EXPOSURE OF PLANTS TO STATIC ELECTROMAGNETIC FIELDS: THE EARLY GROWTH OF BASIL AND WAXY CORN

Punchalee Montriwat[1] and Taweetham Limpanuparb[2*]

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Abstract

The effects of a static low-intensity electromagnetic field (EMF) on higher plants were investigated. Thai basil (*Ocimum basilicum var. thyrsiflora*) and waxy corn (*Zea mays* var. *ceratina*) were chosen as samples for the experiments. There were 2 methods of electromagnetic exposure, indirect exposure (applying magnetically treated water to plants) and direct exposure (plants are grown under the electromagnetic field). For the indirect exposure experiment, magnetically treated water (0.34–4.54 mT, 24 h) was applied to Thai basil seeds daily for 1 week and the experiment was repeated once. No significant difference in the heights was found between the control groups and the treated groups whether deionized or tap water was used. For the direct exposure experiment (0.28–3.83 mT), waxy corn seeds were grown between a pair of electromagnets. Two controls were grown in the absence of an extra magnetic field; 1 control group (no electromagnets (EM)) was grown at room temperature while the other control group (EM-0) was grown between a pair of electromagnets with a similar temperature to the other magnetically treated groups. The experiment was completed in 4 days and was repeated once. The results indicated that there is no height difference between the control (EM-0) and the groups grown between electromagnets; however, the controls (no EM), which were grown at room temperature were shorter compared to those grown between electromagnets. Our results suggest that the level of the applied magnetic field has no effect on the heights of the plants in this study.

Keywords: Magnetotropism, magnetically treated water, static magnetic field, microwave

Introduction

Natural magnetic field (MF) is an environmental factor that living organisms can hardly escape. Earth's MF or geomagnetic field (GMF) is a persistent natural phenomenon throughout the evolution of all species. At present, GMF is static, slowly varying, relatively homogeneous and weak. It ranges from below 30 μT in the area of South Atlantic anomaly near the equator to almost 70 μT close to the magnetic poles in south of Australia and in Northern Canada (Maffei, 2014). GMF is known to act on living system and influence numerous biological processes

[1] *Department of Biology and Biological Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden.*

[2] *Science Division, Mahidol University International College, Mahidol University, Salaya, Nakhonpathom, Thailand 73170.*

* *Corresponding author*

* *Corresponding author*

(Feychting *et al*., 2005).

Nowadays in a modern society, aside from the GMF, human has been introducing a vast and growing range of man-made electromagnetic field (EMF), which are physical fields generated by flows of electric current through an electrical conductor. This results in growing concerns of their effects on biological systems. Magnetic resonance imaging (MRI) and hair dryer are examples of exposure sources, which release static EMF of ~3 T (inside) and ~6-2000 μT (30 cm away), respectively (Feychting *et al.,* 2005). Although initially considered too weak and incapable of inducing physiological function of biomolecular systems, a number of studies suggested otherwise (Adey, 1993; Baan *et al*., 2011; Hardell *et al*., 2013; Liu *et al.,* 2013).

MF drew attention from scientists in various fields for its effects on living organisms. It was suggested that MF acts in a similar cellular metabolic pathway as other factors like osmotic (Munns, 2002), heat (Ruzic and Jerman, 2002; Sabehat *et al*., 1998), or salt stress (Munns, 2002). There were attempts to explain the effects of MF on living systems; magnetotaxis is widely studied in insects, birds and mammals while magnetotropism was observed in some plants (Galland and Pazur, 2005; Maffei, 2014; Occhipinti *et al*., 2001).

From experiments of exposing different subjects to a variety of types of MF with wide spectrum of intensities, both significant changes and null results were obtained. When shallot (*Allium ascalonicum*) sprouts were subjected to a static MF of 7 mT for 17 days, increases in symplastic antioxidant enzyme activities exposed and non-enzymatic antioxidant levels together with changes in leaf apoplast compared to unexposed sprouts were observed (Cakmak *et al*., 2012). In okra (*Abelmoschus esculentus*) seeds, MF treatment of 99 mT for 3 or 11 min exhibited enhancement in germination percentage, numbers of flowers, fruits, and seeds per plants, leaf area, height, and pod mass per plant (Naz *et al*., 2012). In a blind experiment, hypocotyl lengths, gene (CHS, HY5, GST) expression levels, blue-light intensity effects, and influence of sucrose in the growth medium of *Arabidopsis thaliana* grown in MF of 1 mT, 50 mT, and approximately 100 mT were studied and no consistent, statistically significant responses of MF were detected (Harris *et al*., 2009). By treating corn (*Zea mays*) seedlings with static MF of 100 mT for 1 h or 200 mT for 2 h, it was found that growth and root parameters, photosynthesis rate, stomatal conductance, and chlorophyll content increased, while antioxidant enzyme activities decreased (Anand *et al.,* 2012). Increases in germination rate, height, and weight were found when corn seeds were magnetically exposed to 125 or 250 mT of MF for different period of time (Flórez *et al*., 2007). Under field conditions, a randomized design study found that pre-sowing exposure of corn seeds to static MF (100 mT for 2 h and 200 mT for 1 h) was effective in improving all growth measures. Length, fresh weight, and dry weight of leaves, shoots, and roots significantly increased (Shine and Guruprasad, 2012). Limpanuparb (2001) also reported an increase in the heights of corn seedling, which were grown between electromagnets for 4-5 days.

Some experiments were done indirectly through water that was previously exposed to MF, "magnetically treated water" (MTW). There were claims that MF help to descale metal surfaces, improve hydration of cement, alter ζ potential of colloids, accelerate growth of plants, enhance calcium efflux through biomembranes, or modify the structure of model lyposomes (Colic and Morse, 1999). The effects of magnetic treatment on water were claimed to last from 10 minutes up to a week (Baker and Judd, 1996). Besides, in 2006, there was a claim that applying microwaved water can be fatal to the plant (Mikkelson, 2015). Despite a long history of research on the effects of MF on properties of water and biological systems, the topic remains controversial and the true mechanism remains elusive. A comprehensive review can be found in Montriwat's report (Montriwat, 2015).

This study explored how different intensities of EMF affect first stage growth of higher plants when applied directly and indirectly through MTW. Only low intensities EMF (0.28–4.54 mT) was used and the experiments were done under controlled laboratory condition.

Materials and Methods

Preliminary Considerations

There are are two main considerations for the design of our experiments, magnetic field sources and model plants.

Firstly, electromagnets were chosen as a source of static MF due to its resemblance to exposure condition in everyday life and convenience in controlling strength and homogeneity of the MF. Electromagnets can also generate pulse or frequencies of the magnetic field but these are beyond the scope of the current study. As electromagnets are operated by electrical current passing through conductor coils, some heat is always released from the EMF apparatus. The amount of heat usually correlates with the strength of the magnetic field and can be considered an inseparable factor in household EMF exposure conditions. Recognizing that reports on effects of magnetic field on biological systems are controversial and heat may be a confounding variable, we designed our electromagnets such that all of them generate the same amount of heat with varied EMF intensity in a range found in domestic electrical appliances.

The second consideration is on the application of electromagnetic fields to model plants. There are two modes of application, indirect and direct exposure. Water was used as a medium to receive magnetic treatment in indirect exposure. On the contrary, for direct exposure, plants were grown directly in the EMF chamber. The exposure chamber of our apparatus is constrained to a volume of 7.0 × 7.0 × 7.0 cm^3 because we aimed for high intensity and homogeneous magnetic filed. Choices of model plants, growing medium, duration of experiment, and growth measurement must accommodate this space limitation. For early growth of plant, it is not practical and not required to put them into soil so seeds were grown on paper and were only watered. The growth measurement can be either height or dry mass but for tiny seedling it is inefficient to use dry mass. Even in the controlled laboratory conditions, variations in temperature, lighting, humidity and other factors may exist. Two batches were performed for each experiment to confirm the results. Comparison of heights is valid only within the same batch.

Preparation of Electromagnetic Field

The EMF was generated by four pairs of electromagnets made by 1000 turns of 28 SWG copper wire (diameter = 0.376 mm, manufactured by Hitachi) wound around square iron blocks (7.0 × 7.0 × 2.5 cm^3). The iron blocks were the same as Limpanuparb (2001) but we designed the electromagnet so that all the coils have equal number of turns of copper wire, thus dissipating similar amount of heat. For each pair, two identical coils were positioned in parallel, 7.0 cm apart, in the same area with same temperature.

The diagram and physical set up of EMF is shown on Figure 1. For indirect exposure and direct exposure, total current of 1.20 A and 1.00 A was supplied respectively to the four coils in a parallel circuit by a DC power supply (GW Instek, model: GPS-3030DD). Assuming the electrical resistance of all electromagnets are the same, the current per magnet was 0.30 A and 0.25 A for indirect exposure and direct exposure respectively. The temperature between electromagnets was 30°C (± 0.9°C) at $I = 0.25$ A, while room temperature was maintained at 26°C (± 0.5°C) during the course of the experiment. A lower current was used for direct exposure experiment because, in a pilot study, it was found that a current of 1.20 A resulted in a temperature that was too high for maize seeds, which was grown between copper coils, to germinate. About 4.85 W and 3.36 W were generated by each copper coils during indirect and direct exposure experiment, respectively. This is because an electromagnet has the windings resistance, and electrical power is released as heat in a process called Joule heating or ohmic heating (Knirsch *et al.,* 2010).

Opposite direction of turns (CW and CCW) generates MF of opposite direction, which cancels each other out and results in different intensities of MF among each magnetically treated group. The values of MF were measured between the air gaps using a gauss meter (Lutron, model: MG-3002). The properties of each pair and magnetic flux densities are described in Table 1–2. (0.34–4.54 mT for indirect exposure and 0.28–3.83 mT for direct exposure)

Theoretically, EM-0 control should not create any extra MF at all and the intensity of magnetic field should be linear with respect to the number of effective turns. However, the maximum MF obtained for EM-0 was 2.8 and 3.4 G. (4.7 to 5.7 times of GMF) and the magnetic field intensity appears to increase slightly faster than linear. This is due to the fact that copper coils are stacked in layers and the outer layers (counterclockwise turns for cancellation) are longer in length. The validity of results presented in Table 2 is confirmed by the fact that the ratio

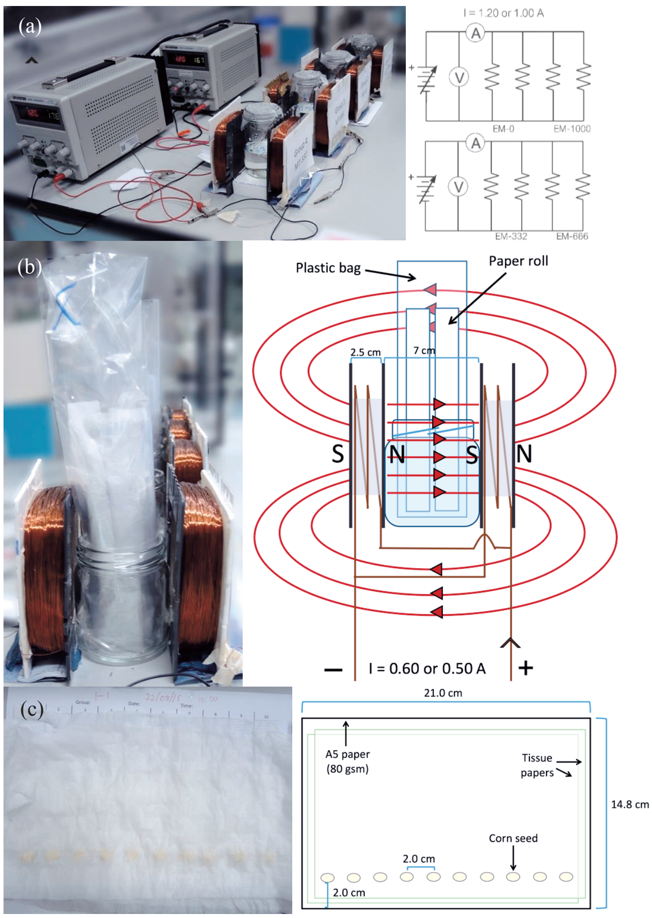


Figure 1. Photos (left) and schematic diagrams (right) of (a) electromagnets circuit wiring (b) electromagnetic exposure chamber and (c) corn seed arrangements for the direct exposure experiment

Table 1. Copper coil properties

Electromagnet	Copper wire (turns)			Resistant at 35°C of electromagnet pairs (Ω)
	Clockwise (CW)	Counterclockwise (CCW)	Effective (CW-CCW)	
Control (EM-0)	500	500	0	53.2 and 53.4
EM-332	666	334	332	53.7 and 54.0
EM-666	833	167	666	56.4 and 53.4
EM-1000	1000	0	1000	53.3 and 53.3

of magnetic field intensity of I = 0.25 and 0.30 A ranges from 82-85% for all electromagnets (theoretical value = 5/6 = 83%).

Plant Sample and Statistical Analysis

Preliminary germination tests were done on seeds of rice (*Oryza sativa*), Thai basil (*Ocimum basilicum* var. *thyrsiflora*), water convolvulus (*Ipomoea aquatic Forsk* var. *reptan*), mung bean (*Vigna radiata*), and sunflower (*Helianthus annuus*). It was found that Thai basil (obtained from Chia Tai Co., LTD) have the highest germination rate and the lowest variation on stem height. Therefore, it was chosen for indirect exposure experiment. However, for direct exposure experiments, waxy corn (*Zea mays* var. *ceratina* obtained from Silverseed Company) were used to allow comparison with the earlier report of Limpanuparb (2001). The two species may be regarded as a representation of eudicot and monocot plants. The number of seeds per treatment or control group is 50 and 20 for indirect and direct exposure experiments respectively and experiments were repeated once. The stem heights of germinated seeds were measured after 7 days (168 h) and 4 days (96 h) for indirect and direct exposure respectively. Ungerminated seeds were considered as outliers and were not taken into account. One-way analysis of variance (ANOVA) in PASW Statistics 18 was used to identify differences between groups. Scheffé's method were used for mean comparisons because of the unequal sample sizes.

Indirect Exposure Experiments

Both deionized (DI) water and tap water were used in the experiments to explore if impurities in the field condition may affect the result. Firstly, four glass jars were each filled with 100 ml water and exposed to MF between pairs of electromagnets for 24 h while the control (No EM) group was left outside. For microwaved water, 200 mL of water containing 4-5 boiling chips was heated up to about 80°C by 700 W microwave (Samsung, model: M1817N, maximum 850 W) for 1.5 min. All of the treated water was left outside electromagnet to cool down to room temperature before applying to the seeds. Both MTW and control water were freshly prepared every day.

For each group, 50 Thai basil seeds were sown on tissue papers in styrofoam trays in which small holes were made throughout to drain water. Every tray was covered with another styrofoam tray to reduce evaporation and interference from the environment. On the first day, 30 mL of treated or untreated water was poured to the assigned group while sowing on tissue papers. From day 2 to 6, seeds were watered with 10 mL of the magnetically treated, microwaved, or control water at the same time every day.

Direct Exposure Experiments

The procedures of the direct exposure experiment were based on that of Limpanuparb (2001) with only the modification on the electromagnetic filed source. Waxy corn seeds were soaked in tap water for 24 h before planting. Only 20 seeds may be assigned to each group due to limited space of the magnetic field. Ten seeds were evenly placed on A5 paper in a straight line and covered with tissue papers and watered with 20 mL of tap water (Figure 1(c)). After that, the paper with seeds was carefully rolled. For each group, two paper rolls were wrapped in the same plastic bag. Each plastic bag

Table 2. Magnetic exposure dosage

Electromagnet	Max magnetic flux density (mT) at 0.30 A (for indirect exposure)	Max magnetic flux density (mT) at 0.25 A (for direct exposure)
Control (No EM)	0.06 (GMF)	0.06 (GMF)
Control (EM-0)	0.34	0.28
EM-332	1.26	1.01
EM-666	2.56	2.18
EM-1000	4.54	3.83

was placed vertically in the glass jar between the pairs of electromagnets except for the control (No EM), which was left in a glass jar outside electromagnet (See Figure 1(b)).

Results and Discussion

Indirect Exposure

Watering Thai basil seeds with water treated with 0.34–4.54 mT MF or microwave once a day had no observable effect on its height after 168 h. Similar results were obtained whether DI or tap water was used. The number of germinated seeds whose stem lengths were recorded are shown in Table 3. In the first trial using DI water, the EM-1000 group yielded highest mean of 1.94 cm while the microwave group yielded lowest mean of 1.71 cm. The null hypothesis, which stated that there is no difference between the mean stem heights of each groups, was rejected by F-test (p-value = 0.023) suggesting that at least one pair of the mean heights is different. However, after performing post hoc tests, Scheffé's test showed that the mean heights of all groups were the same. F-test for second trial of DI water and both batches of tap water confirmed that the difference was not statistically significant. Bar charts of the results are shown in Figure 2.

There is a skeptical attitude toward the mechanism that MF changes properties of pure water, which does not contain any significant amount of ferromagnetic or paramagnetic substances (Bogatin *et al*., 1999). Srisuthikul (2001) observed no change in the surface tension of water after it was exposed to 2000 G and 4000 G magnetic fields for 3 min. Therefore, to investigate whether the MF effect exists based on interaction between water and ions or minerals and to simulate field conditions, the experiment was also conducted using tap water.

Our results were in contrast with some reports in which an increase in several parameters including height, weight, yield, and germination percentage were reported when watered with MTW compared to control (El-Yazied, El-Gizawy, Khalf, El-Satar, and Shalaby, 2012). Since some of the previous experiments were done under the field conditions, several possibilities such as ions suspended in irrigation water, uncontrolled temperature, stage of plant growth and duration of the experiment may contribute to this contradictory results. Moreover, it is possible

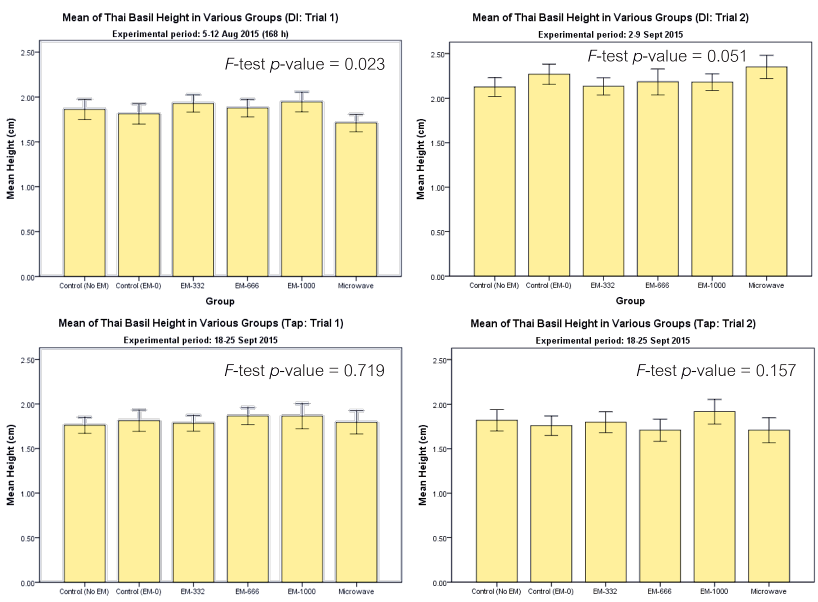


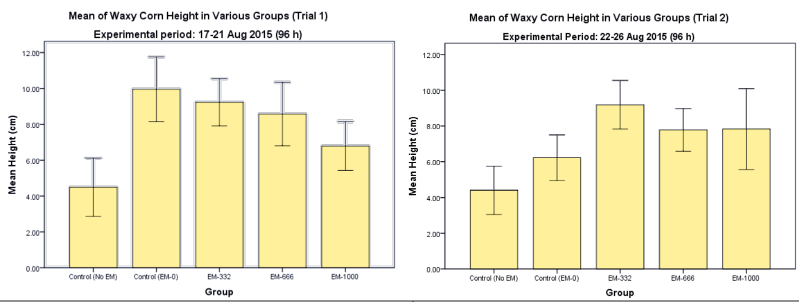
Figure 2. Means of Thai basil height with 95% confident interval

that different species of plant may have different susceptibility to EMF. It is also well accepted that positive and significant results are more likely to be published; hence, null results are relatively rare in the literature.

Direct Exposure

Figure 3 shows mean height of corn grown in 0.28–3.83 mT MF for 96 h. The null hypothesis stating that all groups have the same mean stem height was rejected by F-test in both trials suggesting that difference among groups exists (p-value = 0.000). Scheffé's post hoc comparison confirmed that the mean height of control (EM-0) group was not different from other EM groups (p-value ≥ 0.052 for the first trial and p-value ≥ 0.076 for the second trial). On the other hand, the mean height of control (No EM) was lower than all other groups in electromagnet with two exceptions, EM-1000 (p-value = 0.241) for the first trial and EM-0 (p-value = 0.362) for the second trial. These are summarized in homogeneous subsets in Figure 3.

Since control (EM-0) was not different compared to other EM groups, evidently the



Trial 1			Trial 2		
Group	**Subset for α = 0.05**		**Group**	**Subset for α = 0.05**	
	1	**2**		**1**	**2**
Control (No MT)	4.49		Control (No MT)	4.40	
MT-1000	6.79	6.79	Control (MT-0)	6.22	6.22
MT-666		8.57	MT-666		7.78
MT-332		9.23	MT-1000		7.83
Control (MT-0)		9.96	MT-322		9.18

Figure 3. Means with 95% confident interval and homogeneous subsets for waxy corn height of Trial 1 and Trial 2

Table 3. Percentages of germinated seeds

Group	Indirect exposure				Direct exposure	
	Tap water		DI water			
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Control (No EM)	90%	88%	94%	94%	50%	90%
Control (EM-0)	98%	90%	94%	96%	45%	85%
EM-332	98%	92%	92%	88%	50%	55%
EM-666	96%	98%	94%	94%	55%	70%
EM-1000	84%	90%	98%	96%	65%	55%
Microwave	96%	88%	90%	92%	-	-
Total	94%	91%	94%	93%	53%	71%
	(281/300)	(273/300)	(281/300)	(280/300)	(53/100)	(71/100)

difference between EM group and control reported earlier by Limpanuparb (2001) are due to ohmic heat from electromagnets, not from the MF itself. During the direct exposure experiment (I = 0.25 A), the temperature difference can be as large as 4.6°C (30.4°C between electromagnet and 25.8°C outside the coils). Since plants are known to be sensitive to temperature (Baker and Allen, 1993; Kimball *et al*., 1993; Loveys *et al*., 2002; Went, 1953), it is possible that, like in this experiment, the diverse effects of electromagnets reported in the literature are simply due to heat.

Conclusion and Future Work

No significant difference was observed in the height of plants (waxy corn and Thai basil) exposed to the level of MF used in this experiment (≤ 4.54 mT and household microwave), which is comparable to the level of typical human exposure. In contrast to previous findings where accelerated growth was attributed to magnetic field, our design of electromagnet allowed us to conclude that the elevated growth of the sample plants was due to heat from the electromagnet. To the best of our knowledge, this is the first experiment where (1) effects of both direct and indirect EMF applications were studied (2) the confounding effect of heat from EMF was systematically investigated. Unlike MF from permanent magnet, EMF and heat are inseparable. The two control groups in absence of extra EMF, "EM-0" receiving the same amount of heat with other treatment groups and "No EM" at room temperature allowed us to distinguish the effects of heat from MF on the growth of plants. Though a null result is reported in this paper, the implication of our findings is that elevated temperature due to an electromagnet may explain many contradictory and non-repeatable reports on the effect of EMF on living organisms. Possible future work include the use of permanent magnets as a source of static field and the use of temperature control apparatus (such as water bath or incubator) to overcome limitations in this study.

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