantity separately. Nevertheless, by considering studies that examine the effects of EMF on other root parameters potentially linked to the root length to volume ratio, such as root length, root diameter, and root branching, we can gain some understanding of how EMF impacts the space-use efficiency of root growth. For example: Vashisth and Nagarajan (2008) studied the effect of static magnetic fields on the germination and early growth of chickpeas. They found that magnetic fields increased root length and root diameter, which could potentially affect the root length to volume ratio, although the study did not directly report this ratio. Rajput and Rao (2013) studied the effect of magnetic fields on the growth and yield of cluster beans. They found that magnetic fields increased root length and root number, which could also potentially influence the root length to volume ratio, although this ratio was not directly reported. Bhardwaj et al. (2012b) studied the effect of static magnetic fields on the growth and biochemical parameters of soybeans. They found that magnetic fields affected root length, root branching, and root dry weight, which could potentially impact the root length to volume ratio. While these studies did not directly investigate the effect of EMF on the root length to volume ratio, they demonstrate that EMF influences various root parameters, potentially indirectly affecting this ratio.

***Root volume (cm$^3$)***

Stimulation duration significantly affected root volume. A 30-minute stimulation produced the largest volume (16.669 cm$^3$), while 0 minutes resulted in the smallest (12.410 cm$^3$). EMF strength also significantly influenced root volume. The experimental results indicate that EMF affects root volume, which is an indicator of root system growth and development. The duration of stimulation and the intensity of the EMF are crucial factors. Although there is limited research directly investigating the effect of EMF on root volume, some studies have explored the effects of EMF on other root parameters, such as root diameter, root number, and root branching, which may be related to root volume. For example: Radhakrishnan and Kumari (2013) studied the effect of magnetic fields on the growth, yield, and quality of soybeans. They found that magnetic fields increased root diameter and root number, which could potentially affect root volume, although the study did not directly report root volume. Mahajan and Pandey (2013) studied the effect of pre-sowing static magnetic field treatment on pea seeds. They found that magnetic fields increased root length, root diameter, and root number, which could potentially affect root volume. Turker et al. (2003) studied the effect of static magnetic fields on barley seed germination and seedling growth. They found that magnetic fields affected root length, root diameter, and root branching, which could potentially affect root volume.

***Number of root tips***

Stimulation duration significantly affected the number of root tips. A 45-minute stimulation resulted in the highest count (2893.2), while 0, 15, 30, and 60 minutes produced similar, lower counts. EMF strength also influenced root tip numbers, with 40 mT inducing the highest count (2855.8) and 20 mT the lowest (1892.1). The experimental results demonstrate that EMF influences the number of root tips, which is an indicator of the plant's water and nutrient absorption capacity. The duration of stimulation and the intensity of the EMF are crucial factors. While research directly investigating the effect of EMF on the number of root tips is limited, some studies may be relevant to these findings. For instance: Dumlupinar and Kirnak (2010) studied the effect of pre-sowing magnetic field treatment on safflower seeds. They found that magnetic fields increased root branching, which could potentially affect the number of root tips, although the study did not directly report this number.

***Root average diameter (mm)***

While stimulation duration significantly affected root diameter, the differences were not statistically significant. However, 30 minutes tended to produce the largest diameter (1.1784 mm). An EMF strength of 50 mT resulted in the largest diameter (1.2310 mm). The above results are consistent with several previous studies. For example, Vashisth and Nagarajan (2008) found that static magnetic fields affect the germination and early growth of chickpea seeds, increasing root diameter. Similarly, Shine et al. (2012) studied the effect of pre-sowing static magnetic field treatment on sunflower seeds and found that magnetic fields increased root diameter. Rajput and Rao (2013) also found that magnetic fields increased root diameter in cluster beans. Bhardwaj et al. (2012b) studied the effect of static magnetic fields on the growth and biochemical parameters of soybeans and found that magnetic fields affected root diameter. Finally, Polovinkina et al. (2003) studied the effect of weak magnetic fields on the growth and yield of barley and found that magnetic fields affected root diameter.

***Root width (cm)***

Stimulation durations of 0, 15, 30, and 45 minutes resulted in similar, maximum root widths, while 60 minutes produced the smallest width (17.458 cm). EMF strengths of 10, 30, 40, and 50 mT yielded similar, maximum widths, while 20 mT resulted in the smallest width (17.264 cm). The experimental results show that both the duration of stimulation and the intensity of EMF affect root width. The durations of 0, 15, 30, and 45 minutes resulted in the maximum root width, and the EMF intensities of 10, 30, 40, and 50 mT also resulted in the maximum root width. Since "root width" can have multiple interpretations, it is necessary to distinguish between two cases for clarity in interpreting the results and finding relevant research: Case 1: Root width refers to root diameter. The experimental results are consistent with research showing that EMF affects the increase in root cell size, which results in an increase in root diameter. For example: Vashisth and Nagarajan (2008) studied the effect of static magnetic fields on the germination and early growth of chickpeas and found that magnetic fields increased root diameter. Shine et al. (2012) studied the effect of pre-sowing static magnetic field treatment on sunflower seeds and found that magnetic fields increased root diameter. Rajput and Rao (2013) studied the effect of magnetic fields on the growth and yield of cluster beans and found that magnetic fields increased root diameter. Case 2: Root width refers to the overall width of the root system. The experimental results are consistent with research showing that EMF affects root branching, which results in a wider root system. For example: Dumlupinar and Kirnak (2010) studied the effect of pre-sowing magnetic field treatment on safflower seeds and found that magnetic fields increased root branching, which could lead to a wider root system.

**Table 1.** Effect of electromagnetic field on root physiology of cassava cv. Kasetsart 50 at 30 days after planting under greenhouse experiment.

| Treatment | | Total root length (cm) | Total root surface area (cm$^2$) | Root length/ volume (cm/m$^3$) | Root volume (cm$^3$) | No. of Root tips (roots) | Root average diameter (mm) | Root width (cm) | surface area (cm$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| Time (minute) | | | | | | | | | |
| T1 | 0 min | 433.84$^{B}$ | 24.247$^{A}$ | 1583.0$^{AB}$ | 12.410$^{B}$ | 2096.6$^{B}$ | 1.007 | 18.268$^{A}$ | 455.58$^{B}$ |
| T2 | 15 min | 447.38$^{A}$ | 24.368$^{A}$ | 1592.9$^{AB}$ | 14.373$^{AB}$ | 2312.3$^{B}$ | 1.1253 | 18.136$^{A}$ | 498.42$^{AB}$ |
| T3 | 30 min | 443.77$^{A}$ | 24.215$^{A}$ | 1676.2$^{AB}$ | 16.669$^{A}$ | 2429.3$^{B}$ | 1.1784 | 18.274$^{A}$ | 542.69$^{A}$ |
| T4 | 45 min | 444.95$^{A}$ | 24.266$^{A}$ | 1778.0$^{A}$ | 15.609$^{AB}$ | 2893.2$^{A}$ | 1.1094 | 18.289$^{A}$ | 555.00$^{A}$ |
| T5 | 60 min | 381.67$^{C}$ | 21.287$^{B}$ | 1425.9$^{B}$ | 13.751$^{AB}$ | 2016.0$^{B}$ | 1.1456 | 17.458$^{B}$ | 480.06$^{AB}$ |
| F-test | | * | * | * | * | * | ns | * | * |
| Electromagnetic field (mT) | | | | | | | | | |
| E1 | 10 mT | 439.60$^{B}$ | 24.270$^{A}$ | 1491.2$^{B}$ | 17.595$^{A}$ | 2503.7$^{AB}$ | 1.1982$^{AB}$ | 18.293$^{A}$ | 537.01$^{A}$ |
| E2 | 20 mT | 378.61$^{A}$ | 21.427$^{B}$ | 1540.4$^{B}$ | 10.810$^{B}$ | 1892.1$^{C}$ | 1.0579$^{AB}$ | 17.264$^{B}$ | 402.73$^{B}$ |
| E3 | 30 mT | 443.30$^{A}$ | 24.097$^{A}$ | 1653.0$^{AB}$ | 13.947$^{AB}$ | 2264.6$^{BC}$ | 1.0709$^{AB}$ | 18.264$^{A}$ | 501.18$^{A}$ |
| E4 | 40 mT | 444.41$^{A}$ | 24.297$^{A}$ | 1838.6$^{A}$ | 14.813$^{A}$ | 2855.8$^{A}$ | 1.0076$^{B}$ | 18.291$^{A}$ | 564.35$^{A}$ |
| E5 | 50 mT | 445.70$^{C}$ | 24.293$^{A}$ | 1532.8$^{B}$ | 15.648$^{A}$ | 2231.8$^{BC}$ | 1.2310$^{A}$ | 18.314$^{A}$ | 526.48$^{A}$ |
| F-test | | * | * | * | * | * | * | * | * |

Note: ns: Not significant, *Significant different at $p<0.05$. Means in the same column with different letters are significantly different at $p<0.05$ by LSD.

**Table 2.** Interaction of time and electromagnetic field on root physiology of cassava cv. Kasetsart 50 at 30 days after planting under greenhouse experiment.

| Treatments | | Total root length (cm) | Total Root surface area (cm$^2$) | Root length/ volume (cm/m$^3$) | Root volume (cm$^3$) | No. of Root tips (roots) | Root average diameter (mm) | Root width (cm) | Surface area (cm$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| Time (minute) x Electromagnetic field (mT) | | | | | | | | | |
| 0 min | 0 mT | 411.71$^{D}$ | 24.133$^{A}$ | 1421.9$^{D}$ | 11.542$^{BC}$ | 1996.3$^{BCD}$ | 1.0067$^{AB}$ | 17.971$^{A}$ | 440.18$^{DE}$ |
| 0 min | 10 mT | 424.63$^{C}$ | 24.314$^{A}$ | 1721.1$^{BCD}$ | 13.237$^{ABC}$ | 2099.3$^{BCD}$ | 0.9929$^{AB}$ | 18.427$^{A}$ | 473.35$^{BCDE}$ |
| 0 min | 20 mT | 439.49$^{B}$ | 4.085$^{AB}$ | 1775.8$^{ABCD}$ | 14.412$^{ABC}$ | 2141.8$^{BCD}$ | 1.0254$^{AB}$ | 18.247$^{A}$ | 489.75$^{BCDE}$ |
| 0 min | 30 mT | 445.04$^{AB}$ | 24.276$^{A}$ | 1414.7$^{D}$ | 9.605$^{C}$ | 2192.0$^{BCD}$ | 0.9403$^{B}$ | 18.353$^{A}$ | 413.38$^{E}$ |
| 0 min | 40 mT | 448.32$^{AB}$ | 24.428$^{A}$ | 1581.7$^{BCD}$ | 13.255 $^{ABC}$ | 2053.8$^{BCD}$ | 1.0695$^{AB}$ | 18.352$^{A}$ | 461.25$^{DE}$ |
| 0 min | 50 mT | 411.71$^{D}$ | 24.133$^{A}$ | 1421.9$^{D}$ | 11.542 $^{BC}$ | 1996.3$^{BCD}$ | 1.0067$^{AB}$ | 17.971$^{A}$ | 440.18$^{DE}$ |
| 15 min | 10 mT | 449.59$^{AB}$ | 24.295$^{A}$ | 1483.6$^{CD}$ | 19.349 $^{AB}$ | 2552.5$^{BCD}$ | 1.2894$^{AB}$ | 18.504$^{A}$ | 497.71$^{BCDE}$ |
| 15 min | 20 mT | 451.13$^{A}$ | 24.470$^{A}$ | 1570.5$^{BCD}$ | 11.283 $^{BC}$ | 1788.0$^{D}$ | 1.2384$^{AB}$ | 17.323$^{A}$ | 445.96$^{DE}$ |
| 15 min | 30 mT | 446.15$^{AB}$ | 24.362$^{A}$ | 1554.3$^{BCD}$ | 10.622 $^{C}$ | 2518.0$^{BCD}$ | 0.9376$^{B}$ | 18.314$^{A}$ | 452.80$^{DE}$ |
| 15 min | 40 mT | 442.39$^{AB}$ | 24.371$^{A}$ | 1791.3$^{ABCD}$ | 13.625 $^{ABC}$ | 2505.0$^{BCD}$ | 0.9735$^{B}$ | 18.153$^{A}$ | 548.15$^{ABCDE}$ |
| 15 min | 50 mT | 447.65$^{AB}$ | 24.343$^{A}$ | 1564.7$^{BCD}$ | 16.989 $^{ABC}$ | 2198.2$^{BCD}$ | 1.1876$^{AB}$ | 18.390$^{A}$ | 547.46$^{ABCDE}$ |
| 30 min | 10 mT | 444.73$^{AB}$ | 24.295$^{A}$ | 1247.0$^{D}$ | 15.478 $^{ABC}$ | 2152.3$^{BCD}$ | 1.3251$^{AB}$ | 18.304$^{A}$ | 469.98$^{DE}$ |
| 30 min | 20 mT | 442.94$^{AB}$ | 23.990$^{AB}$ | 2331.6$^{A}$ | 13.985 $^{ABC}$ | 2415.5$^{BCD}$ | 1.0028$^{AB}$ | 18.199$^{A}$ | 505.06$^{BCDE}$ |
| 30 min | 30 mT | 443.89$^{AB}$ | 24.238$^{A}$ | 1542.8$^{BCD}$ | 15.327 $^{ABC}$ | 2585.5$^{BCD}$ | 1.1152$^{AB}$ | 18.314$^{A}$ | 535.42$^{ABCDE}$ |
| 30 min | 40 mT | 442.79$^{AB}$ | 24.266$^{A}$ | 1810.7$^{ABCD}$ | 20.999 $^{A}$ | 2744.7$^{BC}$ | 1.2190$^{AB}$ | 18.247$^{A}$ | 641.08$^{AB}$ |
| 30 min | 50 mT | 444.52$^{AB}$ | 24.285$^{A}$ | 1449.1$^{CD}$ | 17.557$^{ABC}$ | 2248.3$^{BCD}$ | 1.2300$^{AB}$ | 18.304$^{A}$ | 561.91$^{ABCDE}$ |
| 45 min | 10 mT | 445.05$^{AB}$ | 24.314$^{A}$ | 1796.7$^{ABCD}$ | 20.480$^{A}$ | 2967.5$^{B}$ | 1.1391$^{AB}$ | 18.304$^{A}$ | 597.28$^{ABCD}$ |
| 45 min | 20 mT | 445.10$^{AB}$ | 24.305$^{A}$ | 1755.4$^{ABCD}$ | 14.805$^{ABC}$ | 2740.7$^{BCD}$ | 1.0988$^{AB}$ | 18.247$^{A}$ | 559.42$^{ABCDE}$ |
| 45 min | 30 mT | 442.94$^{AB}$ | 24.219$^{A}$ | 1693.5$^{BCD}$ | 15.001$^{ABC}$ | 2161.5$^{BCD}$ | 1.1885$^{AB}$ | 18.285$^{A}$ | 550.14$^{ABCDE}$ |
| 45 min | 40 mT | 443.60$^{AB}$ | 24.285$^{A}$ | 2036.0$^{ABC}$ | 12.785$^{ABC}$ | 3988.0$^{A}$ | 0.8936$^{B}$ | 18.266$^{A}$ | 567.64$^{ABCDE}$ |
| 45 min | 50 mT | 448.04$^{AB}$ | 24.209$^{A}$ | 1608.5$^{BCD}$ | 14.976$^{ABC}$ | 2608.0$^{BCD}$ | 1.2270$^{AB}$ | 18.342$^{A}$ | 500.50$^{BCDE}$ |
| 60 min | 10 mT | 446.91$^{AB}$ | 24.314$^{A}$ | 1752.9$^{ABCD}$ | 21.127$^{A}$ | 2850.0$^{BC}$ | 1.2307$^{AB}$ | 18.380$^{A}$ | 679.91$^{A}$ |
| 60 min | 20 mT | 129.24$^{E}$ | 10.054$^{C}$ | 77.5$^{E}$ | 0.738$^{D}$ | 417.0$^{E}$ | 0.9566$^{B}$ | 14.114$^{B}$ | 13.44$^{F}$ |
| 60 min | 30 mT | 444.02$^{AB}$ | 23.581 $^{B}$ | 1698.8$^{BCD}$ | 14.372$^{ABC}$ | 1913.0$^{CD}$ | 1.0878$^{AB}$ | 18.161$^{A}$ | 494.20$^{BCDE}$ |
| 60 min | 40 mT | 448.22$^{AB}$ | 24.285 $^{A}$ | 2140.2$^{AB}$ | 17.052$^{ABC}$ | 2849.3$^{BC}$ | 1.0118$^{AB}$ | 18.456$^{A}$ | 651.49$^{AB}$ |
| 60 min | 50 mT | 439.96$^{B}$ | 24.200 $^{A}$ | 1460.1$^{CD}$ | 15.465$^{ABC}$ | 2050.8$^{BCD}$ | 1.4412$^{A}$ | 18.180$^{A}$ | 561.28$^{ABCDE}$ |
| F-test | | * | * | * | * | * | * | * | * |
| CV % | | 1.77 | 1.62 | 26.49 | 41.34 | 29.72 | 28.95 | 5.36 | 23.75 |

Note: ns: Not significant, *Significant different at $p<0.05$. Means in the same column with different letters are significantly different at $p<0.05$ by LSD.

### *Surface area (cm$^2$)*

Stimulation durations of 45 and 30 minutes produced the largest root surface areas (555.00 and 542.69 cm$^2$, respectively), while 0 minutes resulted in the smallest (455.58 cm$^2$). EMF strengths of 0, 30, 40, and 50 mT yielded similar, large surface areas, with 40 mT tending to produce the largest (564.35 cm$^2$). The experimental results demonstrate that the duration of stimulation and the intensity of EMF affect root surface area, a crucial factor in water and nutrient uptake in plants. While research directly investigating the effect of EMF on root surface area is limited, some studies may be relevant to these findings. For instance: Yildiz et al. (2007) studied the effects of magnetic fields on yield and nutrient content in barley seeds. They found that magnetic fields influenced the absorption of certain nutrients, which may indicate changes in root surface area, although the study did not directly measure this parameter. However, the fact that EMF affects nutrient uptake may also indicate that EMF affects root surface area. De Souza et al. (2006) investigated the effects of pre-sowing magnetic field treatment on tomato seeds. They observed that magnetic fields enhanced tomato growth and yield, potentially due to increased root surface area, although this was not directly measured. However, the fact that EMF affects growth may also indicate that EMF affects root surface area. Florez et al. (2004) studied the effects of magnetic fields on germination and early growth of barley seeds. They found that magnetic fields influenced root development, which could potentially affect root surface area in the long term, although the study did not measure long-term root surface area changes.

### *Interaction effects and correlation analysis*

Analysis of the Correlation between exposure time and electromagnetic field (EMF) intensity on the physiological characteristics of cassava roots (Table 2 and Table 3) revealed that exposure duration significantly influenced the effects of EMF. Specifically, a 15-minute exposure at 20 mT resulted in the maximum total root length of 451.13 cm. A 30-minute exposure at 20 mT yielded the highest root length to volume ratio, with a root volume of 2,331.6 $cm^3/m^3$. The maximum root volumes of 21.127 $cm^3$ and 20.480 $cm^3$ were achieved with exposure times of 60 minutes at 10 mT and 45 minutes at 10 mT, respectively. The highest number of root tips (3,988) was obtained with a 45-minute exposure at 40 mT. Furthermore, a 60-minute exposure at 50 mT resulted in the maximum root diameter of 1.4412 mm.

Table 2 indicates that the optimal combinations of EMF intensity and exposure time for maximizing root characteristics were 45 minutes at 40 mT and 60 minutes at 10 mT. These combinations produced the highest values for the number of root tips, total surface area, root volume, average root diameter, and root surface area. EMFs stimulate cells by directly interacting with charged particles in DNA and enzymes, leading to enhanced plant growth responses (Reina and Pascual, 2001). This interaction results in improved root development, which enhances nutrient acquisition, water absorption, and cell division. Moreover, the energy from direct electromagnetic stimulation positively impacts growth processes, promoting plant germination. EMFs facilitate the formation of molecules involved in cellular processes, resulting in improved growth and development. The intensity and duration of electromagnetic stimulation differentially affect plant growth across various species.

These findings align with previous research by Rezaei-Zarchi et al. (2012), which demonstrated that electric and magnetic fields enhance electron-ion movement, cell division, and plant growth. Similarly, Kiatgamjorn et al. (2002) observed that electric and electromagnetic fields stimulated stem height and root length compared to controls. However, our study found that stimulation at 60 minutes and 20 mT resulted in the lowest values for total root length, total root surface area, root length to volume ratio, root volume, number of root tips, average root diameter, root width, and root surface area in cassava. Conversely, Senglathsamy et al. (2017) reported that exposure to a 20 mT magnetic field for 60 minutes yielded the highest germination index, final germination percentage, growth, and vigor index in steamed white glutinous rice from Laos compared to controls. This discrepancy may be attributed to the differential responses of cassava tissue cells compared to rice seeds.

Belyavskaya (2004) noted that EMFs could lead to excessive calcium accumulation in the cells and tissues of pea (Pisum sativum L.), which is crucial for growth processes and stress responses. Increased calcium uptake alters conductivity charges, prolonging the duration of magnetic field stimulation. This calcium accumulation may explain the role of stress reactions in mitigating magnetically induced cell damage by free radicals, reducing cell numbers, and inhibiting growth. However, Campbell (2003) reported that plant cell pigments exhibit magnetic attraction properties, moving with the magnetic field, which increases internal energy and influences cellular reactions and development. Nonetheless, excessive magnetic field exposure can reduce pigment levels in plants like maize and black locust (Robinia pseudoacacia L.).

Overall, while EMFs can enhance plant growth under certain conditions, excessive exposure may have detrimental effects, emphasizing the need for precise optimization of treatment parameters for each plant species. The use of static magnetic fields provides a physical method to increase the intensity of ions, free radicals, and charged electrons. This facilitates water absorption by cell membranes, improves ion movement, stimulates physiological processes such as cell division and plant growth, and enhances plant vigor index.

Pre-sowing treatments with cold atmospheric plasma (CAP) and pulsed electromagnetic fields (PEMF) have demonstrated significant positive effects on the growth, physiology, yield, and quality traits of maize seeds with both high and low vigor. These treatments improved germination rate, chlorophyll content, photosynthetic rate, transpiration rate, stomatal conductance, and dry weight of maize plants. The application of CAP and PEMF treatments resulted in increased maize yield by 18-25% for low vigor seeds and 10-20% for high vigor seeds. Notably, a 15-minute CAP treatment increased the total protein and crude fiber content of harvested maize seeds by 26-36% and 29-42% for low and high vigor seeds, respectively, compared to untreated samples. This study suggests that pre-sowing treatments with CAP and PEMF could be alternative tools for enhancing maize growth, yield, and end-product quality. Further research is recommended to explore the mechanisms by which CAP and PEMF treatments stimulate seed germination and improve quality (Chanioti et al., 2021).

The application of magnetic fields as a pre-sowing treatment significantly enhances plant growth and the accumulation of essential chemical elements in the early stages of cotton development. This treatment has been shown to improve transpiration rate, photosynthetic rate, stomatal conductance, root and shoot growth, and the percentage of nitrogen, phosphorus, potassium, calcium, and magnesium in cotton plants, underscoring its efficacy in promoting plant growth. This study highlights the environmentally friendly nature of magnetic field treatments, positioning it as a desirable technique for modern agriculture with positive impacts on nutrient

**Table 3.** Correlation of root traits in cassava cv. Kasetsart 50 at 30 days after planting.

| Parameters | Total root length | Total Root surface area | Root length/volume | Root volume | Root tips | Root average diameter | Root width |
|---|---|---|---|---|---|---|---|
| Total root surface area | 0.9847** | | | | | | |
| Root length/volume | 0.602** | 0.5836** | | | | | |
| Root volume | 0.4328* | 0.4466* | 0.183 | | | | |
| Root tips | 0.4744* | 0.4746* | 0.6134** | 0.2413 | | | |
| Root average diameter | 0.101 | 0.1056 | -0.3091 | 0.6114** | -0.2427 | | |
| Root width | 0.6607** | 0.6698** | 0.3956 | 0.3389 | 0.4481* | -0.0586 | |
| surface area | 0.651** | 0.6685** | 0.6281** | 0.777** | 0.5479** | 0.2486 | 0.4662* |

Note: *Significant different at p<0.05. **Significant different at p<0.05.

uptake from the growth medium, leading to higher concentrations of essential elements in plants. Previous research supports these findings, demonstrating.

## Materials and Methods

### *Experimental setup*

This experiment was conducted in a greenhouse at the Faculty of Technology, Mahasarakham University, Thailand. A completely randomized design (CRD) with a 5x5 factorial arrangement was employed. The experiment involved two factors:
Factors 1 (Duration of exposure). Five levels were used: 0 (T1), 15 (T2), 30 (T3), 45 (T4), and 60 (T5) minutes. Factor 2 ((Electromagnetic Field: EMF) Levels). Five levels were applied: 10 (E1), 20 (E2), 30 (E3), 40 (E4), and 50 (E5) mT. Each treatment combination was replicated four times, resulting in a total of 25 treatments.

### *Planting material and procedure*

It can be divided into 6 things, with the following details: (1) Sand was sieved to remove impurities and packed into black plastic bags (9x18"). (2) Cassava stem cuttings of the Kasetsart 50 (KU50) cultivar were selected for uniformity. (3) Stems were cut to a length of 25 cm. (4) Cuttings were planted vertically into the sand at a depth of 15 cm. (5) Plants were watered to maintain a consistent field capacity (FC) throughout the experiment. (6) No fertilizer was applied during the 30-day experimental period.

### *Electromagnetic design and operating principles*

Wireless power transmission was achieved using a parallel resonance circuit, with an induction heating circuit serving as the frequency generator. This system utilized a MOSFET as a switch to generate the desired frequency in the inductance coil, facilitating wireless power transfer. (Ratnonkheoa and Wongprom, 2019)
(1) Power Transmission Sector (Coil Design and Inductance Calculation), Flat spiral coils were used for both transmitting and receiving the electromagnetic field. The inductance of these coils was calculated using the following equation:

$$L = \frac{(NA)^2}{30A - 11D_1} \qquad [1]$$

$$A = \frac{D_1 + N(W+S)}{2} \qquad [2]$$

Where; L = the inductance (H); N = the number of turns of the coil; A = the diameter of the coil (inches); $D_1$ = inner diameter of the inductor coil (inches); $D_0$ = outer diameter; W = wire diameter (inches); S = distance between windings (inches); Note: 1 inch = 0.0254 m = 2.54 cm = 25.4 mm.
From the calculation of the inductance of a Flat Spiral Coil for both transmitting and receiving sectors. Will get the inductance 15.216 micro-Henry chose to use the inductance 15 micro-Henry (Fig 1.)
(2) Power Receiving Sector, this wireless power receiver utilizes a parallel resonant circuit to capture energy transmitted from the power transmission sector. The receiver circuit comprises a 15 µF inductor and a 0.66 µF capacitor, configured to achieve resonance at the transmission frequency for maximum power transfer (Fig. 2). This configuration allows the receiver to efficiently capture the alternating current (AC) energy induced by the transmitter, with air acting as the transmission medium.

### *Sample collection and analysis*

Thirty days after planting (DAP), samples were harvested by severing shoots and roots 5 cm above the soil line. Roots were carefully cleaned to remove any adhering sand or debris, placed in labeled plastic bags, and stored in a 20% alcohol solution to preserve tissue integrity.

***Root system analysis***, the following root parameters were evaluated: Total root length; Total root surface area (cm$^2$); Root length per volume (cm/m$^3$); Root volume (cm$^3$); Number of root tips; Average root diameter (mm); Root width (cm); Root surface area (cm$^2$); Root systems were scanned using an EPSON STD 4800 scanner, and the resulting images were analyzed using WinRhizo 2013B software.

### *Statistical analysis*

Data were analyzed using analysis of variance (ANOVA) appropriate for a completely randomized design 1 (CRD). Mean differences between treatments were assessed using the least significant difference (LSD) test at significance levels of p ≤ 0.05 and p ≤ 0.01.

## Conclusions

The study demonstrated that varying exposure times to electromagnetic fields (EMFs) significantly influenced several root growth parameters in cassava, including total root length, total root surface area, root length/volume ratio, root volume, number of root tips, root width, and root surface area. Specifically, a 15-minute EMF stimulation period yielded the greatest total root length and total root surface area. However, 30 and 45-minute stimulations produced optimal results for total root

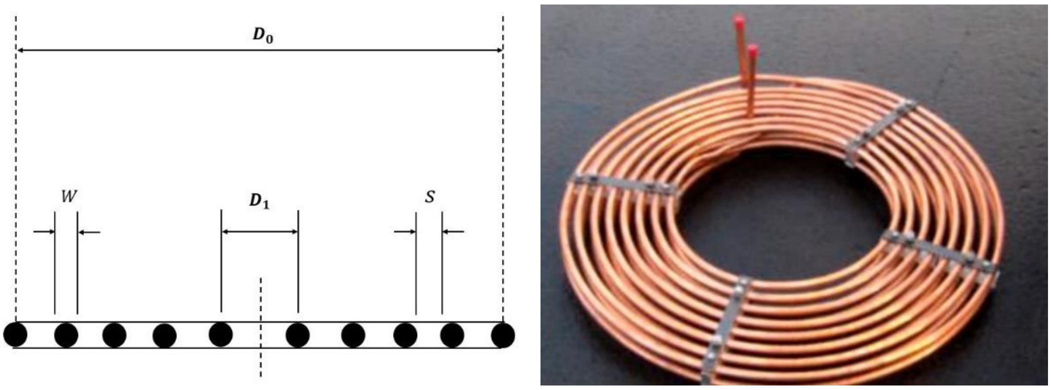

**Fig 1.** Flat Spiral Induction Coil Inductor (Chaiyarak et al., 2022).

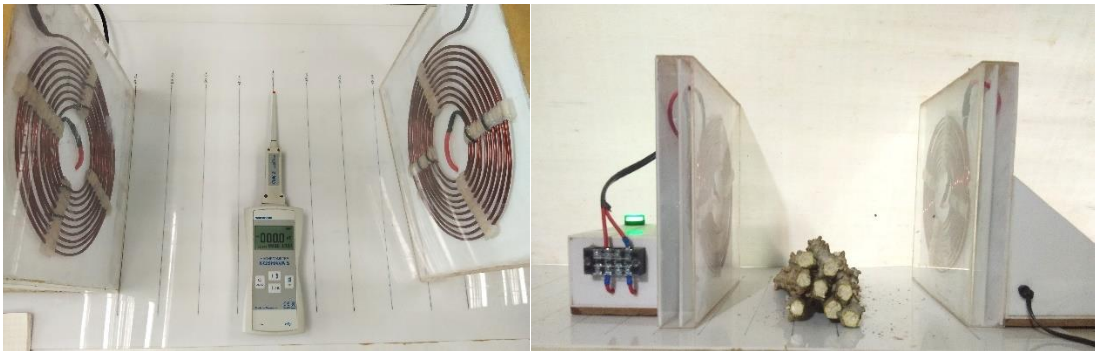

**Fig 2.** Coil inductance of 15 micro-Henry was delivered and integrated into the energy sector.

length, total root surface area, root volume, number of root tips, root width, and surface area. Furthermore, an EMF strength of 40 mT induced significant differences across all measured root parameters, notably resulting in the smallest root diameter. A correlation was observed between stimulation duration and EMF frequency. Analysis of the combined effects of exposure time and EMF strength revealed that cassava cultivar Kasetsart 50 (KU50) exhibited maximal root number, total surface area, root volume, average root diameter, and root surface area subjected to a 45-minute stimulation at 40 mT and a 60-minute stimulation at 10 mT. This study provides compelling evidence that EMF stimulation can be a viable tool for modulating root development in cassava. Further research is warranted to elucidate the underlying mechanisms and optimize EMF parameters for maximizing cassava yield and productivity.

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