Environmental and Experimental Biology (2014) 12: 137–142 *Review*

Impact of magnetic water on plant growth

Jaime A. Teixeira da Silva[1]*, Judit Dobránszki[2]

[1]P.O. Box 7, Miki-cho Post Office, Ikenobe 3011-2, Kagawa-ken, 761-0799, Japan
[2]Research Institute of Nyíregyháza, University of Debrecen, Nyíregyháza, P.O. Box 12, H-4400, Hungary

*Corresponding author, E-mail: jaimetex@yahoo.com

Abstract

Magnetic fields (MFs) can alter plant growth and development. One way of applying a MF is by magnetizing water, thus creating magnetic water (MW). This review focuses on the use of MW in a bid to alter plant growth and development. Irrigation with MW can improve the growth and development of plants both quantitatively and qualitatively. It can improve the germination of seeds, early vegetative development of seedlings and can also alter the mineral content of seeds or fruits. Therefore, MW could be one of the most promising ways of applying a magnetic field in the future to enhance agricultural production in an environmentally friendly way. The effect of MW, which depends on the quality and ion-content of the water and on the type of magnetization, is very strongly species- and genotype-dependent. Researchers seeking to use MW as an abiotic stress agent, or as a growth-inducing or growth-inhibiting factor ought to first test ideal parameters, preferably against the use of permanent magnets with sustained magnetism, since MW can lose its magnetism over time and distance.

Key words: magnetic field, magnetized water, plant growth, seed germination, yield.
Abbreviations: chl, chlorophyll; EMF, electromagnetic field; GMF, geo-magnetic field; MF, magnetic field; MW, magnetized water; nT, nanoTesla; T, Tesla.

Magnetic fields: broad impact on plant growth and research conducted

Plants, like other living organisms on Earth, are under the influence of the Earth's geomagnetic field (GMF). External application of a magnetic field (MF) or an electromagnetic field (EMF), which differ from GMF, alters the growth and development of plants both under *ex vitro* and *in vitro* conditions. Practical application and use of MF and EMF treatments on seed germination, seedling development and yields of different species, such as field, fodder and industrial crops, herbs and medicinal plants, different vegetables and fruits, grasses, ornamentals, and model crops, have been extensively studied during the last 80 to 90 years and summarized elsewhere (Teixeira da Silva, Dobránszki 2014; unpublished) together with their physiological and biochemical influences and possible physiological mechanisms.

Beside greenhouse, pot and field experiments, *in vitro* growth and development of a wide range of species, including field and fodder crops (Dijak et al. 1986; Atak et al. 2003, 2007; Belyavskaya 2004; Alikamanoglu, Sen 2011; Kahrizi et al. 2013; Radhakrishnan, Kumari 2013a, 2013b), herbs and medicinal plants (Criveanu, Taralunga 2006; Alemán et al. 2014), horticultural crops (Rakosy-Tican et al. 2005; Tanaka et al. 2010), fruits (Yan et al. 2009), ornamentals (Van et al. 2011a, 2011b, 2012) and tree species (Celestino et al. 1998; Ham et al. 2004; Çelik et al. 2008) were studied when exposed to external MFs (from super-weak to high MFs) or EMFs. Experiments conducted under an *in vitro milieu* proved that MFs and EMFs affected the growth and development of cultured cells, tissues and organs, and stimulated both axillary and adventitious organogenesis (reviewed in Teixeira da Silva, Dobránszki, 2014; unpublished). The effects of MFs on *in vitro* plant growth and development depend on the exact properties of MFs, such as polarity, intensity, exposure time, and magnet type. Since the observed effects were always genotype-dependent, all MFs should be tested individually before application to a given genotype.

Unlike pot experiments or greenhouse *ex vitro* trials, *in vitro* systems have the advantage of a standard and controlled environment and easy, fast and reliable reproducibility of experiments; moreover, such systems need minimal space and material (Dobránszki, Teixeira da Silva 2010; Tanaka et al. 2010). Therefore they are very suitable as model systems or tools for studying different physiological, biochemical, or molecular changes and processes induced by environmental effects, such as MFs or EMFs.

Most of these studies, however, employed a static (i.e., stationary) magnet (see images in Tanaka et al. 2010). However, some studies have employed magnetized water (MW), and this is the focus of this mini-review. Irrigation with MW is another special aspect of using MFs for improving crop growth and development, although such studies are still very limited.

Changes in the physical and chemical properties of water after magnetization

An externally applied MF causes changes in atomic and molecular and electronic structure of the treated water, such as changes to its solidifying and boiling point, viscosity and dielectric constant, the formation of clustering structures from linear and ring hydrogen-bound chains of molecules, the magnetic interaction between these clustering structures and increasing polarization effects of water molecules, all summarized in Pang and Deng (2008) and briefly described here. The optical features of MW change. The UV absorption intensity of MW, which is higher than that of untreated water, increases exponentially as the period of magnetization increases and as the wavelength of UV light decreases. These changes are related to molecule clustering, atomic polarization and changes in the transition dipole-moment of electrons within molecules, as a direct result of the magnetic treatment. Pang and Deng (2008) also showed that the infrared absorption of MW increased as the field strength and exposure period of the MF increased, but the positions of absorption peaks did not change, indicating that there were no molecular changes. From a practical or application point of view, MW has some important features, including a saturation effect, temperature-dependence of magnetization, a memory effect and changes in the surface tension force. The saturation effect of MW implies that both for exposure time and field strength there is a maximum after which the properties of MW cannot be changed further, either by increasing the exposure period or by increasing the field strength. Studying the changes in infrared absorption of MW, Pang and Deng (2008) showed that the magnetic effect (applied MF: 4400 G for 40 min) decreased as temperature increased between 35 and 95 °C, due to a decrease in the number of molecules in clustering structures caused by the increase in the number of molecules with increased thermal energy. Moreover, changes caused by MF do not disappear immediately after removing MF, which is termed the "memory effect" (or residual effect) of MW, and is an important aspect of its application (Pang, Deng 2008). Pang and Deng (2008) found that the memory time of MW depends on the MF and that applying MFs of 600 G, 2000 G, 3000 G and 4000 G resulted in memory times of 35, 45, 58 and 60 min, respectively. Based on the experiments of Pang and Deng (2008), the surface tension force of MW decreases compared to untreated water, as does its hydrophobicity, due to the clustering structure and increased polarized effect of treated water.

Application of magnetized water to plant growth and development research

The biological effects of MF or EMF treatments depend on the strength and exposure period of water conditioning, in particular the ion content, quality and volume of water, the speed of flow, and water temperature (Lin, Yotvat 1990; Goldsworthy et al. 1999; Pang, Deng 2008; Table 1). An early investigation (Goldsworthy et al. 1999) of the effects of MW on the culture medium of yeasts showed that weak conditioning of tap water with pulsed 100 kHz EMF for 5 to 30 s stimulated the growth of yeasts (with about 53% more cells), due to interaction of the treated water with calcium in the cell membrane, increasing the permeability of the membrane to calcium and therefore activating the calcium-signaling cascade. However, when water was treated strongly (100 kHz for 2 min), growth was inhibited by about 50% because of severe damage caused to the membrane structure. When strongly conditioned water (treated for 2 min) was diluted with non-conditioned water two-fold, the same stimulating effect was detected as when weak water conditioning was performed.

Wheat 'NR-234' seeds with low (45%) viability were exposed to magnetic treatment (seeds were passed through magnetic funnels (Magnetic Technologies LLC, Russia) 2, 4, or 6 times) and irrigated with MW (water was passed through the device 3 or 6 times), alone or in combination (Ijaz et al. 2012). Using magnetized irrigation water (i.e., MW), seed germination increased by 13.3%, but magnetic treatments of seeds did not affect the germination rate. Although the length of shoots (from 9.14 cm to 8.4 and 8.6 cm at 3 and 6 water passing, respectively) and roots (from 12.65 cm to 11.3 and 10.16 cm at 3 and 6 water passing, respectively) decreased as water passages increased, the dry weight of 7-day-old seedlings was increased by treatments with MW and its effect depended on the amount of water passed through the device. Highest (0.57 g) seedling dry weight was observed after seeds were passed through the device 4 and 6 times compared to the control (0.52 g). However, results of direct magnetization of seeds were inconsistent.

Seeds of nine wheat cultivars ('Giza168', 'Sakha 93', 'Masr 1', 'Seds 12', 'Tabouki', 'Kaseemi', 'Yamanei', 'Madini', 'Nagrani') were exposed to weak pulsed MF treatment, exposed either to 0.3 T for 30 min, by placing seeds between the poles of a 58-mm diameter electromagnet and located 30 mm apart, and with a longitudinal axis along the magnetic line of force at MF, or by dipping seeds in MW in which seeds were imbibed with 15 mL of MW exposed to 0.3 T, alone or in combination (Almaghrabi, Elbeshehy 2012). The combined MF treatment (exposure + dipping) resulted in the highest increase in germination percentage, 9 to 30% higher in seven cultivars but a decrease in 'Sakha 93' (96.67 to 66.67%) and 'Masr 1' (86.67 to 76.67%). Growth parameters (shoot and root length) of 21-day-old seedlings were stimulated by the combined MF treatment in the seven cultivars but MF treatment did not affect the growth of 'Masr 1' and decreased the growth of 'Sakha 93' seedlings.

The yield of snow pea (*Pisum sativum* var. *saccharatum*), pea and celery (*Apium graveolens* var. *dulce*) produced in

Table 1. The effects of magnetized water on different plant species (listed alphabetically). chl, chlorophyll; DW, dry weight; EI, Emergence Index (AOSA, 1983); ERI, Emergence Rate Index (AOSA, 1983); FEP, Final Emergence Percentage (AOSA, 1983); FW, fresh weight; MET, Mean Emergence Time (AOSA, 1983); MF, magnetic field; MW, magnetic water; SGI, Seed Germination Index (AOSA, 1983); T, Tesla

Species/cultivar	Treatment			Reference
Wheat (*Triticum aestivum* L.) cultivars 'Giza168', 'Sakha 93', 'Masr 1', 'Seds 12', 'Tabouki', 'Kaseemi', 'Yamanei', 'Madini', 'Nagrani'	Seeds were dipped in MW exposed to 0.3 T	Positive effects	MW increased the germination of all cultivars, shoot and root length, seedling FW and DW of 21-day-old seedlings in 7 cultivars ('Giza168', 'Seds 12', 'Tabouki', 'Kaseemi', 'Yamanei', 'Madini', 'Nagrani'). Protein bands in wheat grain increased after MW treatment in 6 cultivars (Giza168', 'Seds 12', 'Tabouki', 'Kaseemi', 'Madini', 'Nagrani').	Almaghrabi, Elbeshehy 2012
		Negative effects	MW decreased shoot length, seedling FW and DW of 21-day-old seedlings of 'Sakha 93' and 'Masr 1' and root length of 'Masr 1'. Protein bands in wheat grain decreased after MW treatment in 'Yamanei' and 'Sakha 93'.	
		No effect	MW did not affect the root length of 'Sakha 93' and protein bands of 'Masr 1' grain.	
Flax (*Linum usitatissimum* L.)	Irrigation twice a week with MW (magnetization using a Magnetron U.T.3)	Positive effects	FW of capsules (from 0.44 to 0.53 g/plant) and seed yield (from 0.33 to 0.35 g plant^{-1}) increased after irrigation with MW in the first season and plant height (from 56.8 to 58.2 cm and from 58.3 to 61.4 cm) and seed number per plant (from 73.6 to 90.72 and from 85.68 to 107.46) in both seasons. MW increased chl a (17.46%), chl b (67.8%), carotenoids (8.55%), total indole (18.2%) and phenol (33.35%) content.	Amira et al. 2010
		Negative effects	Not reported.	
		No effect	MW did not affect basal branches, fruit branches, number of capsules/plant, 1000-seed weight (in both seasons).	
Wheat (*Triticum* sp.) cultivar 'NR-234'	Seeds with initial low viability (45%) were treated with MW. Water was passed through a magnetic funnel, and MW was used to moisten the paper used for germination. Water was passed through a magnetizing device 3 or 6 times but the "level" of magnetization was not defined or quantified	Positive effects	Germination percentage increased by 15% when water was passed through 6 passages of magnetization. In the case of 3X magnetization, SGI increased from 6.69 to 7.38% and to 7.33% for 6X magnetized water. Seedling DW increased as the level of magnetization of water increased: from 0.52 g in the control up to 0.57 g when magnetized 6 times.	Ijaz et al. 2012
		Negative effects	MW treatment decreased shoot length (9.14 cm in control down to 8.5 cm in 3X magnetized water) and root length (12.65 cm in the control to 11.3 cm and 10.16 cm in 3X and 6X magnetized water), respectively.	
		No effect	Not reported.	

continued

Table 1. *continued*

Species/cultivar	Treatment			Reference
Snow pea (*Pisum sativum* var. *saccharatum*); pea (*Pisum sativum* L.); celery (*Apium graveolens* subsp. *dulce* (Mill.) Schübl. & G. Martens)	Potable, recycled and saline water were magnetized. Saline water: 500 and 1000 ppm NaCl was added to the potable water in the case of snow pea and 1500 and 3000 ppm NaCl in the case of pea and celery. Water was passed twice through a device with a MF of 3.5-136 mT at a flow rate of 10 mL s−1. MW was used to irrigate seedlings	Positive effects	Magnetized recycled and saline (3000 ppm) water increased the FW and DW of celery seedlings by 12 and 23%, and by 12 and 26%, respectively. Snow pea yield increased 7.8%, 5.9% and 6.0% while the DW of pods increased 8.5, 7.0 and 8.2% when magnetized potable water, recycled water and 1000 ppm saline water, respectively were used. The number of pods/pot in snow pea increased by 6.1% after exposure to MW. An increase in water productivity (based on FW and DW) was detected after celery was irrigated with magnetized 1500 and 3000 ppm saline and recycled water. Water productivity (based on FW) of snow pea increased using magnetized potable, recycled or 1000 ppm saline water. 3000 ppm increased the DW of celery roots by 15%. Magnetized recycled and saline water increased the Ca and P content of celery shoots. MW (recycled and 1000 ppm saline) increased the Ca, Mg and Na content of snow pea pods.	Maheshavari, Grewal 2009
		Negative effects	Magnetized potable and 500 ppm saline water decreased the Mg content of snow pea pods. Magnetized 1000 ppm saline water decreased the Na content of snow pea pods.	
		No effect	Neither magnetized potable nor 1500 ppm saline water affected the DW of celery shoots. 500 ppm saline water did not affect the yield and water productivity of snow pea. Shoot DW of snow pea was not affected by MW. MW did not affect the total plant water use in snow pea, pea or celery.	
Maize (*Zea mays* L.)	Tap, saline (contains 1500 ppm NaCl), canal and sewage water was magnetized with a MF of 235 mT at a flow rate of 3 l/min. Maize seeds were soaked in MW for 24 h and planted in sand	Positive effects	Earlier germination was observed when magnetized tap, saline or canal water was used. Germination was completed earlier (by 2-3 days) when any MW was used. MW increased the height (by 10.24-17.09%) and the weight (by 17.4-24.8%) of 15-day-old seedlings but the rate of increase depended on the type of water magnetized. EI and ERI increased when any MW was used.	Mahmood, Usman 2014
		Negative effects	FEP was lower if canal water was magnetized (93.33% vs. 95.59% in the control). More time was necessary for seed emergence when using MW, represented by lower MET values.	
		No effect	Germination started on the same day when magnetized sewage water was used. FEP was not modified when magnetized tap water was used.	
Cowpea (*Vigna unguiculata* L. Walp.) cv. 'Kamran'	Irrigation weekly with MW	Positive effects	MW increased leaf, stem, root and total FW and DW, specific leaf area, leaf area, root weight, stomatal conductance and water use efficiency.	Sadeghipour, Aghaei 2013
		Negative effects	MW decreased the shoot : root ratio.	
		No effect	MW did not affect leaf : stem weight ratio.	

a greenhouse was affected by irrigation with magnetized (3.5 to 136 mT) tap, recycled and saline (500 and 1000 mg L^{-1} NaCl for snow pea and 1500 and 3000 mg L^{-1} NaCl for pea and celery) water (Maheshwari, Grewal 2009). The effect of the magnetized irrigation water (by passing twice through a magnetic device with a MF range of 3.5 to 136 mT (Omni Environment Group Pty Ltd., Australia) with a flow rate of 10 mL s^{-1}, 3 s exposure) depended on the plant species and the type of irrigation water. Magnetized recycled water promoted the yield of celery by 12% and its water productivity (based on the fresh and dry weight of the produce; kg of shoots per kL of water used in celery and kg of pods per kL of water used in snow pea) by 12%. Magnetized tap water enhanced the yield of snow pea more than magnetized recycled water (7.8% vs. 5.9%); similarly, its water productivity was increased by 12 and 7.5% by magnetized tap water and recycled water, respectively. However, the yield of pea was not affected by any type of MW. Magnetic treatment increased the Ca and Mg contents in the shoots of celery independently of water type, and the Ca, Mg and Na contents in snow pea pods. In the latter case, the rate of increase was highest in Ca and Mg content when recycled water was used. The MW also caused changes in the soil properties measured at harvest, such as soil pH, soil electrical conductivity (EC), P and K content.

Both the vegetative growth and the yield of common flax were increased in pot greenhouse experiments (Amira et al. 2010) after irrigation with MW (Magnetron U.T 3). Increases in plant height (6.01%), fresh and dry weight (16.62 and 12.58%) and water content (1.48%) were accompanied by an increase in photosynthetic pigment content, such as chlorophyll *a* (17.46%), chlorophyll *b* (67.8%) and carotenoids (8.55%), and total indole (18.2%) and phenol (33.35%) content. The synthesis and appearance of new proteins was also detected. Consequently, most likely as a result of an increase in all of these parameters, yield per plant also increased 9.1% after irrigation with MW. Control plots were irrigated with tap water twice on a weekly interval, while the remaining half of the pots was irrigated with tap water after magnetization. Fifty days after sowing the growth was improved when cowpea (*Vigna unguiculata* L. Walp.) seeds were irrigated with MW in a pot experiment (Sadeghipour, Aghaei 2013). The fresh and dry weights of leaves (22 and 20%), stems (19 and 20%) and roots (47% both), leaf area (26%), stomatal conductance (22%) and water use efficiency (22%) increased when plants were irrigated with MW (cylindrical magnetic device), but it decreased the shoot/root ratio by 14% and did not affect leaf/stem weight ratio.

Mahmood and Usman (2014) magnetized (235 mT, at 3 L min^{-1} flow rate) different types of water (tap water, saline water by adding 1500 ppm NaCl, canal water and sewage water). MW promoted maize germination; it increased emergence by increasing both the emergence index (to 8.92 from 5.5) and emergence rate index (to 12.84 from 10.06) and decreased the time for emergence by 17.9%. The growth of seedlings was also faster when treated with MW; both the height and weight of seedlings increased by 10.24 to 17.09% and 17.4 to 24.8%, respectively, but this depended on the water type. More pronounced positive effects were detected when sewage water was magnetized.

Conclusions and caution

Summarizing the research results using MW for irrigation, it can be seen that the application of MW might be a very practical way to improve the quantitative and qualitative attributes of agronomic and horticultural production under greenhouse or field conditions. However, further studies are needed to make its use economical. For example, even though Amira et al. (2010) found an increase in several parameters of common flax, and Sadeghipour and Aghaei (2013) managed to increase yield/plant by 9.1% after irrigation with MW, the magnetic potential of MW decreases as a function of time and temperature (i.e., it decreases as time and temperature increase; Goldsworthy et al. 1999; Pang, Deng 2008), and the actual costs on a yield basis as opposed to the use of plain tap water need to be carefully considered before implementation of MW in the field. Moreover, due to the dependence of the magnetic ability of MW on temperature, it may be impractical to use it in *in vitro* experiments because medium needs to be autoclaved first, usually at or near 121 °C, which could/would demagnetize MW, possibly entirely (due to decomposition of hydrogen-bound chains), and thus filter sterilization of large volumes of medium would simply not be practical. One possibility could be to treat sterilized liquid medium with MF, but this has not yet been reported in the literature, and is certainly an option that needs to be explored to expand on current *in vitro* experiments. Finally, as shown by studies detailed in Table 1, the response to MW appears to be dependent on the species and on the genotype or cultivar, and even on the ion content of the water, suggesting that the optimization of a considerable number of parameters may dampen the exploration of MW for practical purposes in agriculture.

Glossary

Geomagnetic field (GMF): MF which surrounds the Earth and generated from the combination of several MFs and dipolar on the surface of the Earth. It is generated mainly from the movement of conducting material inside the Earth (inner and outer cores) (main field). Other sources influence it, such as electric current flows in the ionized upper atmosphere, currents flows within the earth's crust and local anomalies.

Electromagnetic field (EMF): a field which is generated from the acceleration of charged particles. It has two components, an electric field, which surrounds all charged particles, and a magnetic field, which is produced by the motion of charged particles (current).

Magnetic field (MF): A field in the neighbourhood of constant magnets or that of electric currents. It is a vector field, i.e. it is specified by both a direction and strength. It is characterized by magnetic flux density [measurement in Tesla (T)], and magnetic field strength [measurement in amperes (A) per meter (m)].

Units of measure for MF: Ampere (A): measure of electric field intensity; Joule (J): measure of energy; Tesla (T): measure of magnetic field (magnetic flux density) where $1\ T = 1\ kg\ s^{-2}\ A^{-1}$ and 1 T = 10 000 G (Gauss, which is the non-SI measure of MF).

References

Alemán E.I., Nbogholi A., Boix Y.F., González-Olmedo J., Chalfun-Junior A. 2014. Effects of EMFs on some biological parameters in coffee plants (*Coffea arabica* L.) obtained by *in vitro* propagation. *Polish J. Environ. Stud.* 23: 95–101.

Alikamanoglu S., Sen A. 2011. Stimulation of growth and some biochemical parameters by magnetic field in wheat (*Triticum aestivum* L.) tissue culture. *African J. Biotechnol.* 10: 10957–10963.

Almaghrabi O.A., Elbeshehy E.K.F. 2012. Effect of weak electromagnetic field on grain germination and seedling growth of different wheat (*Triticum aestivum* L.) cultivars. *Life Sci. J.* 9: 1615–1622.

Amira M. S., Qados A., Hozayn M. 2010. Response of growth, yield, yield components, and some chemical constituents of flax for irrigation with magnetized and tap water. *World Appl. Sci. J.* 8: 630–634.

AOSA. 1983. Association of Official Seed Analysts. Seed vigour testing hand book. Contribution No. 32 to the Handbook of seed testing. Lincoln, NE. 88 p.

Atak Ç., Emiroğlu O., Alikamanoğlu S., Rzakoulieva A. 2003. Stimulation of regeneration by magnetic field in soybean (*Glycine max* L. Merrill) tissue cultures. *J. Cell. Mol. Biol.* 2: 113–119.

Atak Ç., Çelik O., Olgum A., Alikamanoğlu S., Rzakoulieva A. 2007. Effect of magnetic field on peroxidase activities of soybean tissue culture. *Biotech. Biotechnol. Equip.* 21: 166–171.

Belyavskaya N.A. 2004. Biological effects due to weak magnetic field on plants. *Adv. Space Res.* 34: 1566–1574.

Celestino C., Picazo M.L., Toribio M., Alvarez-Ude J.A., Bardasano J.L. 1998. Influence of 50 Hz electromagnetic fields on recurrent embryogenesis and germination of cork oak somatic embryos. *Plant Cell Tissue Organ Cult.* 54: 65–69.

Çelik O., Atak Ç., Rzakulieva A. 2008. Stimulation of rapid regeneration by a magnetic field in *Paulownia* node cultures. *J. Central Eur. Agric.* 9: 297–304.

Criveanu H.R., Taralunga G. 2006. Influence of magnetic fields of variable intensity on behaviour of some medicinal plants. *J. Central Eur. Agric.* 7 : 643–648.

Dijak M., Smith D.L., Wilson T.J., Brown D.C.W. 1986. Stimulation of direct embryogenesis from mesophyll protoplasts of *Medicago sativa. Plant Cell Rep.* 5: 468–470.

Dobránszki J., Teixeira da Silva J.A. 2010. Micropropagation of apple – a review. *Biotechnol. Adv.* 28: 462–488.

Goldsworthy A., Whitney H., Morris E. 1999. Biological effects of physically conditioned water. *Water Res.* 33: 1618–1626.

Ham L.H., Van N.T.K., Vinh D.N. 2004. The impact of magnetic fields on *in vitro* culture system. *Appl. Biotechnol. Newslett.* 1/2: 42–49. /in Vietnamese/

Ijaz B., Jatoi S.A., Ahmad D., Masood M.S., Siddiqui S.U., Maheshwari B.L., Grewal H.S. 2012. Changes in germination behavior of wheat seeds exposed to magnetic field and magnetically structured water. *African J. Biotechnol.* 11: 3575–3582.

Kahrizi D., Cheghamirza K., Akbari L., Rostami-Ahmadvandi H. 2013. Effects of magnetic field on cell dedifferentiation and callus induction derived from embryo culture in bread wheat (*Triticum aestivum* L.) genotypes. *Mol. Biol. Rep.* 40: 1651–1654.

Lin I.J., Yotvat J. 1990. Exposure of irrigation and drinking water to a magnetic field with controlled power and direction. *J. Magn. Magn. Mater.* 83: 525–526.

Maheshwari B.L., Grewal H.S. 2009. Magnetic treatment of irrigation water: Its effects on vegetable crop yield and water productivity. *Agric. Water Manage.* 96: 1229–1236.

Mahmood S., Esman M. 2014. Consequences of magnetized water application on maize seed emergence in sand culture. *J. Agr. Sci. Tech.* 16: 47–55.

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

Radhakrishnan R., Kumari B.D.R. 2013a. Influence of pulsed magnetic field on soybean (*Glycine max* L.) seed germination, seedling growth and soil microbial population. *Indian J. Biochem. Biophys.* 50: 312–317.

Radhakrishnan R., Kumari B.D.R. 2013b. Protective role of pulsed magnetic field against salt stress effects in soybean organ culture. *Plant Biosys.* 147: 135–140.

Rakosy-Tican L., Aurori C.M., Morariu V.V. 2005. Influence of near null magnetic field on *in vitro* growth of potato and wild *Solanum* species. *Bioelectromagnetics* 26: 548–557.

Sadeghipour O., Aghaei P. 2013. Improving the growth of cowpea (*Vigna unguiculata* L. Walp.) by magnetized water. *J. Biodiv. Env. Sci.* 3: 37–43.

Tanaka M., Van P.T., Teixeira da Silva J.A., Ham L.H. 2010. Novel magnetic field system: Application to micropropagation of horticultural plants. *Biotech. Biotechnol. Equip.* 24: 2160–2163.

Van P.T., Teixeira da Silva J.A., Ham L.H., Tanaka M. 2011a. Effects of permanent magnetic fields on the proliferation of *Phalaenopsis* protocorm-like bodies using liquid medium. *Sci. Hortic.* 128: 479–484.

Van P.T., Teixeira da Silva J.A., Ham L.H., Tanaka M. 2011a. The effects of permanent magnetic fields on *Phalaenopsis* plantlet development. *J. Hortic. Sci. Biotechnol.* 86: 473–478.

Van P.T., Teixeira da Silva J.A., Ham L.H., Tanaka M. 2012. Effects of permanent magnetic fields on growth of *Cymbidium* and *Spathiphyllum*. *In Vitro Cell. Dev. Biol. Plant* 48: 225–232.

Yan D., Guo Y., Zai X., Qin P. 2009. Effects of electromagnetic fields exposure on rapid micropropagation of beach plum (*Prunus martima*). *Ecol. Engin.* 35: 597–601.

Zaidi S., Khatoon S., Imran M., Zohair S. 2013. Effects of electromagnetic fields (created by high tension lines) on some species of family Mimosaceae, Molluginaceae, Nyctaginaceae and Papilionaceae from Pakistan–V. *Pak. J. Bot.* 45: 1857–1864.

Received 18 July 2014; received in revised form 16 September 2014; accepted 19 October 2014