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Tratamiento magnético de agua de riego y semillas en agricultura

AGRICULTURAL ENGINEERING

Magnetic treatment of irrigation water and seeds in agriculture

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Resumen
El objetivo de este artículo de revisión es el de exponer las ventajas de los tratamientos magnéticos en la agricultura, así como señalar los vacíos que impiden su uso extendido y/o complementario a las prácticas tradicionales. Se realizó una revisión bibliográfica exhaustiva de los últimos ochenta años en las bases de datos de ciencias agrícolas y ciencias básicas, usando los descriptores agua-propiedades fisicoquímicas, bio-magnetismo, producción de cultivos, y tratamientos magnéticos. El agua tratada magnéticamente exhibe diversos fenómenos a nivel molecular, de donde se infieren sus efectos directos e indirectos sobre el crecimiento y la productividad de los cultivos, relacionados con una mayor eficiencia en el riego y uso del agua, modificación del perfil de humedad del suelo y una óptima disponibilidad de nutrientes en el mismo. De igual forma, los campos magnéticos aplicados a semillas estimulan la germinación, el vigor y la tasa de crecimiento vegetal, lo que influye al final en la producción neta y el rendimiento. A pesar de lo anterior, se carece de un protocolo estandarizado de tratamientos magnéticos para agua y semillas, en virtud de las numerosas y diversas metodologías evaluadas en cada estudio. No obstante, ya existen algunos dispositivos patentados disponibles en el mercado. La tecnología de tratamientos magnéticos para aguas de riego y semillas presenta efectos positivos sobre la productividad vegetal, es de fácil aplicación y de menor impacto sobre el medio ambiente en comparación con otras prácticas. Por otra parte, una modelación adecuada de las interacciones entre los campos magnéticos, el agua y los procesos fisiológicos en semillas y plantas podría conducir a una estandarización de ésta práctica, subsanando los vacíos metodológicos existentes a este nivel.

Palabras clave: *Agro-tecnología, bio-magnetismo, fisiología, productividad.*

Abstract
The aim of this review article is to expose the advantages of magnetic treatments in agriculture, and to identify the gaps that prevent their spread and/or complementary use to traditional practices. A comprehensive literature review of the last eighty years was carried out on the databases of agricultural sciences and basic sciences, using the descriptors water-physicochemical properties, bio-magnetism, crop production, and magnetic treatments. The magnetically treated water exhibits various phenomena at the molecular level, which are thought to have direct and indirect effects on growth and productivity of crops, related with a greater efficiency in irrigation and water use, modification of soil moisture profile and an optimal nutrient availability therein. Similarly, magnetic fields applied to seeds stimulate the seed germination, vigor, and plant growth rate, which influences the final net production and yield. Despite this, there is a lack of a standardized magnetic treatment for water and seeds, due to the many different methodologies evaluated in each study. However, there are already some patented available devices in the market. The technology of magnetic treatments for seeds and irrigation water has positive effects on plant productivity, it is easy to apply and have less impact on the environment compared to other practices. Moreover, an accurate modeling of the interactions between magnetic fields, water, and seed and plant physiological processes could lead to a standardization of this technique, which remedy the existing methodological gaps at this level.

Keywords: *Agro-technology, bio-magnetism, physiology, productivity.*

1. Introduction

The scientific literature has shown that biological systems are not indifferent to magnetic fields. In fact, the Earth behaves like a giant magnet, whose geomagnetic field has accompanied the evolution of living beings. Migratory birds, insects, protists and magneto-tactics bacteria have plenty identified biophysical mechanisms of magneto-perception, as magnetosomes, paramagnetic nanoparticles and some pigments (Galland & Pazur, 2005; Lohman & Johnsen, 2000). Although this class of receptors are unknown on plants, it is known with certainty that they can exhibit physiological phenomena associated with exposure to magnetic fields. Reports on magnetic seed treatments dating from the early twentieth century (Sawostin, 1930).

If the magnetic treatments may or may not be a beneficial factor for plants has been discussed for more than a century, although some authors have classified them as a "mysterious force" for plant growth (Eşitken & Turan, 2004). The above description shows that the mechanisms that produce these responses in plants are not clearly known, although there have been breakthrough discoveries in the last 10 years, mainly related to enzyme activity and water uptake in seeds (Radhakrishnan & Kumari, 2012; Vashisth & Nagarajan, 2010a; De Souza et al., 2006). This supports the theory that other mechanisms unrelated to magneto-receptors trigger these responses on seeds subjected to magnetic fields.

Moreover, it is acknowledged the use of magnetic devices for treating water, mainly at the industrial level, as a mechanism to avoid scale formation in pipes (Baker & Judd, 1996). The way in which magnetic fields affect the physical and chemical properties of water, is linked to specific effects on the dissolved ions, the hydrogen bonds, the clustering of water molecules, the viscosity and surface tension (Huo et al., 2011; Pang & Deng, 2008; Chang & Cheng, 2006). However, in this topic also persists several conceptual gaps on the mechanisms that modify the physiology of plants irrigated with magnetically treated water (MTW). The great challenge of producing more food on less arable land, demand the generation and transfer of new agricultural technology, which enhances yield and be environmentally sustainable. In this regard, the magnetic treatment of irrigation water and seeds could be one of the most promising ways in the future to improve agricultural production in an ecological manner (Teixeira da Silva & Dobránszki, 2014).

In this review article will be presented orderly the essential concepts of magnetism, its effects on the properties of water, the studies on its use at the agricultural level, and furthermore, it will be mentioned critically the areas where remaining gaps need to be addressed to make the transition from the pilot phase to the practice.

As a methodology, an exhaustive literature review was donde using five databases, namely: Science Direct, Scielo, ResearchGate, Springer, Redalyc, and Google Academics. The information was systematized and integrated in a friendly way, in order to show it from the broad concepts to the specific ones.

2. Basic concepts of magnetism

It is important to distinguish three essential concepts related to magnetism in materials, which are: ferromagnetism, paramagnetism and diamagnetism. Ferromagnetism is a property of certain metals and their alloys, mainly iron, nickel and cobalt, which can align their electron spins permanently in the presence of a magnetic field (MF), then resulting magnetized. Paramagnetism is a property of many other non-ferromagnetic metals (as aluminum and titanium) which is manifested in a transitory rearrangement of electron spins in the presence of a MF, which makes them attracted by it. On the other hand, substances such as water, organic compounds and living tissues, are considered diamagnetic materials, because their electron spins do not undergo rearrangement in the presence of a MF, and always are repelled by it. This is possible to demonstrate at very high magnetic inductions, as in the famous levitating frog experiment (Berry & Geim, 1997).

In terms of magnetic susceptibility, that is, the degree of magnetization of a given material under the influence of a MF, ferromagnetic materials exhibits very high values for this feature, followed by the paramagnetic, and the diamagnetic having the less magnetic susceptibility. The magnetic field has two interrelated variables, the magnetic intensity (H) and magnetic induction (B), with units of Amperes per meter ($A \cdot m^{-1}$) and Tesla (T), respectively. Regarding the investigation of this article, B and its units Tesla, and submultiples micro Tesla (mT) will be the reference variable and units.

3. Physical and chemical properties of MTW

3.1. Surface tension

Surface tension is one of the most studied properties of MTW. Huo et al. (2011), found a decreasing tension coefficient on the surface of normal and deionised water, reaching a minimum value around 0.4 T - 0.7 T of magnetic treatment. Pang & Deng (2008) reported differences in surface tension of MTW, based on the contact angle of a droplet on a smooth surface of copper and graphite, finding that this angle is slightly lower than in the pure untreated water, which indicates a decrease in hydrophobicity. The above is in accordance with Otsuka & Ozeki (2006), who observed that the contact angle of droplets of MTW was lower than that of untreated water, measured on a copper surface. Other authors as Amiri & Dadkhah (2006), Cai et al. (2009) and Hasaani et al. (2015) also have verified a reduction in surface tension under different experimental conditions (Figure 1).

3.2. Viscosity and evaporation rate

Cai et al. (2009) observed that the activation energy in ultrapure water and the viscosity increased by a practically linear pattern, according to the time of effective exposure to MF. The authors explain that, according to Eyring model, more energy is needed to embed a molecule into the system, which is consistent with the observed changes in viscosity and the theoretical calculations. Chang & Cheng, 2006 indicated that the application of MF decreases the coefficient of self-diffusion of water molecules, which restricts its movement, and therefore modifies its viscosity in the liquid state. However, the authors do not mention whether this change increases or decreases it. According to the Stokes-Einstein equation, the auto-diffusion coefficient and the viscosity are inversely related, so that a reduction of the first means an increase of the second.

Other authors report contradictory findings. Hasaani et al. (2015), found that by treating potable water for a period of two minutes with a magnetic induction of 656 mT, the viscosity was reduced by 23 % compared to control. These results are attributed to the use of ordinary tap water, whose concentration of solutes can alter the molecular interactions between water molecules and within clusters, which are properties very sensitive to MF, as it will be mentioned here after.

As it is indicated by several authors, the water evaporation rate is also affected when is subjected to MF. Yun-Zhu et al. (2012), reported that under a strong MF (more than 8 T), the evaporation rate

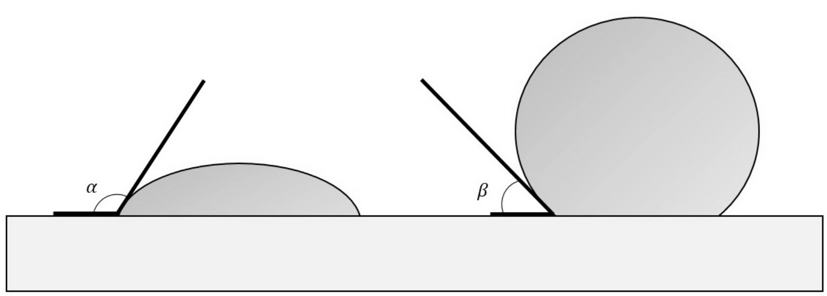

Figure 1. *Changes on the surface tension according the contact angle. α: MTW, β: tap water. Adapted from Otsuka & Ozeki (2006) and Pang & Deng (2008)*

increases significantly. This parameter depends on the surface of the liquid/gas interface, the change in the intensity of the hydrogen bonds and Van der Waals forces, and on the convection rate near the liquid/gas interface. Likewise, the work of Szcześ et al. (2011) point out an increase in the rate of evaporation of water under MF. Holysz et al. (2007) also observed this trend, but they make clear that the rate of evaporation of MTW is altered if it contains electrolytes in solution, in which case a high concentration may cause the opposite effect. This is because the thickness of the hydration layer around the ions affects this property.

3.3. Interaction with radiations

Other physical properties as Raman scattering and X-ray diffraction were used to compare the changes between the MTW and untreated water. In this regard, Otsuka & Ozeki (2006) conducted a careful experiment in vacuum conditions, concluding basically that ultra-pure water does not react to MF, but when it contains air and/or calcium carbonate, changes occur in the Raman bands and the intensity of X-ray diffraction. The first is related to the vibrational and rotational modes of water molecules linked by hydrogen bonds, while the second represents the forms of calcite or aragonite precipitation of calcium carbonate. These means that the MF modify the intermolecular interactions of water and in consequence, promote the formation of aragonite instead of calcite.

Pang & Deng (2008) conducted a wide assessment of radiations, verifying increases in the absorption of infrared and ultraviolet radiation, as well as more pronounced Raman bands and X-ray spectra significantly different. Some of these effects were maintained even several minutes after the removal of the magnetic treatment, suggesting the existence of a magnetic memory of water. Otsuka & Ozeki (2006) also mention this attribute in their work.

Another physical modification of MTW is that the refractive index increases slightly, an effect that was not observed in a nonpolar substance, such as n-hexane. One possible explanation is that the average lifetime of hydrogen bonding is prolonged due to electron delocalization in the molecules of MTW, which affects its optical properties (Hosoda et al., 2004).

One possible explanation for these phenomena is that the MF produces changes in water cluster structure and/or in the formation of clathrates within the gases dissolved in it. Results by Chang & Cheng (2006) showed that more hydrogen bonds were formed under the influence of MF from 1 T to 10 T. This implies that the cluster size of water can be varied according to the applied magnetic induction. According to the experimental and theoretical data given by Toledo et al. (2008), the competition between the intramolecular and intermolecular networks of hydrogen bonds leads to the formation of smaller clusters but with stronger bonds (Figure 2). However Cai et al. (2009) suggest that the magnetic treatment of water exposed to 0.5 T leads to the formation of larger clusters.

Figure 2. *Modification of water clusters due to MF. Left: Tap water; Right: MTW. Based on information by Toledo et al. (2008) Omni Enviro Water Systems*

Finally, it can be said that the effects of MF on water are indifferent to its diamagnetic nature, being more related to its molecular properties, and that those effects are to some extent subordinated to the particles presented in it. Strictly speaking, the concept of magnetization of water *per se* is incorrect, since no rearrangements of their electron spins are generated.

4. Magnetic treatment devices for irrigation water

A system for magnetic treatment of irrigation water consists basically in an unit with permanent magnets which is coupled to a pipe. MF's magnetic induction is usually between tens and hundreds of mili Teslas. Many of the devices are designed so that N-S polarity alternates along the same, or also varying the magnetic induction (Figure 3 and 4).

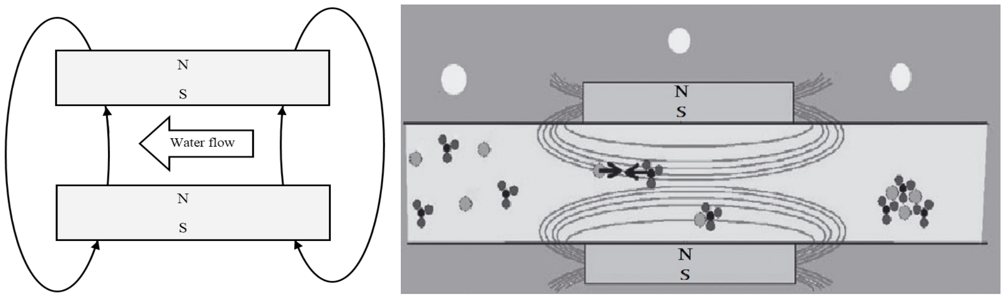

Figure 3. *Magnetic treatment scheme according to two authors. Left: Maheshwari & Grewal (2009) Right: Khoshravesh et al. (2011)*

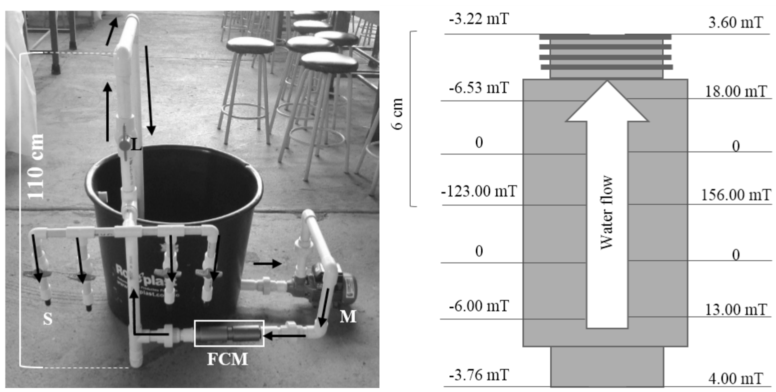

Figura 4. *Left: Magnetic system for irrigation water according to Benavides (2015) L: Water stopcock, S: MTW output connected to the irrigation system, FCM: Magnetic field source, M: Electric pump; the arrows indicate the recirculation in/out flow; Right: Detail of the magnetic induction device from Quantum Biotek (Benavides, 2015)*

The variations in polarity and intensity throughout the device produces more excitation in the water molecules, making their clusters more effectively rearranged. The water flow rate and the effective time of exposure to MF are other variables to consider. Hilal et al. (2013) indicate that when water passes through a MF acquires a magnetic memory which will be held from 24 to 48 hours. The magnetic water treatment will then depend on the intensity of the magnetic field, the composition of dissolved salts and the speed of crossing the source of the MF (Hilal et al., 2013).

Benavides (2015) used the device developed by OmniEnviro exposed in Figure 4 (right) to treat irrigation water in a crop of turmeric (*Curcuma longa L*.). The manufacturer claims that this device differs from the traditional magnets because, besides producing a magnetic field, the gradient of magnetic induction and polarity generates an effective breaking of water clusters. From this device, it can be highlighted the versatility of coupling to a pipeline quickly and safely. Although no studies verify this specific effect on water clusters, Maheshwari & Grewal (2009) note that this device improves yield in some crops but not in others, and leave open the question of how it can affect the properties of soil and water, which indirectly influence plants.

This technology is easy to use and has a low environmental impact because it does not produce waste of any kind nor harmful radiation, and it does not need a power source to operate (Otsuka & Ozeki, 2006). These same authors propose that the Raman spectra and contact angle measurements can both be used as indicators of the degree of MF-interaction with water.

5. MWT effects on plants

The investigation about this issue suggests that changes in the physicochemical properties of MTW might affect directly or indirectly several physiological processes in plants. Hence, supplying MTW to plants produce incremental effects on the growth and development. Several authors have reported that prior exposure of irrigation water to MF leads to an increase in plant productivity and changes in its water and mineral metabolism (Maheshwari & Grewal, 2009; Mulook Al-Khazan et al., 2011; Abou El-Yazied et al., 2012; Hozayn et al., 2013; Mahmood & Usman, 2014).

Maheshwari & Grewal (2009) found that magnetic treatment buffers the deleterious effects of recycled water from a wastewater treatment plant and saline water (1500 ppm and 3000 ppm NaCl), used for irrigation in celery (*Apium graveolens*) and bean (*Phaseolus vulgaris*), using a similar device to that shown in figure 4. The yield and productivity of plants grown with this MTW, was increased almost to the level of those irrigated with quality potable water, and it was higher than that of the plants without magnetic treatment, under controlled greenhouse conditions. These results are consistent to that reported by Marei et al. (2014) who used saline water for irrigation treated with MF, showing a significant increase in yield and in water use efficiency (WUE) in pepper (*Capsicum annuum* L.).

Similar results were obtained by Mahmood & Usman (2014), who evaluated the effect of a magnetic treatment (235 mT; flow 3 L / min) in four types of irrigation water (sewage, saline, irrigation channel and tap) on seed germination of maize (*Zea mays*), submerging them in the water for 24 hours. Some attributes as the rate and speed of germination, the emergence index and the growth of roots and stems underwent significant increases. It was found that MTW promoted germination of maize seeds, reducing the emergency time in 17.90 %.

Ferrari et al. (2015) mention that lettuce plants supplied with a half or a quarter of the water lost by evaporation, increased their biomass (by fresh and dry weight and by root length) when the water was treated with a magnetic device, counteracting the deleterious effect of a limited water supply. However, the authors did not provide a description of the dose of MF or the specifications of the magnetic device.

Other authors have found similar patterns of responses in different crops treated with MTW. For instance, Mulook Al-Khazan et al. (2011) observed that irrigation with MTW at different moisture regimes increased the relative water content and WUE in plants of jojoba (*Simmondsia chinensis*), as well as the content of magnesium, calcium and phosphorus. This effect was preserved even in treatments with lower moisture regime, indicating that the ability of these plants to manage water is optimized because of magnetic treatment. However, the study does not specify the magnetic treatment used.

Hozayn et al. (2013) also reported an increase of 19 % in WUE in sugar beet supplied with MTW compared to that with untreated water. It was observed that this treatment reduced the values of impurities in the recovered sugar by 13 %, 12 % and 16 % for sodium, potassium and amino acids, respectively. There was also an increase in weight and root length, and in total sugars. Unfortunately, these authors did not provide details of the magnetic doses.

Zúñiga et al. (2016), by using two devices Quantum Biotek (3.5 mT - 156 mT) serially coupled to a recirculation system (as shown in figure 4), found that an exposure time of 30 minutes at a flow of 10 L /min, produced significant increases in the growth of turmeric (*C. longa*) under greenhouse conditions. This effect was observed in the length of the main stem, the amount of rhizomes, the number of tillers, and the fresh and dry biomass.

When using MTW it should be considered that the total mass of a plant contains 85 % to 95 % of water, which has a certain percentage of paramagnetic and ferromagnetic metals, and a negligible portion of non-metals. Therefore, it has been stated that not only the effects on water but on the solutes can elicit changes in the metabolism of the plant, in terms of photosynthesis and water absorption (Yano et al., 2004). The Ion-Cyclotron Resonance Theory proposes that the motion of ions across the cell membrane is affected in the presence of MF (Galland & Pazur, 2005). This theory could explain at least the increases in mineral content observed in the latter studies.

Here, we can propose from our own experience and from other authors that the magnetic treatment of irrigation water could contribute to the sustainability of water resources by the exploitation of low quality water, and by more efficient irrigation and WUE in some crops. According to the most verifiable researches, a dose about 100 mT - 200 mT is the most recommended for this purpose.

6. Magnetic treatments applied to seeds

The experimentation about MF applied to seeds is abundant and diverse. Tests have been done from weak magnetic induction, in the order of nanoteslas (nT) to more than 1 T, among exposure times from minutes to days. It is worth mentioning that in many cases it has been evaluated non-static MF, i.e. not generated by permanent ferromagnetic magnets but by electromagnets, which generates a new variable to consider, as the frequency. In general, the technique is straightforward and consists of placing sexual seeds in the middle of two coils prior to imbibition. Subsequently, germination and seedling growth parameters are evaluated. It has been found that the growth and physiological responses arise even in later stages of the treatment of seeds, such as in harvesting of adult plants. Table 1 shows a summary of the most recent and relevant work regarding this topic.

Table 1. *Highlights in magnetic treatments of seeds*

Author	B (Frequency)	Exposition time	Species	Results
Fischer et al. (2004)	20 µT (162/3 Hz)	12 days	*Helianthus annuus* and *Triticum aestivum* seeds	Significant increase in the total fresh weight of *H. annuus* and in roots of *T. aestivum* in relation to water uptake.
De Souza et al. (2005)	120 mT 80 mT (NI)	10 min 5 min	*Solanum lycopersicon* seeds	Significant increases in: fresh and dry weight of roots, stems and leaves in seedlings. Augment in the leaf area in vegetative and productive states. Increase in the RGR in vegetative state but not in productive state. Increase in the number and average weight of fruits.
De Souza et al. (2006)	90 mT 154 mT (NI)	10 min 3 min	*Solanum lycopersicon* seeds	Significant rises in the dry weight of leaves and leaf area during the vegetative period on both treatments. Increments in the RGR of leaves, stems and roots during this stage. Increase in the total dry weight on both treatments. Significant gain in the weight of fruits per plant on both treatments, but not on the number of fruits.
Flórez et al. (2007)	125 mT 250 mT (NI)	1, 10, 20 min 1, 24 h Continuous	*Zea mays* seeds	Reduction in the average germination time when the seeds were continuously exposed to the magnetic field. Higher length of plants at the seventh day of germination. Increase in the fresh weight of the seedlings exposed continuously.

Table 1. *Highlights in magnetic treatments of seeds*

Vashisth & Nagarajan (2008)	50 mT 100 mT 150 mT 200 mT 250 mT (NI)	1, 2, 3 and 4 h	*Cicer arietinum* seeds	Improved dry weight, length of shoots and roots, speed of germination and seedlings vigor. Rises in stem and root length and dry weight. Decrease in the electrical conductivity of seed tissue, which indicates major integrity of the cell membrane.
Nimmi & Madhu (2009)	62 µT (NI)	4, 8, 12 and 24 h	*Capsicum frutescens* seeds	Significant increase in the length of germinated seedlings and in the germination velocity.
Domínguez-Pacheco et al. (2010)	160 mT 560 mT (NI)	30, 60, 120, 240, 360 and 480 min	*Zea mays* seeds	Better physiological quality of the seed, higher dry weight of the aerial part, emergency speed and establishment percentage.
Vashisth & Nagarajan (2010a)	50 mT 100 mT 150 mT 200 mT 250 mT (NI)	1, 2, 3 and 4 h	*Helianthus annuus* seeds	Increase in the rate and germination speed, root and shoot length and dry weight. Significant increase at field test, in the length and dry weight of roots and shoots. Greater activity of α-amylase, protease and dehydrogenase enzymes.
Vashisth & Nagarajan (2010b)	100 mT 200 mT (NI)	1 and 2 h	*Zea mays* seeds var. Ganga Safed-2	Augmented water transport in the tissues to mobile and metabolically available forms in treated seeds. Higher activity of the enzymes α-amylase, protease and dehydrogenase during imbibition.
Shine et al. (2011)	50 mT 100 mT 150 mT 200 mT 250 mT 300 mT (NI)	30, 60 and 90 min	*Glycine max* seeds	Greater water absorption, speed of germination, seedling length, fresh weight, dry weight, and seed vigor under laboratory conditions. The initial magnetic effect persisted in plants after germination and led to increased photosynthetic efficiency, by quantum efficiency of photosystem II. Increasing in the concentration of the photosynthetic enzyme Rubisco contributed to a higher carbon fixation under field conditions.
Hajnorouzi et al. (2011)	22 µT (10 KHz)	5 h day per 4 days	*Zea mays* cv. 704 seeds	Superoxide dismutase activity was significantly reduced in treated seeds as well as iron content, indicating lesser oxidative stress and improved membrane integrity. Lower calcium content.
Radhakrishnan & Kumari (2012)	1500 nT (10 Hz)	5 h day per 20 days	*Glycine max* seeds	Significant increase in the viability of treated seeds. Eight-day seedlings exhibited greater height, fresh and dry weight. Higher protein content. Reduction in the activity of α-amylase, but increased activity of β-amylase and other enzymes. Larger number of leaves per plant and seeds per pod.
Bhardwaj et al. (2012)	50 mT 100 mT 150 mT 200 mT 250 mT (NI)	1, 2 and 3 h	*Cucumis sativus* var. Barsati seeds	Increment in germination rate, length and dry weight of roots and shoots. Greater water uptake and activity of β-amylase and protease enzymes. Major activity of antioxidant enzymes, particularly catalase and glutathione reductase.
Jiménez et al. (2013)	30 mT 60 mT (NI)	30, 60 and 120 min	*Capsicum frutescens* seeds	Significant differences in the rate of germinated seeds per day, showing that with increasing intensity and time of exposure to MF, a reducing germination time was achieved. The treatments had an effect on the germination time but not in the percentage of germination of pepper.

NI: Not indicated; RGR: Relative growth rate

Despite these promising results, so far there is no magnetic treatment for seeds reliable and available in the market. The device that showed to have the most consistent trends is described by Vashisth et al. (2008, 2010a, 2010b), basically two coils with variable distance between them. Further specifications are provided in detail in their papers (Figure 5).

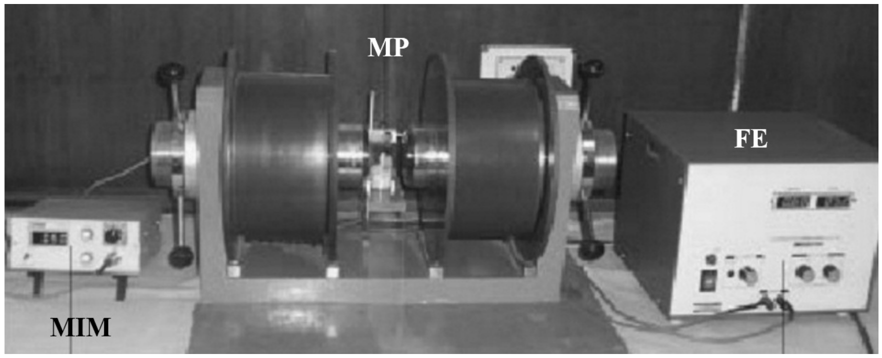

Figure 5. *Testron EM-20 magnetic field generator. MIM: magnetic induction meter, MP: sample located between the pole pieces, FE: Power supply (Vashisth et al., 2010a)*

Although seed magnetic treatments generally produce beneficial effects, some reports of adverse effects are known (Table 2). Apparently, exposing seeds to weak MF (in the order of nano and micro Tesla) of low frequency causes these responses, but more recent studies are needed. For a more complete review in this regard, refer to the work of Zhadin (2001). This author made a very detailed review of the research about MF interactions with biological systems carried out in the former Soviet Union, which for linguistic and cultural issues remained hidden to the Western world.

Table 2. *Deleterious effects of magnetic fields on plants*

Author	B (Frequency)	Species	Results
Kursevich & Travkin (1973)	50 nT (NI)	Bean, barley, millet and peas	Inhibition of root growth.
Bogatina et al. (1978 & 1979) and Sytnik et al. (1984)	0.5 µT, 2 µT (NI)	Wheat, beet, peas	Inhibition of growth of wheat seedlings, beets and peas, at least during the time of exposure to such fields.
Ben-Izhak et al. (2003)	0.7 mT (50Hz a 100Hz)	*Spirodela oligorrhiza*	Accumulation of stress-related metabolites, mainly alanine.
Nanush'yan & Murashev (2003)	Variable magnetic fields similar to the geomagnetic	Onion	Abnormalities in cells of apical meristems of onion, as polyploidy, and multinucleated giant cells.
Yano et al. (2004)	48 µT, 50 µT (60Hz)	*Raphanus sativus*	Decrease in CO_2 assimilation rate, fresh weight, dry weight and leaf area in relation to control plants.

NI: Not indicated.

At a physiological level, several mechanisms have been proposed to explain the effect of MF in the metabolism of germinating seeds. Shine et al. (2011) mention that reactive oxygen species (ROS) act as a signal that leads to improved germination of soybean seeds treated with MF.

Increased ROS production in these seeds is facilitated by the oxidative reaction of peroxidase, while its antioxidant capacity promotes scavenging of the excess of free radicals. Therefore, the balance between ROS production and its scavenging has an improving effect on the germination of seeds treated magnetically.

Moreover, Balouchi & Sanavy (2009) mention that the MF affects the structure of cell membranes and this way increases the permeability and transport of ions through ion channels, affecting several metabolic activities. This finds support in the results of Vashisth & Nagarajan (2010a), who found that exposure of sunflower seeds to 50 mT - 250 mT strengthen membrane integrity, while lowering cell filtering and electrical conductivity. As it is known, low quality seeds have poor membrane structure; as a result, high levels of filtration are characteristic of seed lots of low vigor, even those with acceptable levels of germination. Conversely, seed lots with low electrolyte leakage (measured as low electrical conductivity) during imbibition are considered of high vigor (AOSA, 2009).

Other mechanisms involve equilibrium of radical pairs in chemical reactions mediated by enzymes or by light, which can be altered under the influence of a MF. This phenomena was observed in the practice by Kuciauskas et al. (1998) and theoretically modeling by Adair (1999).

7. Effects of MTW in soils and irrigation systems

Magnetic treatment of irrigation water has proved to influence the precipitation of salts, the concentration of ions, the pH and the electrical conductivity. This directly affects the performance of irrigation systems, particularly the drip one, whose disadvantage is having obstructions by scale formation. The technology here presented has been used as an alternative of application of strong acids to prevent clogging of drip emitters. For example, Aali et al. (2009) indicated that the magnetic treatment of water slightly decreased flow losses in drip emitters, but was less effective than the application of sulfuric acid. However, it is worth mentioning that it is a greener and safer option.

Other effects of MTW on the soil is related to a greater movement of several ions in the soil solution, as well as to changes in the moisture profile. In table 3 some of the most important results are summarized thereon.

Table 3. *MTW relationship with soil and irrigation systems*

Author	Water type	Dose	Results
Noran et al. (1996)	Tap water	0.9 m^3/h, MF not specified	Decreased movement of minerals in the soil at short distance from emitters, especially Ca, Mg and P.
Duarte et al. (2004)	Tap water	Not provided	Major irrigation uniformity and average flow per emitters. Lower clogging by precipitation of salts.
Maheshwari & Grewal (2009)	Tap water, saline and recicled from waste water plant	10 mL/s, 3.5 – 136 mT effective exposure of about 3 s	Reduction in soil pH, particularly when using normal and saline water. Increase in electrical conductivity, available extractable phosphorus and potassium in the soil, when using the three types of water.
Khoshravesh et al. (2011)	Saline	Flow not specified, MF 0.3 T	Average soil moisture at different depths, under drip system, was higher compared to the water without magnetizing.
Mostafazadeh-Fard et al. (2011)	Saline	Not provided	The average concentration of sulfates in the area of wet bulb was lower when using MTW compared to untreated water in a drip irrigation system. Potential benefits to reclaim saline soils.
Grewal & Maheshwari (2011)	Deionised	10 mL/s, 3.5 – 136 mT effective exposure of about 3 s	The pH values of MTW underwent a significant reduction, from 5.75 to 5.71. electrical conductivitywas found to have an increase from 0.991 to 0.995 mS/cm. However, there was no effect on N, P and K contents of water.
Sadeghipour & Aghaei (2013)	Tap water	Not provided	Reduction in electrical conductivity and in the content of Ca^{2+}, Mg^{2+} and hardness ($CaCO_3$) in the water used for irrigation.

Several theories have been proposed for explaining the interactions between MTW, the minerals and soil particles. Khoshravesh et al. (2011) theorize that in the magnetization process, water molecules react with the ions, loosening from the Van der Waals forces and the hydrogen bonding, to become more cohesive to the surroundings. Hence, the water molecules are more easily linked to soil particles, penetrating the micropores of the soil and preventing to move to greater depths. This can be correlated to the lesser hydrophobicity of MTW observed in other studies.

It is known that carbonate precipitation process is altered when water is subjected to MF. Alimi et al. (2006) mention that the formation of crystals of calcium carbonate in MTW goes through a process of homogeneous nucleation which leads to the formation of calcite and aragonite, while in normal water there is predominantly vaterite. Similarly, Kney & Parsons (2006) report a faster rate of calcium carbonate precipitation at different pH conditions using MTW. These processes are mediated by magneto-hydrodynamic mechanisms (dependent on water flow rate), or by hydration of cations (changes in proton transfer to the water molecule due to MF).

The above results indicate that the MTW improves overall crop conditions indirectly, by modifying water or soil features. This finds support in Maheshwari & Grewal (2009), who attributed the relatively higher soil acidification in the rhizosphere of celery and peas plants irrigated with MTW to a greater release of organic acids. Organic acids released into the rhizosphere may be responsible for better availability of nutrients for the plant. Zúñiga et al. (2011) indicate that the magnetic treatment of water and bio-fertilizer solution was an effective technology for the recovery of salt-affected soils, since it accelerates microbial activity, decreases the time of reclamation and enriches the soil. This in turn improved the yield of maize grown under this treatment.

8. Conclusions

Although one cannot speak *sensu stricto* of "magnetization" of water, experimentation has shown that several physicochemical and molecular effects occur when it is subjected to MF, which are manifested in the surface tension, the formation of clusters, the viscosity, the rate of evaporation and the absorption of different wavelengths. We here propose that these changes are responsible, directly or indirectly, of the positive responses in growth, development and production of various crops when irrigated with MTW.

The optimal buffering of the detriments caused by adverse conditions using MTW, gives a chance to its widespread use in agriculture. In particular, the magnetic treatment of irrigation water is an applicable alternative in Colombia, where conditions as poor water quality, salinity and unavailability of nutrients in the soil are presented. Additionally, this technology could optimize water use in crop production, since it also moderates the effect of a limited water supply.

Improving germination and vigor of seeds by magnetopriming is an option to consider if there are no high quality seeds available. It is concluded that the later increase in the final production of crops emerged from seeds so-treated is the result of higher seedling vigor.

This technology does not generate wastes of any kind, does not emit harmful radiation and neither does require power, so it is environmentally friendly and sustainable. However, there is a needing of further research, since the variety of magnetic devices tested makes it difficult to apply. Current knowledge allows us to say that the technology of magnetic treatment of irrigation water and seeds, alone or combined with others, is an interesting alternative tool for improving productivity in crops, with negligible deleterious effects.

9. References

Aali, K.H., Liaghat, A. & Dehghanisanij, H. (2009). The effect of acidification and magnetic field on emitter clogging under Saline Water Application. *Journal of Agricultura Sciencie* 1 (1), 132-141.

Abou El-Yazied, A., El-Gizawy, A.M., Khalf, S.M., El-Satar, A. & Shalaby, O.A. (2012). Effect of magnetic field treatments for seeds and irrigation water as well as N, P and K levels on productivity of tomato plants. *Journal of Applied Sciences Research* 8 (4), 2088-2099.

Adair, R.K. (1999). Effects of very weak magnetic fields on radical pair reformation. *Bioelectromagnetics* 20 (4), 255-263.

Alimi, F., Tlili, M., Gabrielli, C., Maurin, G. & Ben-Amor, M. (2006). Effect of a magnetic water treatment on homogeneous and heterogeneous precipitation of calcium carbonate. *Water research* 40 (10), 1941-1950.

Amiri, M.C. & Dadkhah, A.A. (2006). On reduction in the surface tension of water due to magnetic treatment. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 278 (1-3), 252–255.

AOSA (Association of Official Seed Analysts). (2009). *Seed Vigor Testing Handbook Contribution No. 32 to the handbook on seed testing*, Ithaca, New York, United States of America.

Baker, J.S. & Judd, S.J. (1996). Magnetic amelioration of scale formation. *Water Research* 30, 247-260.

Berry, M.V. & Geim A.K. (1997). Of flying frogs and levitrons. *European Journal of Physics* 18, 307-313.

Balouchi, H.R. & Sanavy, S.A.M.M. (2009). Electromagnetic field impact on annual medics and dodder seed germination. *International Agrophysics* 23 (2), 111-115.

Ben-Izhak, M.E., Parola A.H., & Kost, D. (2003). Low-frequency electromagnetic fields induce a stress effect upon higher plants, as evident by the universal stress signal, alanine. *Biochemical and Biophysical Research Communications* 302 (2), 427-434.

Benavides, B.J. (2015). *Respuesta del cultivo de cúrcuma (Curcuma longa) a la aplicación de biofertilizante líquido estimulado electro-magnéticamente y de agua de riego estimulada magnéticamente*. Tesis de pregrado para optar el título de ingeniero agrícola, Escuela de Ingeniería de los Recursos Naturales y del Ambiente, Facultad de Ingenierías, Universidad del Valle, sede Meléndez, Cali, Colombia.

Bhardwaj, J., Anand, A. & Nagarajan, S. (2012). Biochemical and biophysical changes associated with magnetopriming in germinating cucumber seeds. *Plant Physiology and Biochemistry* 57, 67-73.

Bogatina, N.I., Verkin, B.I. & Kordyum, V.A. (1978). Effect of permanent magnetic fields with different intensities on the wheat growth rate. *Doklady Akademii Nauk* SSSR 4, 352-356.

Bogatina, N.I., Verkin, B.I., Kulabukhov, V.M., Litvin, V.M. & Nikulina, V.F. (1979). Determination of sensitivity threshold of wheat seedlings and roots to magnetic field value. *Plant physiology* 26 (3), 620-624.

Cai, R., Yang, H., He, J. & Zhu, W. (2009). The effects of magnetic fields on water molecular hydrogen bonds. *Journal of Molecular Structure-Theochem* 938, 15-19.

Chang, K. & Cheng-I, W. (2006). The effect of an external magnetic field on the structure of liquid water using molecular dynamics simulation. *Journal of Applied Physics* 100 (4), 043917-1 – 043917-6.

De Souza, A., García, D., Sueiro, L., Licea, L., & Porras, E. (2005). Pre-sowing magnetic treatment of tomato seeds: effects on the growth and yield of plants cultivated late in the season. Spanish *Journal of Agricultural Research* 3 (1), 113-122.

De Souza, A., García, D., Sueiro, L., Gilart, F., Licea, L. & Porras, E. (2006). Pre-sowing magnetic treatments of tomato seeds increase the growth and yield of plants. *Bioelectromagnetics* 27 (4), 247 – 257.

Domínguez-Pacheco, A., Hernández-Aguilar, C., Cruz-Orea, A., Carballo-Carballo, A., Zepeda-Bautista, R. & Martínez-Ortíz, E. (2010). Semilla de maíz bajo la influencia de irradiación de campos electromagnéticos. *Revista fitotecnia mexicana* 33 (2), 183-188.

Duarte, C., Guevara, G. & Méndez, M. (2004). Uso del agua activada y con tratamiento magnético del tomate en condiciones de organopónico. *Revista Ciencias Técnicas Agropecuarias* 13 (3), 1010-2760.

Eşitken, A. & Turan, M. (2004). Alternating magnetic field effects on yield and plant nutrient element composition of strawberry *(Fragaria x ananassa cv. Camarosa). Acta Agriculturae Scandinavica, Section B - Soil & Plant Science* 54 (3), 135-139.

Ferrari, F., Almeida, L., Klar, A., Ferreira da Silva, J., Pires, C. & Ludwig, R. (2015). Response of lettuce crop to magnetically treated irrigation water and different irrigation depths. *African Journal of Agricultural Research* 10 (22), 300-2308.

Fischer, G., Tausz, M., Köck, M. & Grill, D. (2004). Effects of weak 162/3 Hz magnetic fields on growth parameters of young sunflower and wheat seedlings. *Bioelectromagnetics* 25 (8), 638-641.

Flórez, M., Carbonell, M.V. & Martínez, E. (2007). Exposure of maize seeds to stationary magnetic fields: Effects on germination and early growth. *Environmental and Experimental Botany* 59 (1), 68-75.

Galland, P. & Pazur, A. (2005). Magnetoreception in plants. *Journal of Plant Research* 118 (6), 371-389.

Grewal, H.S. & Maheshwari, B.L. (2011). Magnetic treatment of irrigation water and snow pea and chickpea seeds enhances early growth and nutrient contents of seedlings. *Bioelectromagnetics* 32 (1), 58-65.

Hajnorouzi, A., Vaezzadeh, M., Ghanati, F., Jamnezhad, H. & Nahidian, B. (2011). Growth promotion and a decrease of oxidative stress in maize seedlings by a combination of geomagnetic and weak electromagnetic fields. *Journal of Plant Physiology* 168 (10), 1123-1128.

Hasaani, A.S., Hadi, Z.L. & Rasheed, K.A. (2015). Experimental study of the interaction of magnetic fields with flowing water. *International Journal of Basics and Applied Science* 3 (3), 1-8.

Hilal, M.H., El-Fakhrani, Y.M., Mabrouk, S.S., Mohamed, A.I. & Ebead, B.M. (2013). Effect of magnetic treated irrigation water on salt removal from a sandy soil and on the availability of certain nutrients. *International Journal of Engineering and Applied Sciences* 2 (2), 36-44.

Holysz, L., Szczes, A. & Chibowski, E. (2007). Effects of a static magnetic field on water and electrolyte solutions. *Journal of Colloid and Interface Science* 316 (2), 996-1002.

Hosoda, H., Mori, H., Sogoshi, N., Nagasawa, A. & Nakabayashi, S. (2004). Refractive indices of water and aqueous electrolyte solutions under high magnetic fields. *Journal of physical chemistry A* 108 (9), 1461-1464.

Hozayn, M., Abd-El Monem, A.A., Abdelraouf, R.E. & Abdalla, M. (2013). Do magnetic water affect water efficiency, quality and yield of sugar beet (*Beta vulgaris L.*) plant under arid regions conditions? *Journal of Agronomy* 12 (1), 1-10.

Huo, Z.F., Zhao, Q. & Zhang, Y.H. (2011). Experimental study on effects of magnetization on surface tension of water. *Procedia Engineering* 26, 501-505.

Jiménez, C., Méndez, M., Daza, M.C. & Zúñiga, O. (2013). Germinación de semillas de ají (*Capsicum sinense*) estimuladas electromagnéticamente. *Revista Colombiana de Ciencias Hortícolas* 7 (1) 46-54.

Khoshravesh, M., Mostafazadeh-Fard, B., Mousavi, S.F. & Kiani, A.R. (2011). Effects of magnetized water on the distribution pattern of soil water with respect to time in trickle irrigation. *Soil Use and Management* 27 (4), 515-522.

Kuciauskas, D., Liddell, P.A., Moore, A.L., Moore, T.A. & Gust, D. (1998). Magnetic switching of charge separation lifetimes in artificial photosynthetic reaction centers. *Journal of the American Chemical Society* 120 (42), 10880-10886.

Kney, A.D. & Parsons, S.A. (2006). A spectrophotometer-based study of magnetic water treatment: Assessment of ionic vs. surface mechanisms. *Water Research* 40 (3), 517-524.

Kursevich, N.V. & Travkin, M.P. (1973). *Effects of magnetic fields with different intensities on some enzymes' activities in barley seedlings*. In: Belgorod Teacher's Training College Publishing Co., Effects of Natural and Weak Artificial Magnetic Fields on Biological Objects. Belgorod, Russia. pp. 102-104.

Lohman, K.J. & Johnsen, S. (2000). The neurobiology of magnetoreception in vertebrate animals. *Trends in Neurosciences* 23, 153-159.

Maheshwari, B.L. & Grewal, H.S. (2009). Magnetic treatment of irrigation water: Its effects on vegetable crop yield and water productivity. *Agricultural Water Management* 96 (8), 1229-1236.

Mahmood, S. & Usman, M. (2014). Consequences of Magnetized Water Application on Maize Seed Emergence in Sand Culture. *Journal of Agricultural Science & Technology* 16 (1), 47-55.

Marei, A., Rdaydeh, D., Karajeh, D. & Abu-Khalaf, N. (2014). Effect of Using Magnetic Brackish Water on Irrigated Bell Pepper Crop (*Capsicum annuum* L.) Characteristics in Lower Jordan Valley/West Bank. *Journal of Agricultural Science and Technology A* 4, 830-838.

Mostafazadeh-Fard, B., Khoshravesh, M., Mousavi, S.F. & Kiani, A.R. (2011). *Effects of magnetized water on soil sulphate ions in trickle irrigation*. In 2nd International Conference on Environmental Engineering and Applications, IACSIT Press, Singapore, p. 94-99.

Mulook Al-Khazan, Batoul M. & Nabila Al-Assaf (2011). Effects of magnetically treated water on water status, chlorophyll pigments and some elements content of Jojoba (*Simmondsia chinensis* L.) at different growth stages. *African Journal of Environmental Science and Technology* 5 (9), 722-731.

Nanush'yan, E.R., Murashev, V.V. (2003). Induction of multinuclear cells in the apical meristems of *Allium cepa* by geomagnetic outrages. *Russian Journal of Plant Physiology* 50 (4), 522-526.

Nimmi, V. & Madhu, G. (2009). Effect of pre-sowing treatment with permanent magnetic field on germination and growth of chilli (*Capsicum annum* L.). *International Agrophysics* 23 (2), 195-198.

Noran, R., Shani, U. & Israel, L. (1996). The effect of irrigation with magnetically treated water on the translocation of minerals in the soil. *Magnetic and Electrical Separation* 7 (2), 109-122.

Otsuka, I. & Ozeki, S. (2006). Does magnetic treatment of water change its properties? *Journal of Physical Chemistry* B 110 (4), 1509-1512.

Pang, X. & Deng, B. (2008). Investigation of changes in properties of water under the action of a magnetic field. *Science in China Series G: Physics, Mechanics & Astronomy* 51 (11), 1621-1632.

Radhakrishnan, R. & Kumari, B.D.R. (2012). Pulsed magnetic field: A contemporary approach offers to enhance plant growth and yield of soybean. *Plant Physiology and Biochemistry* 51, 139-144.

Sadeghipour, O. & Aghaei, P. (2013). Improving the growth of cowpea (*Vigna unguiculata* L. Walp.) by magnetized water. *Journal of Biodiversity and Environmental Sciences* 3 (1), 37-43.

Sawostin, P.W. (1930). *Magnetic growth reaction in plants. Planta* 12, 265-269.

Shine, M.B., Guruprasad, K.N. & Anand A. (2011). Enhancement of germination, growth, and photosynthesis in soybean by pre-treatment of seeds with magnetic field. *Bioelectromagnetics* 32 (6), 474-484.

Sytnik, K.M., Kordym, E.L., Nedukha, E.M., Sidorenko, P.G. & Fomicheva, V.M. (1984). Plant cell under alterations in geophysical factors. *Naukova Dumka*, Kiev.

Szcześ, A., Chibowski, E., Hołysz, L. & Rafalski, P. (2011). Effects of static magnetic field on water at kinetic condition. *Chemical Engineering and Processing: Process Intensification* 50 (1), 124-127.

Teixeira da Silva, J. & Dobránszki, J. (2014). Impact of magnetic water on plant growth. *Environmental and Experimental Biology* 12, 137-142.

Toledo, E.J.L., Ramalho, T.C., Magriotis, A.M. (2008). Influence of magnetic field on physical–chemical properties of the liquid water: Insights from experimental and theoretical models. *Journal of Molecular Structure* 888 (1-3), 409-415.

Vashisth, A. & Nagarajan, S. (2008). Exposure of seeds to static magnetic field enhances germination and early growth characteristics in chickpea (*Cicer arietinum* L.). *Bioelectromagnetics 29 (7), 571-578.*

Vashisth, A. & Nagarajan, S. (2010a). Effect on germination and early growth characteristics in sunflower (*Helianthus annuus*) seeds exposed to static magnetic field. *Journal of Plant Physiology* 167 (2), 149-156.

Vashisth, A. & Nagarajan, S. (2010b). Characterization of water distribution and activities of enzymes during germination in magnetically-expose maize (*Zea mays* L.) seeds. *Indian Journal of Biochemistry Biophysics* 47 (5), 311-318.

Yano, A., Ohashi, Y., Hirasaki, T. & Fujiwara, K. (2004). Effects of 60 Hz magnetic field on photosynthetic uptake and early growth of radish seedlings. *Bioelectromagnetics* 25 (8), 572-581.

Yun-Zhu, G., Da-Chuan, Y., Hui-Ling, C., Jian-Yu, S., Chen-Yan, Z., Yong-Ming, L., Huan-Huan, H., Yue, L., Yan, W., Wei-Hong, G., Ai-Rong, Q. & Peng, S. (2012). Evaporation rate of water as a function of a magnetic field and field gradient. *International Journal of Molecular Sciences* 13 (12), 16916-16928.

Zhadin, M.N. (2001). Review of Russian literature on biological action of DC and low-frequency AC magnetic fields. *Bioelectromagnetics* 22, 27-45.

Zúñiga, O., Osorio, J., Cuero, R. & Peña, J. (2011). Evaluación de tecnologías para la recuperación de suelos degradados por salinidad. *Revista Facultad Nacional de Agronomía Medellín* 64 (1), 5769-5779.

Zúñiga, O., Benavides, J.A., Jiménez, C.O., Gutiérrez, M.A. & Torres, C. (2016). Efecto del agua tratada magnéticamente en el desarrollo y la producción de cúrcuma (*Curcuma longa* L.). *Revista Colombiana de Ciencias Hortícolas* (en impresión).