Bioelectromagnetics 32:58–65 (2011)

Magnetic Treatment of Irrigation Water and Snow Pea and Chickpea Seeds Enhances Early Growth and Nutrient Contents of Seedlings

Harsharn S. Grewal and Basant L. Maheshwari*

School of Natural Sciences, University of Western Sydney, Penrith South DC, NSW, Australia

The effects of magnetic treatment of irrigation water and snow pea (*Pisum sativum* L var. macrocarpon) and Kabuli chickpea (*Cicer arietinum* L) seeds on the emergence, early growth and nutrient contents of seedlings were investigated under glasshouse conditions. The treatments included (i) magnetic treatment of irrigation water (MTW), (ii) magnetic treatment of seeds (MTS), (iii) magnetic treatment of irrigation water and seeds (MTWS) and (iv) no magnetic treatment of irrigation water or seeds as control treatment. A magnetic treatment device with two permanent magnets (magnetic induction: 3.5–136 mT) was used for the above treatments. Seeds were sown in washed sand and seedlings were harvested at 20 days. The results showed that MTW led to a significant ($P < 0.05$) increase in emergence rate index (ERI; 42% for snow pea and 51% for chickpea), shoot dry weight (25% for snow pea and 20% for chickpea) and contents of N, K, Ca, Mg, S, Na, Zn, Fe and Mn in both seedling varieties compared to control seedlings. Likewise, there were significant increases in ERI (33% for snow peas and 37% for chickpea), shoot dry weight (11% for snow pea and 4% for chickpea) and some nutrients of snow pea and chickpea seedlings with MTS in comparison with the controls. The results of this study suggest that both MTW and MTS have the potential to improve the early seedling growth and nutrient contents of seedlings. Bioelectromagnetics 32:58–65, 2011.

Key words: magnetic treatment; irrigation; seedling growth; emergence rate index; seedling nutrient content

INTRODUCTION

The response of biological systems to magnetic fields have been reported by various researchers [Goodman et al., 1983; Vakharia et al., 1991; Paradisi et al., 1993; Danilov et al., 1994; Alexander and Doijode, 1995; Blank, 1995; Amaya et al., 1996; Duarte Diaz et al., 1997; Moon and Chung, 2000; Reina et al., 2001; De Souza et al., 2006, 2008; Tenuzzo et al., 2006; Chou, 2007; Florez et al., 2007; Trebbi et al., 2007; Maheshwari and Grewal, 2009]. External electric and magnetic fields influence both the activation of ions and polarisation of dipoles in living cells [Moon and Chung, 2000]. Electromagnetic fields (EMFs) can alter plasma membrane structures and functions [Paradisi et al., 1993; Blank, 1995]. Goodman et al. [1983] reported an alteration in the level of some mRNA in plants after their exposure to EMFs.

A marked increase in the germination percentage of lettuce seeds by treatment with a 10 mT stationary magnetic field was observed by Reina et al. [2001]. Reina and Pascual [2001] reported that magnetically treated seeds resulted in a significant increase in the water absorption rate of lettuce seeds, and thus may have contributed to the increased germination percentage. In cereals and beans, the magnetic exposure of seeds prior to sowing led to an improvement in germination rate and early growth [Pittman, 1963a,b; Pittman and Anstey, 1967]. Similarly, the magnetic exposure of seeds by applying a stationary magnetic field before sowing had a significant increase in germination rate and seedling vigour in groundnut, onion and rice seeds [Vakharia et al., 1991; Alexander and Doijode, 1995]. Podleoeny et al. [2004] studied the

Grant sponsor: Omni Environmental Group, Sydney, Australia.

*Correspondence to: Basant L. Maheshwari, School of Natural Sciences, University of Western Sydney, Locked Bag 1797, Penrith South DC, NSW 1797, Australia.
E-mail: b.maheshwari@uws.edu.au

Received for review 11 November 2009; Accepted 13 August 2010

DOI 10.1002/bem.20615
Published online 5 October 2010 in Wiley Online Library (wileyonlinelibrary.com).

impact of magnetic treatment by exposing broad bean seeds to variable magnetic strengths before sowing and observed beneficial effects on seed germination and emergence. The seedling emergence was more regular after the use of the magnetic treatment and occurred 2–3 days earlier in comparison to seedlings in the control treatment. The gain in crop yield resulting from the magnetic treatment of broad bean seeds was attributed to the higher number of pods per plant and the fewer plant losses per unit area during the growing season [Podleoeny et al., 2004]. In tomato, magnetically treated tomato seeds improved the leaf area, leaf dry weight and yield of tomato crop under field conditions [De Souza et al., 2006].

The beneficial effects of magnetically treated irrigation water have also been reported on germination percentages of seeds [Hilal and Hilal, 2000; Morejon et al., 2007]. Morejon et al. [2007] observed an increase in germination of *Pinus tropicalis* seeds from 43% in the control to 81% with magnetically treated water. Furthermore, they observed a marked improvement in seedling growth after germination due to the magnetically treated irrigation water. Hilal and Hilal [2000], working on tomatoes, pepper, cucumber and wheat seeds, reported improvements in germination and seedling emergence when magnetically treated water and seeds were used. In particular, they observed that the germination of pepper seeds was higher with magnetically treated seeds compared to seeds with magnetically treated irrigation water. Cucumber seeds had the highest germination percentage when both irrigation water and seeds were magnetically treated. They also reported that tomato seeds responded more favourably to magnetically treated irrigation water than the magnetically treated seeds.

In general, the past studies have indicated that there are some beneficial effects of magnetic treatment on seed germination and seedling emergence. However, there is no clear understanding yet as to the mechanisms behind these effects and the changes that magnetic treatment brings about in nutritional aspects of seed germination and seedling growth. Magnetic treatment of water has been reported to change some of the physical and chemical properties of water, mainly hydrogen bonding, polarity, surface tension, conductivity, pH and solubility of salts [Smikhina, 1981; Srebrenik et al., 1993; Amiri and Dadkhah, 2006; Otsuka and Ozeki, 2006; Chang and Weng, 2008]. These changes in water properties may be capable of affecting the growth of plants. The purpose of this study was to determine the effects of magnetic treatment of irrigation water and snow pea and chickpea seeds on the speed of emergence, early growth and nutrient content of seedlings under glasshouse conditions.

MATERIALS AND METHODS

Plant Material

Snow pea (*Pisum sativum* L.) of variety "Oregon Giant" and Kabuli chickpea (*Cicer arietinum* L.) of variety "Bumper" were used in this study. Since the seeds were procured from reliable sources (snow pea seeds from a nursery shop and chickpea seeds from a chickpea breeder), the possibilities of genetic variability in the seeds were minimised. The moisture content values of snow pea and chickpea dry seeds at time of sowing were 8.2% (±0.07) and 7.9% (±0.05), respectively. The moisture content of seeds was determined on an oven-dry basis, and a representative sample of seeds from the same group of pots was used in this study.

Magnetic Treatment

The magnetic treatment device, supplied by Omni Environmental Group (Sydney, Australia), has a magnetic induction in the range of 3.5–136 mT and was used for the treatment of irrigation water and seeds. The device consists of a 100 mm long polycarbonate pipe with an internal diameter of 22 mm. It contains two permanent magnets that are 50 mm in length, separated by a distance of 24 mm. The arrangement of their north and south poles and direction of the magnetic field generated are shown in Figure 1. The permanent magnets were made of Neodymium Ferrite Boron (NdFeB), a rare earth material that generated a high intrinsic coercive force. A static non-uniform magnetic field was generated between the two permanent magnets.

Dry snow pea and chickpea seeds were exposed to four treatments. The following treatments were applied: (i) magnetic treatment of irrigation water (MTW), (ii) magnetic treatment of seeds (MTS), (iii) magnetic treatment of irrigation water and seeds (MTWS) and (iv) no magnetic treatment of irrigation water or seeds as control treatment.

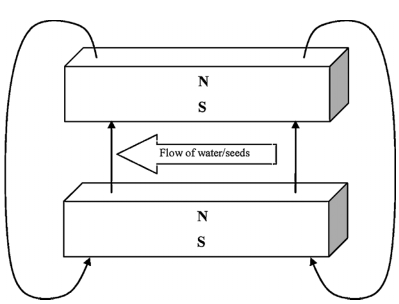

Fig. 1. Magnetic device with two permanent magnets showing their north and south poles, the direction of magnetic field generated, and water and seed flow between the two magnets.

The values of the magnetic field intensity (B_x) generated by the two magnets varied from 3.5 to 136 mT along the axis of the pipe (centre line). The intensity was measured along the longitudinal and cross-sectional directions of the pipe using a tesla meter (Model 5070, Sypris, Orlando, FL). Figure 2 shows the distribution of the magnetic field generated between the two permanent magnets along the length and diameter of the pipe. The peak value of the magnetic field intensity (136 mT) was observed at the middle section of the pipe (between 30 and 80 mm distance from the beginning of the pipe length) with a trend of decreasing values toward the end of the pipe length. Depending on the distance along the pipe length, the values of the magnetic field intensity also varied across the pipe diameter, from 3.3 to 136, 3.2–94, 3.2–97 and 1.8–118 mT at distances of 5, 10, 15 and 20 mm, respectively, from one end of the pipe wall to the other (Fig. 2). The magnetic inhomogeneity of the field ($\Delta B/B_{av}$) was very high (225%). The magnetic field intensity gradient was initially positive along the *x*-axis (10–30 mm of pipe length) and increased sharply (>4500 mT/m) between 20 and 30 mm length. The gradient then decreased and the value was lower (<2750 mT/m) along the length of 30–70 mm and was negative afterward. The value of the negative gradient was highest (>−6300 mT/m) between 80 and 90 mm length.

For the MTW, triple deionised irrigation water was exposed to a static non-uniform magnetic field for about 3 s by passing water through the magnetic treatment device with magnetic induction in the range of 3.5–136 mT. To ensure adequate exposure to the magnetic field, the water for magnetic treatment was passed twice through the device. The magnetic treatment of the water was under dynamic conditions because there was a continuous flow of water at the rate of 10 ml/s through the device. For the magnetic treatment of snow pea and chickpea seeds, the dry seeds were passed twice through the magnetic treatment device with an exposure of about 5 s during each pass. It should be noted that the seeds passed through the device smoothly when dropped into its funnel for the treatment. Seeds for the control treatment were passed through a tube without magnets.

Experiments in Glasshouse

Two glasshouse experiments, one for snow peas and the other for chickpeas, were conducted in this study. After magnetic treatment, snow pea and chickpea seeds were grown in a washed sand medium for 20 days. The sand was air-dried and passed though a 2 mm sieve, and 100 g of this sand was placed in small plastic pots (70 mm long and 50 mm diameter). The sand used was analysed for its chemical properties (sand/water ratio of 1:5 for pH and EC). The sand had an average $pH_{1:5}$ value of 5.6, electrical conductivity ($EC_{1:5}$) 10.8 µS/cm, available P (Olsen P) 1.44 mg/kg, K (0.05 M HCL-extractable) 3.8 mg/kg and N (NO_3-N) 0.8 mg/kg.

Both magnetically treated seeds and control seeds were sown at a uniform depth of 20 mm. Sixteen uniform seeds of snow peas (224.33 ± 4.04 mg per seed) and chickpeas (520.67 ± 5.13 mg per seed) were used in each experimental treatment. Plastic pots were arranged in a completely randomised design, and there were four replications per treatment with a total of 16 plastic pots. The experiment was performed blind and the pots were randomly moved every day to have unbiased results.

Glasshouse experiments, both for snow peas and chickpeas, were conducted under controlled environmental conditions with temperatures of 20 ± 2 °C during the day and 15 ± 2 °C during the night. The relative humidity in the glasshouse varied between 50% and 55% during the study period. There were about 11 h per day of natural light available over the duration of experiments. The glasshouse used in the study was made of polycarbonate materials with automatic

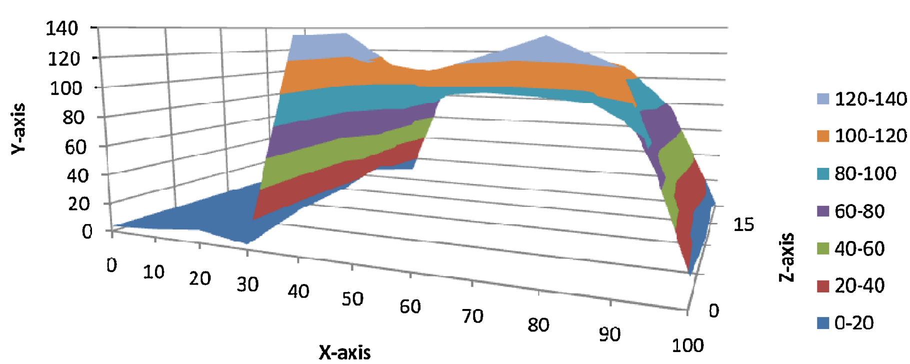

Fig. 2. Distribution of magnetic field intensity generated by the two magnets along the length and diameter of the pipe in the magnetic treatment device. *x*-axis: distance along the length of the pipe in mm; *y*-axis: magnetic field intensity in mT and *z*-axis: distance along the diameter of the pipe in mm.

temperature and humidity control systems similar to those used for growth chambers. There was an automatic temperature control system on the air conditioning unit of the glasshouse. An air thermometer was installed in the glasshouse to monitor the temperature during the study period.

Triple deionised irrigation water was used for growing seedlings to avoid any nutrient use through water, and ensure that the seeds were the main source of nutrients for emerging seedlings. Measured volume (15 ml/pot) of the water, with or without magnetic treatment, was applied in each pot soon after sowing according to the treatments described earlier. The pots were weighed every day and irrigated with triple deionised irrigation water to compensate the loss of water through evaporation and transpiration. The estimation of the amount of water applied in each pot was based on the evapotranspiration loss between two consecutive irrigations.

Growth Measurements

The number of seedlings emerged was counted daily for each treatment during the entire duration of the study for determining the emergence percentage. The emergence rate index (ERI), which is a measure of the speed of emergence, was calculated by a formula given by Bartlett [1937]:

$$\mathrm{ERI} = \frac{\sum(\chi_1 + \chi_2 \ldots + \chi_n)}{n n_\mathrm{p}} \quad (1)$$

where x_1, x_2, etc. are the number of seedlings emerged on 1st, 2nd, etc. day after sowing, n is total number of observations and n_p is number of seeds planted per treatment per replication. From this equation, the ERI can be defined as the ratio of the sum of seedlings emerged during the observation period to number of observations and number of seeds planted per treatment in each replication.

The emergence of seedlings was completed within 10 days of sowing. However, irrigation was continued for another 10 days to observe differences in seedlings' growth and vigour. The seedlings in both experiments were then harvested for shoot and root dry matter accumulation analysis. At harvest, seedling shoots were separated from roots, and the sand was washed off the roots using triple deionised water. The harvested seedlings were dried in an oven at 65 °C for 48 h and weighed. These dried seedlings were then analysed for nutrient concentration by inductively coupled plasma (ICP), a method described by Zarcinas et al. [1987]. The dried roots and shoots of snow pea and chickpea seedlings were digested in nitric acid, and these digested samples were used for simultaneous determination of P, K, S, Ca, Mg, Na, Cu, Zn, Mn, Fe and B concentrations. Nitrogen concentration of roots and shoots was determined by an auto analyser. Seedlings' nutrient content (nutrient uptake) was calculated by multiplying the nutrient concentration of seedlings with their respective dry weight.

Statistical Analysis

All the data relating to seedlings' emergence percentage, emergence state index, dry weight and nutrient content were subjected to one-way ANOVA using Microsoft Excel. Since washed sand used as growing medium in the study was homogenous, there was very little variation between one replication and another under each treatment. All data of different attributes of snow peas and chickpea were observed to have normal distribution based on the Kolmogorov–Smirnov test [Massey, 1951]. Bartlett's test was used to test the homogeneity of variances. It was observed that the variances were homogenous for all the data relating to different attributes. In addition, Tukey's test was performed to differentiate the mean treatment values at a probability of 0.05.

RESULTS

Water Properties

The pH and EC values of magnetically treated irrigation water were significantly affected by magnetic treatment. There was a significant ($P < 0.05$) reduction in pH (from 5.75 to 5.71) and an increase in EC values (from 0.991 to 0.995 µS/cm) with exposure of the water to magnetic fields. However, there was no effect on N, P and K contents of water (data not shown).

Seedling Growth

The results reveal a statistically significant ($P < 0.05$) increase (50%) in seedling emergence of snow pea with MTWS treatment compared to the control treatment (Table 1). However, there was a trend of increased seedling emergence in snow pea for MTW (20%) and MTS (10%) treatments, but the increase was not statistically significant. In chickpeas, there was a trend of improved seedling emergence with the MTW, MTS and MTWS treatments, but the increase was also not statistically significant.

The values of ERI for snow pea and chickpea seedlings were significantly ($P < 0.05$) increased by different magnetic treatments. MTW seedlings showed an increase of 41.6% for snow pea and 51% for chickpea, MTS seedlings showed an increase of 33.2% for snow pea and 37.3% for chickpea, and MTWS

TABLE 1. Effects of Magnetic Treatment of Irrigation Water and Seeds on Seedling Emergence (%) and Emergence Rate Index (ERI) of Snow Pea and Chickpea Seeds (Number of Seeds for Each Treatment = 16)

Treatments	Emergence (%) snow peas	% increase over control	Emergence (%) chickpeas	% increase over control	ERI snow peas	% increase over control	ERI chickpeas	% increase over control
Control	62.5^a		68.8^a		0.375^a		0.455^a	
MTW	75.0^a	20.0	93.8^a	36.4	0.532^b	41.6	0.688^b	51.0
MTS	68.8^a	10.1	81.3^a	18.2	0.500^b	33.2	0.625^b	37.3
MTWS	93.8^b	50.1	87.5^a	27.3	0.688^c	83.3	0.652^b	43.2
SE	5.7		6.5		0.030		0.040	
Tukey's test	S		NS		S		S	

SE, standard error; S, significant; NS, non-significant.
Superscripts a, b and c indicate significantly different means at $P < 0.05$. In columns, means followed by the same letter did not show significant differences ($P < 0.05$) based on SE and Tukey's test.

seedlings showed an increase of 83.3% for snow pea and 43.2% for chickpea, compared to the control seedlings (Table 1). The highest increase in ERI for snow pea (83.3%) was observed with MTWS treatment.

Magnetic treatments led to a significant ($P < 0.05$) increase in shoot dry weight of both snow pea and chickpea seedlings (Table 2). Shoot dry weight increased 7.8% for snow pea and 6.5% for chickpea with MTWS, 11% for snow pea and 4.1% for chickpea with MTS and 24.7% for snow pea and 19.8% for chickpea with MTW, compared to the control. The highest increase in seedling shoot dry weight of snow pea (24.7%) and chickpea (19.8%) was observed with MTW treatment. Also, the results indicate that there was no additional advantage gained in terms of shoot dry weight with MTWS compared with MTS for both crops.

Root dry weight for snow pea seedlings was significantly ($P < 0.05$) influenced by MTW and MTWS treatments. There was an 11.6% increase in root dry weight with MTW treatment while there was a significant reduction (3.9%) in root dry weight with MTWS, in comparison with the control treatment (Table 2). However, root dry weight was unaffected by MTS in snow pea, and by MTW, MTS and MTWS in chickpea compared to the control.

The mean nutrient contents of both snow pea (Table 3) and chickpea (Table 4) seedlings were significantly ($P < 0.05$) influenced by MTW. In snow pea seedlings, the MTW treatment resulted in a significant increase in N (23%), K (14%), Ca (33%), Mg (14%), S (13%), Na (33%), Zn (17%), Fe (15%) and Mn (37%) contents when compared to the control seedlings. However, the effects of the MTW treatment were not significant for P, Cu and B contents of snow pea seedlings. On the other hand, the MTW treatment significantly increased P and Cu contents in chickpea seedlings, in addition to significantly ($P < 0.05$) increasing contents of N, K, Ca, Mg, S, Zn, Fe and Mn (Table 4). The increase with the MTW treatment in N, P, K, Ca, Mg, S, Zn, Fe, Mn and Cu contents in chickpea seedlings were 17%, 11%, 16%, 14%, 18%, 11%, 14%, 12%, 18% and 12%, respectively.

Similar to the MTW treatment, the MTS treatment also significantly ($P < 0.05$) increased the contents of N, Ca, S, Zn, Fe and Mn in snow pea seedlings (Table 3). The increases in the nutrients contents of these elements in snow pea seedlings were 11%, 28%, 9%, 19%, 14% and 25%, respectively. In chickpea seedlings, a

TABLE 2. Effects of Magnetic Treatment of Irrigation Water and Seeds on Mean Shoot and Root Dry Weights (mg/Plant) of Snow Pea and Chickpea Seedlings 20 Days After Sowing (Number of Seedlings for Each Treatment = 8)

Treatments	Shoot weight, dry snow peas	% increase over control	Shoot weight, dry chickpeas	% increase over control	Root weight, dry snow peas	% increase over control	Root weight, dry chickpeas	% increase over control
Control	62.3^a		46.3^a		38.62^a		89.4^a	
MTW	77.6^c	24.7	55.5^c	19.8	43.11^c	11.6	90.8^a	1.6
MTS	69.1^b	11.0	48.2^b	4.1	38.95^a	0.8	89.8^a	0.5
MTWS	67.1^b	7.8	49.3^b	6.5	37.10^b	−3.9	88.7^a	−0.7
SE	0.54		0.33		0.34		0.55	
Tukey's test	S		S		S		NS	

SE, standard error; S, significant; NS, non-significant.

TABLE 3. Effects of Magnetic Treatment of Irrigation Water and Seeds on Nutrient Contents (μg/Plant) of Snow Pea Seedlings 20 Days After Sowing (Number of Seedlings for Each Treatment = 8)

Treatments	N (μg/ plant)	P (μg/ plant)	K (μg/ plant)	Ca (μg/ plant)	Mg (μg/ plant)	S (μg/ plant)	Na (μg/ plant)	Zn (μg/ plant)	Cu (μg/ plant)	Fe (μg/ plant)	Mn (μg/ plant)	B (μg/ plant)
Control	3201^{a}	579^{a}	1199^{a}	36^{a}	173^{a}	267^{a}	14.6^{a}	4.67^{a}	0.99^{a}	10.72^{a}	3.84^{a}	1.20^{a}
MTW	3923^{c}	621^{a}	1372^{b}	48^{b}	198^{b}	302^{b}	20.0^{b}	5.48^{b}	1.19^{a}	12.29^{b}	5.26^{c}	1.43^{a}
MTS	3563^{b}	602^{a}	1304^{a}	46^{b}	190^{a}	291^{b}	16.8^{a}	5.56^{b}	1.11^{a}	12.26^{b}	4.81^{b}	1.41^{a}
MTWS	3469^{b}	589^{a}	1239^{a}	42^{a}	182^{a}	282^{a}	15.6^{a}	5.44^{b}	1.04^{a}	11.39^{a}	4.61^{b}	1.26^{a}
SE	47	11	32	1.8	4.1	6	0.8	0.10	0.05	0.28	0.09	0.06
Tukey's test	S	NS	S	S	S	S	S	S	NS	S	S	NS

SE, standard error; S, significant; NS, non-significant.

significant ($P < 0.05$) increase with the MTS treatment was observed (14%) only for Mg content. The MTWS significantly increased the contents of N and Zn for snow pea and Mg for chickpea seedlings. The inclusion of the MTWS treatment did not have any additional improvement in nutrient contents of snow pea and chickpea seedlings when compared with the MTW treatment.

DISCUSSION

It is important to mention that the significant effect of the MTW and MTS treatments on seedling growth including ERI (reflecting speed of seedling emergence), seedling shoot dry weight and nutrient content of both snow peas and chickpeas indicate that the MTW and MTS treatments have a potential to improve early seedling growth. This improved growth may lead to an early canopy cover and a better competition against weeds, and thus more efficient use of nutrients and irrigation water.

The results also reveal a greater beneficial effect of the MTW treatment than MTS in both snow pea and chickpea seeds in terms of increases in ERI and shoot dry weight. These findings confirm the trends due to MTS and irrigation water observed by Hilal and Hilal [2000] for the germination and emergence of tomatoes, pepper, cucumber and wheat seeds, and by Morejon et al. [2007] for germination of Pinus seeds. Similar to our results, Reina et al. [2001] observed a significant increase in germination by exposing lettuce seeds to magnetic fields. Podleoeny et al. [2004] also reported a significant increase in seeds germination and emergence by exposing broad bean seeds to variable magnetic strengths before sowing.

According to Vallée et al. [2005], the magnetic treatment could act on the gas bubble/water interface and may lead to destabilisation of bubbles, thus disturbing the ionic balance between the shell of adsorbed negative ions and counter ions. In the present study, it is likely that such interfacial effects through the gas bubble/water interface are responsible for the remarkable effects of magnetically treated irrigation water.

The reduction in pH and increase in EC in magnetically treated water may be due to changes in hydrogen bonding and increased mobility of ions. Chang and Weng [2008] reported changes in hydrogen bonding and increased mobility of Na^{+} and Cl^{-} ions with exposure of water to magnetic fields. Several researchers have also found changes in physical and chemical properties of water such as hydrogen bonding, polarity, surface tension, conductivity, pH, refractive

TABLE 4. Effects of Magnetic Treatment of Irrigation Water and Seeds on Nutrient Contents (μg/Plant) of Chickpeas Seedlings 20 Days After Sowing (Number of Seedlings for Each Treatment = 8)

Treatments	N (μg/ plant)	P (μg/ plant)	K (μg/ plant)	Ca (μg/ plant)	Mg (μg/ plant)	S (μg/ plant)	Na (μg/ plant)	Zn (μg/ plant)	Fe (μg/ plant)	Mn (μg/ plant)	Cu (μg/ plant)	B (μg/ plant)
Control	2825^{a}	332^{a}	764^{a}	29.8^{a}	114^{a}	180^{a}	6.88^{a}	3.52^{a}	8.89^{a}	1.87^{a}	0.98^{a}	1.06^{a}
MTW	3292^{b}	370^{b}	887^{b}	33.9^{b}	135^{b}	200^{b}	7.14^{a}	4.03^{b}	9.91^{b}	2.20^{b}	1.10^{b}	1.19^{a}
MTS	2951^{a}	353^{a}	799^{a}	29.9^{a}	130^{b}	178^{a}	6.69^{a}	3.78^{a}	8.80^{a}	1.93^{a}	1.02^{a}	1.12^{a}
MTWS	2979^{a}	354^{a}	810^{a}	30.1^{a}	128^{b}	176^{a}	6.57^{a}	3.82^{a}	8.96^{a}	1.93^{a}	1.00^{a}	1.09^{a}
SE	38.4	5.8	19.6	0.9	2.1	3.0	0.22	0.1	0.2	0.06	0.03	0.04
Tukey's test	S	S	S	S	S	S	NS	S	S	S	S	NS

SE, standard error; S, significant; NS, non-significant.

index and solubility of salts because of magnetic field exposure [Smikhina, 1981; Srebrenik et al., 1993; Amiri and Dadkhah, 2006; Otsuka and Ozeki, 2006; Chang and Weng, 2008].

Although the changes induced in pH and EC in magnetically treated irrigation water were small but statistically significant, they resulted in accentuated biological activity in seeds and consequently affected the speed of emergence of seedlings. The significant changes in pH and EC in magnetically exposed water indicate that magnetic effects last for a long time, the so-called "memory effect of water." Pang and Deng [2008] found that the effect of magnetic treatment of water does not disappear for some time and its intensity of infrared absorption decreases gradually with increasing time and finally acquires the same properties as those of pure water.

It is worth mentioning that the significant effect of MTS could also be attributed to greater absorption of water by magnetically treated seeds. Reina and Pascual [2001] and Reina et al. [2001] reported that magnetically exposed lettuce seeds increased water uptake rate and speed of emergence compared to untreated seeds. The brief exposure of snow pea and chickpea seeds to magnetic fields with high gradient of 225% may be responsible for activations of enzymes and hormones involved in the germination process and mobilization of nutrients. As a result, there is probably an improvement in the mobilization and transportation of nutrients to the embryonic axis and a resultant increase in speed of emergence and nutrient content of seedlings. The confirmation of these mechanisms, whether there is an activation of enzymes and hormone production within seeds due to the magnetic treatment, is beyond the scope of this study and warrants further research. The noticeable enhancement of nutrient content of both snow pea and chickpea seedlings derived from magnetically treated seeds may be ascribed to the long-lasting effects of magnetic fields on nutrient mobility in seeds, which might lead to an increase in hormonal production. Turker et al. [2007] found an increase in gibberellic acid-equivalents (GAs), indole-3-acetic acid and trans-zeatin hormones in the sunflower plant as a result of magnetic exposure.

A significant increase in seedling emergence of snow peas with MTWS treatment compared to the control treatment is most likely attributed to the application of a high gradient magnetic field to both seeds and water. Furthermore, the high gradient resulted in faster activations of enzymes and hormones during the germination process, making the inactive embryo grow.

The results of the current study demonstrate some significant effects of magnetically treated irrigation water and seeds on seedling emergence, growth and nutrient content of snow pea and chickpea seedlings under glasshouse conditions. Although static, non-uniform magnetic fields interact with deionised water and seeds for brief exposure times, the results indicate that the magnetic treatment of irrigation water and snow pea and chickpea seeds led to a marked change in physical and chemical properties of water, early seedling growth and nutrient content of seedlings. It seems that the combined effect of gradient and non-uniform magnetic fields applied to water and seeds for a brief exposure could induce significant changes that could have an effect on late plant growth as an indirect effect of the initial magnetic stimulation. However, before the benefits of magnetic treatment can be exploited for crop production, it will be important to conduct field trials to understand the extent to which the MTWS will be effective under field conditions.

Overall, the results of faster seedling emergence and the significant increase in seedling shoot dry weight and nutrient contents owing to the MTW and MTS treatments has a potential practical significance, particularly through better seedling establishment and early vegetative growth. This may also enable the plants to utilise the nutrients, water, atmospheric CO_2 and radiation more effectively and influence crop yields.

CONCLUSION

The treatment of irrigation water and seeds with non-uniform magnetic fields for a brief exposure significantly increased seedling ERI and shoot dry weight in both snow peas and chickpeas. The MTW resulted in a significant ($P < 0.05$) increase in N, K, Ca, Mg, S, Zn, Fe and Mn contents in snow pea and chickpeas seedling. Similarly, the MTS also resulted in an increase in N, Ca, S, Zn, Fe and Mn contents for snow peas seedlings only. The MTW was more effective than the MTS for seedling emergence and seedling growth. There was no additional advantage gained by treating both irrigation water and seeds for any of the attributes of snow pea and chickpea seedlings, except for a significant increase in seedling emergence percentage of snow peas when compared with the control. The obtained effects are mainly attributable to the application of a high gradient magnetic field to both seeds and water because the exposure time was very brief.

ACKNOWLEDGMENTS

The authors thank Dr. B. Simmons from the University of Western Sydney for his valuable input during this study.

REFERENCES

Alexander MP, Doijode SD. 1995. Electromagnetic field: A novel tool to increase germination and seedling vigour of conserved onion (*Allium cepa* L.) and rice (*Oryza sativa* L.) seeds with low viability. Plant Genet Resour Newsl 104:1–5.

Amaya JM, Carbonell MV, Martinez E, Raya A. 1996. Effects of stationary magnetic fields on germination and growth of seeds. Hort Abst 68:1363.

Amiri MC, Dadkhah AA. 2006. On reduction in the surface tension of water due to magnetic treatment. Colloids Surf A Physicochem Eng Aspects 278:252–255.

Bartlett MS. 1937. Some examples of statistical methods of research in agriculture and applied biology. Suppl J Res Statist Soc 4:137–170.

Blank M. 1995. Biological effects of environmental electromagnetic fields: Molecular mechanisms. BioSystems 35: 175–178.

Chang KT, Weng CI. 2008. An investigation into structure of aqueous NaCl electrolyte solutions under magnetic fields. Comput Mater Sci 43:1048–1055.

Chou CK. 2007. Thirty-five years in bioelectromagnetics research. Bioelectromagnetics 28:3–15.

Danilov V, Bas T, Eltez M, Rizakulyeva A. 1994. Artificial magnetic field effects on yield and quality of tomatoes. Acta Hort 366: 279–285.

De Souza A, Garci D, Sueiro L, Gilart F, Porras E, Licea L. 2006. Presowing magnetic treatments of tomato seeds increase the growth and yield of plants. Bioelectromagnetics 27:247–257.

De Souza A, Sueiro L, Gonzalez LM, Licea L, Porras E, Gilart F. 2008. Improvement of growth and yield of lettuce plants by non-uniform magnetic fields. Electromagn Biol Med 27:173–184.

Duarte Diaz CE, Riquenes JA, Sotolongo B, Portuondo MA, Quintana EO, Perez R. 1997. Effects of magnetic treatment of irrigation water on the tomato crop. Hort Abst 69:494.

Florez M, Carbonell MV, Martinez E. 2007. Exposure of maize seeds to stationary magnetic fields: Effects on germination and early growth. Environ Exp Bot 59:68–75.

Goodman R, Basset CA, Henderson A. 1983. Pulsing electromagnetic fields induce cellular transcription. Science 220: 1283–1285.

Hilal MH, Hilal MM. 2000. Application of magnetic technologies in desert agriculture: I. Seed germination and seedling emergence of some crops in a saline calcareous soil. Egypt J Soil Sci 40:413–422.

Maheshwari BL, Grewal HS. 2009. Magnetic treatment of irrigation water: Its effects on vegetable crop yield and water productivity. Agric Water Manage 96:1229–1236.

Massey FJ. 1951. The Kolmogorov–Smirnov test for goodness of fit. J Am Stat Assoc 46:68–78.

Moon J, Chung H. 2000. Acceleration of germination of tomato seeds by applying AC electric and magnetic fields. J Electrostatics 48:103–114.

Morejon LP, Castro Palacio JC, Velazquez Abad LG, Govea AP. 2007. Simulation of pinus tropicalis M. seeds by magnetically treated water. Int Agrophys 21:173–177.

Otsuka I, Ozeki S. 2006. Does magnetic treatment of water change its properties? J Phys Chem 110:1509–1512.

Pang XF, Deng B. 2008. Investigation of changes in properties of water under the action of a magnetic field. Sci China Ser G Phys Mech Astron 51:1621–1632.

Paradisi S, Donelli G, Santini MT, Straface E, Malorni W. 1993. A 50-Hz magnetic field induces structural and biophysical changes in membranes. Bioelectromagnetics 14: 247–255.

Pittman UJ. 1963a. Magnetism and plant growth. 1. Effect on germination and early growth of cereal seeds. Can J Plant Sci 43:512–518.

Pittman UJ. 1963b. Magnetism and plant growth. III. Effect on germination and early growth of corn and beans. Can J Plant Sci 45:549–555.

Pittman UJ, Anstey TH. 1967. Magnetic treatment of seed orientation of a single harvest snap bean (*Phaseolus vulgaris* L). Proc Am Soc Hort Sci 91:310–314.

Podleoeny J, Pietruszewski S, Podleoena A. 2004. Efficiency of the magnetic treatment of broad bean seeds cultivated under experimental plot conditions. Int Agrophys 18: 65–71.

Reina FG, Pascual LA. 2001. Influence of a stationary magnetic field on water relations in lettuce seeds. Part I: Theoretical considerations. Bioelectromagnetics 22:589–595.

Reina FG, Pascual LA, Fundora IA. 2001. Influence of a stationary magnetic field on water relations in lettuce seeds. Part II: Experimental results. Bioelectromagnetics 22:596–602.

Smikhina LP. 1981. Changes in refractive index of water on magnetic treatment. Colloid J 2:401–404.

Srebrenik S, Nadiv S, Lin LJ. 1993. Magnetic treatment of water–a theoretical quantum model. Magn Electr Sep 5:71–91.

Tenuzzo B, Chionna A, Panzarini E, Lanubile R, Tarantino P, Di Jeso B, Dwikat M, Dini L. 2006. Biological effects of 6 mT static magnetic fields: A comparative study in different cell types. Bioelectromagnetics 27:560–577.

Trebbi G, Borghini F, Lazzarato L, Torrigiani P, Calzoni GL, Betti L. 2007. Extremely low frequency weak magnetic fields enhance resistance of NN tobacco plants to tobacco mosaic virus and elicit stress-related biochemical activities. Bioelectromagnetics 28:214–223.

Turker M, Temirci C, Battal P, Erez ME. 2007. The effects of an artificial and static magnetic field on plant growth, chlorophyll and phytohormone levels in maize and sunflower plants. Phyton Ann Rei Botanicae 46:271–284.

Vakharia DN, Davariya RL, Parameswaran M. 1991. Influence of magnetic treatment on groundnut yield and yield attributes. Indian J Plant Physiol 34:131–136.

Vallée P, Lafait J, Mentré P, Monod MO, Thomas Y. 2005. Effects of pulsed low frequency electromagnetic fields on water using photoluminescence spectroscopy: Role of bubble/water interface. J Chem Phys 122:114513–114518.

Zarcinas BA, Cartwright B, Spouncer LR. 1987. Nitric acid digestion and multi-element analysis of plant material by inductively coupled plasma spectrometry. Commun Soil Sci Plant Anal 18:131–146.