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Effects of an electromagnetic field on cassava root growth (cv. Rayong 72) under greenhouse conditions

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Abstract

An electromagnetic field is electrical energy that occurs in nature. There exist free charges that influence the evolutionary process of living, which have created a safe and new alternative way to develop crop production. This investigation aimed to study the optimal management of time and resources of an electromagnetic field for cassava root development (cv. Rayong 72). Our experiment was conducted in 4x3 factorial arrangements, in a completely randomized design (CRD), with four replications. The two experimental variables were: 1) four simulation times; 0, 15, 30, and 45 minutes; and 2) three levels of electromagnetic field intensity; 30, 40, and 50 milli Tesla (mT). The root physiology; total root length, total root surface area, root length/volume, root volume, number of root tips, root average diameter, root width, and root surface area were measured to test the effect of each electromagnetic field at 30 days after planting (DAP) under greenhouse conditions. The results showed that the interaction between time (45 minutes) and electromagnetic field intensity (30, 40, and 50 mT) produced the highest total root length, total root surface area, root length/volume, root volume, number of root tips, root diameter, root width, and surface area in Rayong 72 cassava. Additionally, changes in total root length correlated with the total root surface area (r = +0.7295**), root length per volume (r = +0.6509**), root volume (r = +0.6539**), number of root tips (r = +0.6919**), root diameter (+0.3149*), root width (r = +0.1197), and root surface area (r = +0.7130**); whereas a negative correlation existed between root length and increased volume (*Significantly different at $p \leq 0.05$, **Significantly different at $p \geq 0.01$). The increased diameter directly affected root width (r = -0.1000), resulting in decreased root width (r = -0.0360).

Keywords: Electromagnetic field, Cassava production, Growth, Root physiology

1. Introduction

Cassava (*Manihot esculenta* Crantz) is one of the most economically important crops in Thailand. Cassava production (2019/2020) was reported to cover a plantation area of 1.43 hectare (ha), yielding 28.7 million tons, equivalent to an average yield of 22 tons per ha. Cassava and its products account for 21.47 % of Thailand's exports [1, 2]. In Thailand, cassava is primarily grown in the northeastern region, encompassing approximately 62 percent of the total area cultivated. Cassava is a plant that can be quickly grown and propagated at a low cost. It is drought-tolerant and can be productive in soil with low mineral fertility and little rainfall [3]. However, significant yields are negatively affected by low soil fertility, as well as the amount of precipitation and distribution of rain. High-yielding cassava cultivars have, therefore, been introduced; such as Kasetsart 50, Rayong 5, Rayong 72, and Rayong 9 (21.25 – 28.13 tons per ha, percentage dry weight 19-26 %). Therefore, the productivity in each area depends on the properties of the soil and the amount and diffusivity of rainfall. Increasing the yield by expanding the planting area would not be feasible under the current conditions. Due to limited space, the increase in yield (yield per ha) must be achieved through increased root germination percentages.

According to both domestic and international studies, electromagnetic fields are a safe and alternative method used to boost germination in plants [4-8]. An electromagnetic field stimulates cells by reacting directly with the moving charges in DNA and enzymes, resulting in better plant responses to growth; more roots, greater ability to absorb water and find food, and also to become more resistant to environmental changes through drought tolerance [4]. Ling et al. [5]; reported that constant electric and magnetic fields promote water absorption of dry seeds and shorten seed germination time. Their electromagnetic fields (125 and 250 milli Tesla; mT) affected the development of root and stem segments, resulting in increased growth and live weights in corn [9]. The employment of a double electromagnetic field resulted in a 39 % increase in the germination rate of Indian yams (*Dioscorea opposite*), an 8 % increase in root numbers, and an increase in mean root lengths by as much as 2.62 cm [10]. Their study was consistent with the increased root volume and yields of sugar beets (*Beta vulgaris var. saccharifera*) exposed to electromagnetic field strengths at 16 Hz and 5 mT [11]. Similarly, a study of chickpeas (*Cicer Arietinum*) showed an increase in root length, root surface area, and root volume, after exposure to electromagnetic fields from 0 to 250 mT, in which the concentration was increased by 50 mT each hour for four hours [12]. Additionally, the effects of electromagnetic fields on sunflower seedlings produced greater dry seedling weights, root lengths, surface areas, and maximum root volumes; as well as having significantly higher enzymatic activities of α-amylase, dehydrogenase, and protease than that of the control formulation [13]. Chaiyarak (Personal Communication); found that studies under experimental greenhouse conditions determined that an electromagnetic field with a wave intensity of 40 mT for 45 minutes resulted in increased root development of cassava (Kasetsart 50).

However, the existing studies did not extend to the effects of electromagnetic or permanent magnetic fields on cassava growth. We, therefore, applied the physics involved in electromagnetic fields in conjunction with traditional harvesting methods to stimulate root germination, development, and strength; which will lead to a reduction in production costs and increased cassava yields.

2. Material and methods

2.1 Preparation of the electromagnetic generator

An electromagnetic field is created from an inductor coil, through the use of a circuit involving induction heating as a frequency generator that increases the circuit frequency and transmits power to the electric power transmission sector, which is then forwarded to the power receiving sector. Both the transmission and power sectors are explained in further detail below.

Transmission: Calculations of the inductance of the transmitting and receiving windings via a flat spiral coil inductor are calculated through the following equations:

$$L = \frac{(NA)^2}{30A-11} \quad (1)$$

$$A = \frac{D_1+N(W+S)}{2} \quad (2)$$

Where: L = the inductance (Henry; 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)
1 inch = 0.0254 m = 2.54 cm = 25.4 mm

The calculations from the above equations produced an inductance of 15.216 H, transmitting and receiving, to and from the Flat Spiral Coil inductor (Figure 1). Therefore, the micro Henry (μH) inductance of 15 H was selected.

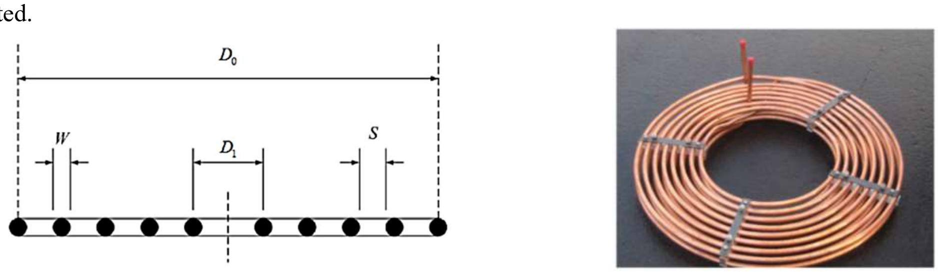

Figure 1 Flat Spiral Coil Inductor.

Power sector: Using a resonant circuit in parallel to receive power from the transmission sector, the electric receiver circuit consists of an inductor (15 µH) and a capacitor (0.66 µF), which is the same size as the powerful resonance (Figure 2). To receive the maximum power, the electric power receiving circuit, induced by the receiver, transmits electrical energy in the form of alternating current [14].

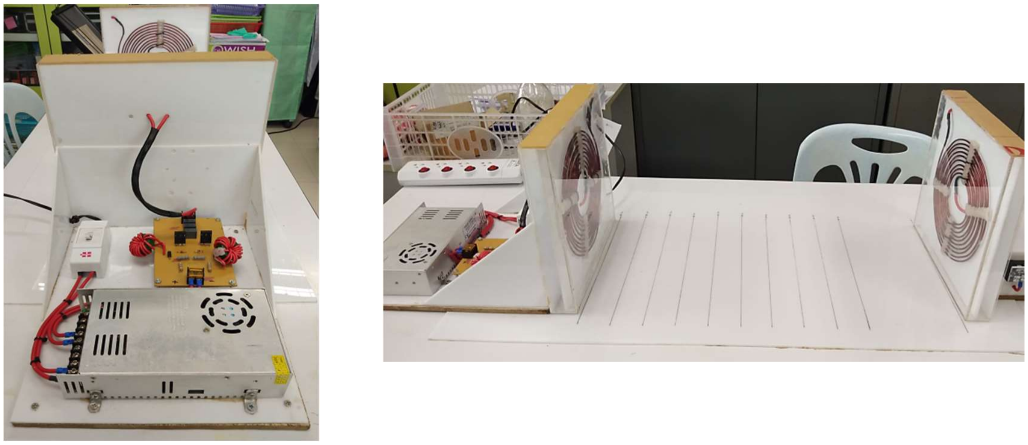

Figure 2 Coil inductance (15 micro Henry; µH) delivered and integrated into the energy sector.

2.2 Experiment method

This study was conducted in experimental greenhouse conditions from February-March 2021. Factorial 4x3 plots in a completely randomized design (CRD) with four replications were employed in this experiment. Two variables: the electromagnetic stimulation of the stems in four periods; 0, 15, 30, and 45 minutes; and three levels of intensity of the electromagnetic fields; 30, 40, and 50 mT; created twelve different treatments. The cultivated cassava (Rayong 72) was then prepared according to the prescribed experimental scheme. Cassava stalks were cut into 25 cm lengths for successive planting and placed 15 cm deep into the soil, with sandy soil desiccated in shady areas and each seeding bag filled with sandy soil. Pots consisted of a 9x18 inch plastic nursery bag filled with soil. We studied them in nill nutrient river sand to observe the conditions of root growth. Relative humidity and water levels were controlled at acceptable FC levels throughout the experiment.

2.3 Data recording and statistical analyses

Root cassava characteristics were assessed 30 days after planting (DAP). Cassava samples were collected above-ground and underground to determine fresh weight. The roots were then carefully rinsed with clean water to remove soil and dirt from the root samples. Root physiology was analyzed via an EPSON STD 4800 Scanner. The WinRhizo® 2012B root analysis program allowed us to determine eight root analytical properties: total root length; total root surface area (cm^2); root length/volume (cm/m^3); root volume (cm^3); number of root tips; root average diameter (mm); root width (cm); and surface area (cm^2). Data were analyzed for the data variance according to the CRD experimental plan. Means were compared between treatments from the error mean square by least significant difference (LSD) at $p \leq 0.05$ and $p \leq 0.01$.

3. Results and discussion

3.1 Total root length

Variances in the times (Variable 1) and intensity (Variable 2) of the electromagnetic fields caused statistically different total root lengths in the cassava. The 45-minute exposure resulted in a maximum total root length of 444.78 cm, whereas the 50 mT intensity created the maximum total root length of 434.69 cm. In combination, cassava stalks stimulated for 45 minutes at 30 mT and 50 mT resulted in the maximum total root lengths of 446.03 and 444.76 cm, respectively (Table 1).

3.2 Total root surface area

Variances in the times and intensity of the electromagnetic fields also caused statistically different total root surface areas, in which 45 minutes of exposure created the maximum total root surface area of 24.353 cm^2. The greatest root surface area of 24.476 cm^2 was achieved with an electromagnetic field intensity of 50 mT for 45 minutes (Table 1).

3.3 Root length/volume

Again, the times and electromagnetic field intensities resulted in statistically different roots lengths and volumes of cassava. When stimulated with electromagnetic field intensity at 50 mT, the cassava had a maximum root length per volume of 1046.0 cm/m^3. Cassava stalks stimulated for 45 minutes at 50 mT created the greatest maximum root length per volume of 1209.4 cm/m^3 (Table 1).

Table 1 Effects of various electromagnetic fields on root physiology of cassava (cv. Rayong 72) at 30 DAP under greenhouse conditions.

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)									
A1	0 min	412.09 ^{c}	23.693 ^{c}	608.5 ^{b}	11.343 ^{c}	1375.8 ^{c}	1.4056 ^{b}	17.676	141.62 ^{c}
A2	15 min	432.07 ^{b}	24.131 ^{ab}	1102.7 ^{a}	16.018 ^{b}	1763.2 ^{ab}	1.5332 ^{b}	17.959	411.21 ^{b}
A3	30 min	430.23 ^{b}	24.015 ^{b}	1122.8 ^{a}	16.490 ^{b}	1686.0 ^{b}	1.5745 ^{b}	17.218	444.85 ^{b}
A4	45 min	444.78 ^{a}	24.353 ^{a}	1096.3 ^{a}	20.725 ^{a}	1937.6 ^{a}	1.9452 ^{a}	17.608	552.57 ^{a}
F-test		*	*	*	*	*	*	ns	*
Electromagnetic field (mT)									
B1	30 mT	424.68 ^{b}	23.896 ^{b}	917.0 ^{b}	15.741	1597.8	1.5553	17.641	351.91 ^{b}
B2	40 mT	428.95 ^{ab}	24.073 ^{ab}	984.7 ^{ab}	15.920	1681	1.6197	17.653	414.49 ^{a}
B3	50 mT	434.69 ^{a}	24.176 ^{a}	1046.0 ^{a}	16.771	1790.9	1.6688	17.552	396.30 ^{a}
F-test		*	*	*	ns	ns	ns	ns	*
Time (minute) x Electromagnetic field (mT)									
0 min	30 mT	401.90 ^{e}	23.409 ^{d}	573.7 ^{b}	10.213 ^{f}	1160.5 ^{d}	1.5311 ^{b}	17.587	148.40 ^{f}
0 min	40 mT	416.60 ^{d}	23.974 ^{bc}	604.3 ^{b}	11.166 ^{f}	1475.3 ^{cd}	1.3520 ^{b}	17.676	149.22 ^{f}
0 min	50 mT	417.78 ^{d}	23.695 ^{cd}	647.4 ^{b}	12.650 ^{ef}	1491.5 ^{cd}	1.3337 ^{b}	17.764	127.24 ^{e}
15 min	30 mT	426.66 ^{cd}	24.076 ^{abc}	1042.6 ^{a}	16.661 ^{cd}	1590.8 ^{bc}	1.4861 ^{b}	17.879	354.53 ^{e}
15 min	40 mT	429.83 ^{bcd}	24.038 ^{bc}	1133.1 ^{a}	16.205 ^{cde}	1763.7 ^{abc}	1.5971 ^{b}	17.879	437.54 ^{cd}
15 min	50 mT	436.73 ^{abd}	24.279 ^{ab}	1132.3 ^{a}	15.187 ^{cde}	1935.0 ^{ab}	1.5164 ^{b}	18.12	441.57 ^{cd}
30 min	30 mT	425.40 ^{cd}	23.754 ^{cd}	1024.6 ^{a}	15.453 ^{cde}	1553.3 ^{bc}	1.5929 ^{b}	16.774	403.87 ^{de}
30 min	40 mT	425.82 ^{cd}	24.038 ^{bc}	1148.7 ^{a}	13.174 ^{def}	1564.3 ^{bc}	1.5166 ^{b}	16.761	446.36 ^{cd}
30 min	50 mT	439.49 ^{abc}	24.254 ^{ab}	1195.0 ^{a}	20.845 ^{ab}	1940.3 ^{ab}	1.6140 ^{b}	18.12	484.33 ^{bcd}
45 min	30 mT	446.03 ^{a}	24.343 ^{ab}	1026.9 ^{a}	20.638 ^{ab}	2086.5 ^{a}	1.6111 ^{b}	18.323	500.83 ^{bc}
45 min	40 mT	443.55 ^{ab}	24.241 ^{ab}	1052.6 ^{a}	23.136 ^{a}	1920.8 ^{ab}	2.0133 ^{a}	18.298	624.85 ^{a}
45 min	50 mT	444.76 ^{a}	24.476 ^{a}	1209.4 ^{a}	18.402 ^{bc}	1796.7 ^{abc}	2.2113 ^{a}	16.203	532.04 ^{b}
F-test		*	*	*	*	*	*	ns	*
CV %		2.34	1.27	15.47	16.68	15.98	14.44	8.74	14.91

ns: not significant, *Significantly different at $p \leq 0.05$.
Means in the same column with different letters are significantly different at $p \leq 0.05$ by LSD.

3.4 Root volume

Cassava root volume was also affected by the electromagnetic shields' length of exposure and intensity, which differed statistically. Forty-five minutes of exposure resulted in a maximum root volume of 20.725 cm^3, regardless of the level of electromagnetic intensity. The greatest root volume (23.136 cm^3) was achieved with the combination of 45 minutes of stimulation with an intensity of 40 mT (Table 1).

3.5 Number of root tips

The number of root tips increased when stimulated for 45 minutes (1937.6 roots). However, the intensity of the electromagnetic field resulted in non-statistically different numbers of root tips. The greatest number of root tips was achieved when the cassava roots were stimulated for 45 minutes with an electromagnetic field intensity of 30 mT for a total of 2086.5 roots. (Table 1)

3.6 Root average diameter

The cassava root average diameters increased exponentially with the intensity of the electromagnetic field and increased time of exposure. Cassava stalks stimulated for 45 minutes with an electromagnetic field intensity of 50 mT, the maximum in both variables, produced the largest root diameter of 2.2113 mm (Table 1).

3.7 Root width

In all combinations, the root widths of the experimental cassava were not significantly different; however, the combination of 30 mT for 45 minutes produced the largest root width of 18.323 cm (Table 1).

3.8 Surface area

The electromagnetic fields also had a significant impact upon the surface areas of the cassava roots, wherein the maximum root surface area of 624.85 cm^2 was achieved through the electromagnetic field intensity of 40 mT for 45 minutes (Table 1). Notably, the greatest result was not achieved through the maximum level of electromagnetic intensity.

Our interactions with electromagnetic intensities over varied periods demonstrated the plants' heightened root systems, water absorption, and cell division; resulting in increased total root length, total root surface area, root length/volume, root volume, number of root tips, root diameter, root width, and surface area [15]. The experiment found that the intensity of the electromagnetic field and the duration of contact with the electric field increased, resulting in more root length and more root growth. The roots could absorb more water while planting. Thus, growth developed for the increased root length [16]. It observed that the electromagnetic field did not energize the electromagnetically stimulated cassava with a longer root length. Plant roots generate electrical currents and associated electrical fields due to electrogenic ion transport at the root surface. Total root surface area is important for absorbing water and nutrients from the soil, leading to the development of drought stress resistance. The number of fibrous roots is important for the number of storage roots (yield), as some fibrous roots will develop into storage roots. The roots also further evolved total root surface, root length/volume, root volume, average root diameter, and surface area. Consistent with the work of Shorstkii et al. [17]; when an electric field touches a seed, it results in a gap at the surface of the cell wall, and when immersed in water, the cell wall can better accept the water mass from the outside into the cell. It helps promote water absorption and cell division, accelerates rooting faster, increases the number of roots, and improves the root system.

The energy produced by direct electromagnetic stimulation is also accountable for stimulating the growth process, thereby improving plant germination. The magnetic field stimulates the formation of molecules in the cell's process for better growth and development. The concentration of the electromagnetic field and the duration of magnetic stimulation in different plants also affect plant growth. This growth may be due to the electromagnetic fields' exertion of force on the charged particles within the grain, where the seeds have both positive and negative charges. Under an electromagnetic field, the positively charged ions within the grain move towards the direction of the negatively charged electromagnetic field. Simultaneously, the negatively charged ions within the grain will move towards the direction of the electromagnetic field, causing a positive charge [7, 15]. When the charges within the original grain are scattered, they are subjected to the electromagnetic field, which causes movement of the charged ions and molecules, thereby increasing the chances of molecular collisions and accelerating the chemical reactions within the grain. For example, an acceleration of amylase enzyme activity decomposes food accumulated in plants from dry plants into sugars that plants can utilize. Thus, energy can be generated and used for seed germination and cell division [7, 5]. Payez et al. [18]; studied the effects of wheat grain exposed to a 30 mT constant magnetic field and a 10 kHz electromagnetic field for four days. The wheat grain subjected to electromagnetic fields showed increased germination speeds compared to the control group, indicating their positive effects upon cell membrane integrity and growth characteristics of the wheat seedlings (*Triticum aestivum* L.). The *'ion cyclotron resonance'* theory states that ions should circulate in a plane perpendicular to the external magnetic field (MF) at the frequency of Lamor, which can interfere with alternating electromagnetic fields [19, 20]. Such interactions occur between MF and ionic currents in plant embryonic cell membranes, perhaps due to a change in ion concentration and osmotic pressure on both sides of the membrane [21].

The results of our study of cassava (cv. Rayong 72 at 30 DAP under greenhouse conditions), herein, found correlations in total root length with total root surface area, root length/volume, root volume, number of root tips, root diameter, root width, and surface areas of 0.7295, 0.6509, 6539, 0.6919, 0.3149, 0.1197, and 0.7130, respectively (Table 2). The correlations between total root surface area with root length/volume, root volume, number of root tips, root diameter, root width, and surface area were 0.5311, 0.4381, 0.5195, 0.1636, 0.0876, and 0.5547, respectively. Correlations between root length/volume with root volume, the number of root tips, root diameter, root width, and surface area were 0.5046, 0.4974, 0.3153, -0.0360, and 0.7488, respectively. Correlations between root volume with the number of root tips, root diameter, root width, and surface area were 0.6121, 0.5190, 0.1877, and 0.7986, respectively. The number of root tips correlated with root diameter, root width, and surface area at 0.2793, 0.2521, and 0.6051, respectively. Root diameter, root width, and surface area were -0.1000 and 0.6001, respectively. And, the correlation between root width and surface area was 0.0424. In summary; positive correlations were found between total root length and root length/volume, root volume, number of root tips, root diameter, root width, and surface area 30 DAP; whereas root length per volume was negatively correlated with root width, and root diameter had a negative relationship with root width as well.

Table 2 Correlations for total root length, total root surface area, root length/volume, root volume, number of root tips, root average diameter, root width, surface area on the root physiology of cassava cv. Rayong 72 at 30 DAP under greenhouse conditions.

Parameters	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)
Total root surface area	+0.7295**						
Root length/volume	+0.6509**	+0.5611**					
Root volume	+0.6539**	+0.4381*	+0.5046**				
No. of root tips	+0.6919**	+0.5195**	+0.4974*	+0.6121**			
Root average diameter	+0.3149*	+0.1636	+0.3153*	+0.5190**	+0.2793		
Root width	+0.1197	+0.0876	−0.0360	+0.1877	+0.2521	−0.1000	
Surface area (cm^2)	+0.7130**	+0.5547**	+0.7488**	+0.7986**	+0.6051**	+0.6001**	+0.0424

*Significantly different at $p \leq 0.05$, **Significantly different at $p \geq 0.01$.
Means in the same column with different letters are significantly different at $p \leq 0.05$ and $p \leq 0.01$ by LSD.

4. Conclusion

The 45-minute exposure of cassava stalk cultivars (Rayong 72) to an electromagnetic field at varied intensity levels (30, 40, and 50 mT) resulted in increased cassava total root lengths, root surface areas, root length/volumes, root volumes, number of root tips, root diameters, root widths, and produced the greatest surface areas. A positive correlation was observed between total root length with the total root surface area, root length/volume, root volume, number of root tips, root diameter, and root width. We also noted that given a positive surface area, a negative correlation existed between root length and volume, resulting in decreased root width; and, that an increase in root diameter also affected root width.

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