



Magnetic field regulates plant functions, growth and enhances tolerance against environmental stresses

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Abstract Global climatic fluctuations and the increasing population have been responsible for the decline in the crop productivity. The chemical fertilizers, pesticides, and suitable genetic resources are commonly used for improving the crop yield. Magnetic field (MF) therapy for plants and animals has been found to be an effective and emerging tool to control diseases and increase tolerance against the adverse environment. Very limited studies have been attempted to determine the role of MF on plant tolerance against various stress conditions. This review aims to highlight the mitigating effect of MF on plants against abiotic and biotic stresses. MF interacts with seeds and plants and accelerates metabolism, which leads to an improved germination. The primary and secondary metabolites, enzyme activities, uptake of nutrient and water are reprogrammed to stimulate the plant growth and yield under favorable conditions. During adverse conditions of abiotic stress such as drought, salt, heavy metal contamination in soil, MF mitigates the stress effects by increasing antioxidants and reducing oxidative stress in plants. The stunted plant growth under different light and temperature conditions can be overcome by the exposure to MF. An MF treatment lowers the disease index of plants due to the modulation of calcium signaling, and proline and polyamines pathways. This review explores the basic and recent information about the impact of MF on plant survival against the adverse environment and emphasizes that thorough research is required to elucidate the mechanism

of its interaction to protect the plants from biotic and abiotic stresses.

Keywords Diseases · Drought · Heavy metals · Magnetic field · Plant growth · Salt

Introduction

The earth is a giant magnet and its geomagnetic field (GMF) has a huge impact on the productivity of crops. Specifically, the electromagnetic radiations coming from the sun stimulate the growth and development of plants through the process of photosynthesis. The other possibility to increase plant growth could be a alteration in electrostatic balance of the plant system at the cell membrane level, as it is the primary of plant growth. The GMF can influence basic biological functions such as rhythmicity (Wever 1968), orientation (Brown 1962), and development (Asashima et al. 1991). The effects of the magnetic field (MF) on plants, fungi, and microbes can be elucidated by ion-cyclotron-resonance (ICR) and the radical-pair model. These two mechanisms also play an essential role in the magneto-reception of organisms.

Many scientists have proposed various theories about the biological effects of MF, these are as follows: a moving electric charge generates an MF around it (like an electron, ion or polarized particle). The organic material, constituting living organisms, has a polar structure due to various polarized chemical bonds, which may be linked to water molecules and dissociated mineral salts conferring magnetic properties (Chepts et al. 1985). The hypothetical interaction of weak magnetic field (WMF) and the living organism has been proposed by Binhi (2001). The experimental analysis of electromagnetic fields (EMF) applied to

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biological systems has gained a rapid interest in the past few years. The applications of MF are being explored in several areas, particularly in the agricultural science. The effects of MF on seed germination, biochemical, hormonal changes, plant growth, and yield have been subject to several investigations. The enhancement of growth in crops under precise magnetic conditions has been confirmed but a systematic and extensive study is still necessary to delineate the mechanisms of magnetic action in cells and tissues. Although attempts have been made to understand the mechanisms of action of extremely low-frequency EMFs in biological systems, still more detailed studies need to be undertaken (Belyavskaya 2004).

An application of 20–30 mT of MF on crop plants revealed an enhancement in their growth. The plant cells contain ferritin and each cell has about 4500 iron atoms involved in growth and metabolism. The magnetic rotator moment of ultimate iron atoms creates an external MF, and collectively generates oscillations, which generate energy and finally re-position the atoms in the direction of MF. This increases the temperature in plants, which depends upon the duration and the frequency of MF treatment (Vaezzadeh et al. 2006). WMF modulates cryptochrome and phytochrome mediated plant responses in plants (Dhiman and Galland 2018). Very limited information is available on the molecular basis and the function of the putative WMF receptors and their activation by physiological signals, therefore their involvement in directing the overall response in different plant organs is yet to be determined.

Savostin (1930) first reported a two-fold increase in wheat seedling elongation under MF. Murphy (1942) observed the positive effects of MF on seed germination. Audus (1960) and Pittman (1965) also studied a strong magnetotropic effect on root development. MF influences the normal tendency of Fe and Co atoms and utilizes their energies to continue the translocation of microelements in root meristems, which leads to an increased plant growth (Mericle et al. 1964). The different dosage of MF alters the root biomass, stems girth, and leaf size. Further, the root growth is more sensitive than shoots to MF (Kato 1988; Kato et al. 1989; Smith et al. 1993). The pretreatment of seeds by MF resulted in seedling growth, seed vigor, and increased crop yield (Pieturszewski 1993). MF accelerates growth by triggering the protein synthesis and activates the root tropism by altering the intracellular movement of amyloplasts in the statocyst of root cap cells (Kuznetsov et al. 1999; Pieturszewski 1999). A positive effect on seed germination, uptake of nutrients, flowering, and crop yield can be achieved by applying MF (Duarte-Diaz et al. 1997; Samy 1998; Souza-Torres et al. 1999). MF treatments also affect the plant metabolisms that involve free radicals and stimulate the activity of proteins and enzymes to enhance seed vigor (Morar et al. 1993).

The effects of continuous as well as pulsed MF on plant growth and development have been investigated in a large number of plant species (Yano et al. 2001). Aladadjijyan (2002) revealed that the exposure of MF (150 mT) stimulated shoot development which led to an increase in the germination, fresh weight, and shoot length in maize. The mechanism of action of MF on plant growth promotion is still not very clearly understood, therefore an optimal external EMF may accelerate the plant growth, especially seed germination (Esitken and Turan 2004). Yinan et al. (2005) observed a positive effect of MF pretreatment on cucumber seedlings by stimulating seedling growth and development. The promotion of seed germination and the growth of plants depend on the magnetic flux densities, frequencies, and pretreatment of the plant material (Davies 1996).

Several harsh environmental conditions such as drought, salinity, low or high temperatures, flood, pollution, radiation, and diseases are the important stress factors that adversely affect the growth, metabolism, and the yield of plants and thereby limit the productivity of crops (Lawlor 2002). The productivity of plants can be increased by the application of plant growth promoting substances, microbial inoculation to the soil, organic and inorganic manure and several other non-conventional approaches such as plant breeding and genetic engineering (Radhakrishnan and Lee 2013; Radhakrishnan et al. 2014; Radhakrishnan et al. 2015). The application of MF is a novel approach to improve plant growth and the overall productivity (Radhakrishnan and Ranjitha-Kumari 2012; Maffei 2014).

Plant growth promoting effect of MF on plant physiology under favorable condition: seed germination

Many researchers reported an increase in seed germination under MF exposure. MF stimulates the initial growth stages and early sprouting of seeds (Carbonell et al. 2000). Recently, Radhakrishnan and Ranjitha-Kumari (2012) observed an increased rate of seed germination in soybean under pulsed MF. Morar et al. (1993) also reported that MF influences the free radical formation and stimulates the activity of proteins and enzymes to enhance the seed vigor. The paramagnetic properties of plastid may be responsible for the enhanced seed vigor. MF increases the energy in plants and disperses this energy to biomolecules, which in turn stimulates the metabolism to enhance the seed germination. A metabolically active plant cell contains free radicals that play a vital role in electron transfer and the kinetics of biochemical reactions. These free radicals possess non-paired electrons with magnetic activities that can be oriented under an external MF. The microwave

energy is absorbed as a result of the interaction between the external MF and the magnetic action of unpaired electrons. Finally, this energy is converted into a chemical form and accelerates the fundamental processes in seeds (Commoner et al. 1954). The overall effects of MF on crop plants are summarized in Fig. 1 and Table 1.

Vegetative growth phase

MF positively influences the growth of plants by increasing shoot and root length (Dayal and Singh 1986; Florez et al. 2007). Root growth depends upon the cell division in the root meristems and subsequent differentiation and elongation of the descendant cells (Beemster and Baskin 1998). The root cap cells were notably larger and the metaxylem cells became significantly longer starting from the quiescent center to periphery in MF treated plants. The induction of metaxylem cells by EMF is an important component of the increase in the rate of root elongation (Bitonti et al. 2006). MF exposure to seeds accelerates their growth, activates protein formation and the root growth (Pieturszewski 1999). In an experiment, sunflower seedlings exposed to MF showed a substantial increase in the shoot and root fresh weight (Fischer et al. 2004). MF treated plants also showed, at the vegetative stage, a significantly larger leaf area and higher leaf dry weight than the controls. This effect may be attributed to the increased photosynthetic rates due to the better perception of light and nutrients available for vegetative growth (Souza-Torres et al. 1999, 2006).

Reproductive growth phase

Very limited studies have documented the effect of MF on reproductive development in crops. Matsuda et al. (1993) reported that MF enhanced the yield in strawberry. Similar effects were also witnessed for flax, buckwheat, pea, wheat, tomato, pepper, soybean and cotton by Gubbels (1982), Grabrielian (1996), Phirke and Umbarkar (1998), Pieturszewski (1993), Ogolnej et al. (2002), Vasilevski (2003), Leelapriya et al. (2003) and Esitken and Turan (2004), respectively, and it was suggested that the enhancement in growth and yield of the tomato plants may be attributed to an MF-induced energetic excitement of cellular proteins and carbohydrates and/or water inside the dry seeds.

Endogenous bio-molecular changes

The plant growth is regulated by various biochemical processes. MF may cause changes in one or more parameters that affect the enzymatic activity, the transportation of metabolites, growth regulators, ions, and water, thereby regulating the overall plant growth (Leelapriya et al. 2003). The transport of carbohydrate and plant growth hormones from the site of synthesis to the distant growth zones (fruits) could be stimulated at lower MF intensity (Esitken and Turan 2004). Hirano et al. (1998) also observed that the increase in MF intensity from 0.0005 to 0.1 T showed a positive effect on the growth and photosynthesis in *Spirulina platensis*. MF showed an increase in the chlorophyll content in onion (Novitsky et al. 2001), cotton (Leelapriya et al. 2003), potato and wild *Solanum* species (Tican et al. 2005).

Fig. 1 Effect of magnetic field on functional changes in plants for their growth improvement. Magnetic field (MF+) treatment triggers seed germination, plant growth, water and nutrient uptake, pigments synthesis, protein and enzyme activities as compared to the control (MF-)

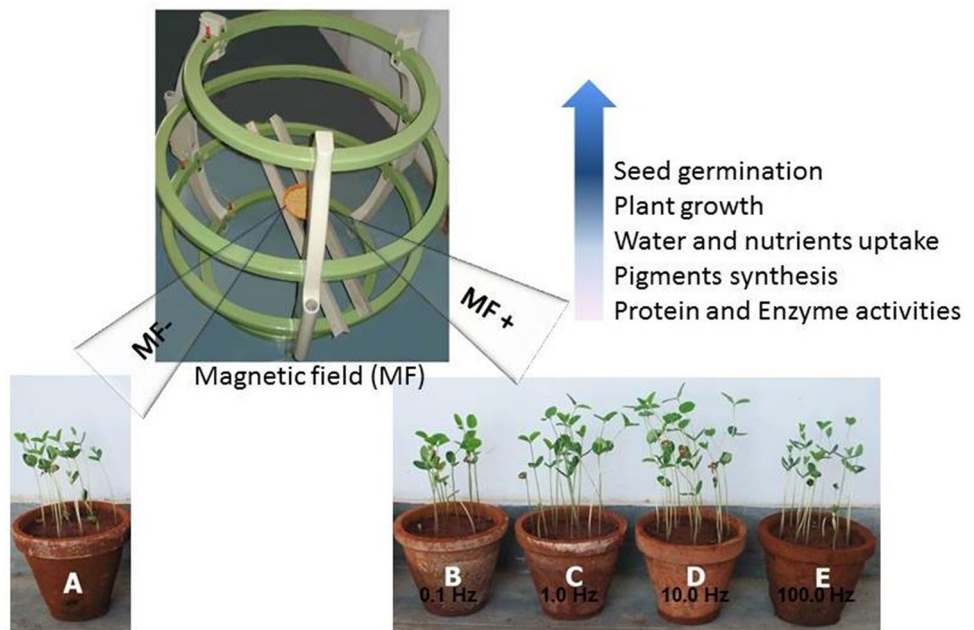


Table 1 MF induced biochemical and physiological changes improve crop production at different environmental conditions

MF treatments	Crops	Plant functions	References
<i>Plant growth promoting activity</i>			
150 mT- 250 mT of SMF	<i>Oryza sativa</i> L.	Improve seed germination	Carbonell et al. (2000)
1500 nTat 10.0 Hz of PMF	<i>Glycine max</i> L.	Increase plant height, biomass, number of leaves, pods, seeds, weight of seeds, proteins, β -amylase, acid phosphatase, polyphenol oxidase, catalase, Fe, Cu, Mn, Zn, Mg, K and Na contents Decrease α -amylase, alkaline phosphatase, protease and nitrate reductase activities and Ca content	Radhakrishnan and Ranjitha-Kumari (2012)
500 gauss -1550 gauss MF	<i>Lycopersicum esculentum</i> L.	Increase branches of shoots	Dayal and Singh (1986)
125 mT-250 mT SMF	<i>Zea mays</i> L.	Faster seed germination, increase length and biomass of plants	Florez et al. (2007)
7 T EMF	<i>Zea mays</i> L.	Accelerate meristem activity and cell division in roots	Bitonti et al. (2006)
20 μ T at 16 2/3 Hz SSMF	<i>Helianthus annuus</i> L. and <i>Triticum aestivum</i> L.	Increase germination rate and growth of plants	Fischer et al. (2004)
100 mT -170 mT SSMF	<i>Lycopersicum esculentum</i> L.	Enhance plant growth, pigments synthesis and fruit yield	Souza-Torres et al. (1999, 2006)
1500 nT at 100 Hz SSMF	<i>Gossypium</i> species	Increase germination percentage, growth, pigments synthesis and yield	Leelapriya et al. (2003)
0.096 T-0.384 T AMF	<i>Fragaria</i> \times <i>ananassa</i> cv. <i>camarosa</i>	Increase fruit yield, N, K, Ca, Mg, Cu, Fe, Mn, Na and Zn in plants Reduce P and S content	Esitken and Turan (2004)
403 A/m WMF	<i>Allium cepa</i> L.	Increase chlorophylls, proteins and enzyme activities in plants	Novitsky et al. (2001)
<i>Drought tolerance</i>			
Magnetic funnel	<i>Lycopersicum esculentum</i> L.	Stimulate plant growth, cambium differentiation activity, thickness of mesophyll tissue, water uptake, proline concentration and photosynthetic pigments	Selim and El-Nady (2011)
100 mT-150 mT EMF	<i>Zea mays</i> L.	Improve plant growth, chlorophyll, photosynthesis rate, transpiration rate, stomatal conductance, substomatal CO ₂ concentration, photochemical quenching and nonphotochemical quenching reactions	Javed et al. (2011)
100 mT-200 mT SMF	<i>Zea mays</i> L.	Increase plant growth, leaf water potential, turgor potential, water content, photosynthesis and stomatal conductance Decrease H ₂ O ₂ , POX,CAT and SOD activities	Anand et al. (2012)
2.9 mT-4.7 mT SMF	<i>Triticum aestivum</i> L.	Increase chlorophyll and carotenoids Decrease SOD, POX, APX and CAT activities	Sen and Alikamanoglu (2014)
<i>Salinity tolerance</i>			
4 mT-7mT SMF	<i>Triticum aestivum</i> L. and <i>Phaseolus vulgaris</i> L.	Increase seed germination, biomass and growth of plants	Cakmak et al. (2010)
1500 nT at 0.1,1.0,10.0 and 100.0 Hz PMF	<i>Glycine max</i> L.	Enhance the frequency of shoot and root regeneration, length and number of roots	Radhakrishnan and Ranjitha-Kumari (2013)
200 mT SMF	<i>Glycine max</i> L. and <i>Zea mays</i> L.	Increase seed germination, seedling growth, α -amylase, protease and free-radicals	Kataria et al. (2017)
200 mT SMF	<i>Glycine max</i> L.	Enhance root nodules, biomass, yield, pigments synthesis, photosynthetic rate, stomatal conductance, transpiration, internal CO ₂ concentration, carbon metabolism, nitrogen metabolism, leghemoglobin and hemechrome content in root nodules	Baghel et al. (2016)
1500 nT at 1.0 Hz PMF	<i>Glycine max</i> L.	Increase callus biomass, sugars, proteins, phenols, flavonoids, flavonoles, alkaloids and saponins Decrease lipid peroxidation and CAT activity	Radhakrishnan et al. (2012)
<i>Heavy metal tolerance</i>			

Table 1 continued

MF treatments	Crops	Plant functions	References
600 mT MF	<i>Vigna radiata</i> L.	Increase plant growth, photosynthesis, nitric oxide synthase and nitric oxide Decrease lipid peroxidation, H ₂ O ₂ , O ₂ ⁻ and electrolyte leakage	Chen et al. (2011)
<i>Temperature and light stress tolerance</i>			
150 mT MF	<i>Zea mays</i> L.	Increase chilling tolerance, plant growth, chlorophyll, total phenolics, gaseous exchange, seed protein, and oil Reduce membrane permeability	Afzal et al. (2015)
400 A/m WMF	<i>Raphanus sativus</i> L.	Increase polar lipids at light and chilling stresses	Novitskaya et al. (2010)
<i>Biotic stress resistance</i>			
10 kHz WMF	<i>Citrus aurantifolia</i> L.	Increase biomass of leaves, MDA, proline and protein content Decrease H ₂ O ₂ and carbohydrates	Abdollahi et al. (2012)
-17 to 13 μT (SMF) + 10 Hz at 25.6 to 28.9 μT (SSMT)	<i>Nicotiana tabacum</i> L.	Decrease number and area of lesions Increase ODC and PAL activities	Trebbi et al. (2007)

AMF alternative magnetic field, EMF electro magnetic field, MF magnetic field, PMF pulsed magnetic field, SMF static magnetic field, SSMT sinusoidal magnetic field, T tesla

The GMF may affect a variety of enzymes in many living organisms. The activity of Ca²⁺/calmodulin dependent cyclic nucleotide phosphodiesterase at 20 μT (Liboff et al. 2003) and cytochrome C oxidase at 50 Hz (Nossol et al. 1993) were altered by MF. It is well known that MF can influence biological processes involving photochemical reactions (Boxer et al. 1982), the biological effects of MF are still debatable (Azanza and Del-Moral 1994; Grissom 1995). However, the mechanisms of some of the alterations in enzyme activity during MF exposure have been identified (Grissom 1995). MF effects are exerted by the interconversion of singlet and triplet rotatory states of the radical pair of bio-molecules (Salikhov et al. 1984). Some enzyme reactions are sensitive and their kinetics are affected by MF.

MF treatments are expected to enhance seed vigor by influencing activity of proteins and enzymes and the biochemical processes that involve free radicals (Jia-Ming 1988; Kurinobu and Okazaki 1995; Morar et al. 1993), auxin content (Mitrov et al. 1988), nutrient (Duarte-Diaz et al. 1997), and water uptake (Reina et al. 2001). Auxin is a signaling molecule, present in root apices, which manages the activities of adjacent cells via electrochemical signaling. The transport of auxin in plants is associated with environmental factors such as gravity, MF, and light (Baluska et al. 2005). MF increases the auxin content as well as enzymes activities that regulate the elongation of the plant cell wall (Mitrov et al. 1988). The studies on the influence of MF on the modifications in protein profile and

enzyme activity are scarce and no information is available on its chemical constituents so far (Novitsky et al. 2001). The total protein contents of onion leaves were increased in MF treated plants. MF at different levels altered distribution of polypeptide in eukaryotic and bacterial cells (Blank et al. 1994; Goodman et al. 1994; Radhakrishnan and Ranjitha-Kumari 2012).

Xiao-ju and Guo (1999) found an increase in the activity of catalase and peroxidase enzymes in tomato seeds pretreated with MF. The amplitude, gradient and high frequency of the non-uniform MF together cause a combined effect on dry seeds and induced the changes in living matter and was called as “ponderomotive effects”. This effect reprograms the enzymatic activity, transport of the metabolites including growth regulators, and also the transport of charged solutes possibly through “Hall” effect for plant growth improvement (Balcavage et al. 1996; Souza-Torres et al. 2006). The stationary MF (150 and 200 mT) stimulates reactive oxygen species in germinating seeds to enhance plant growth (Shine et al. 2012). The changes in amylase and nitrate reductase activities were detected in germinating seeds treated with different levels of EMF (Levedev et al. 1975; Bathnagar and Deb 1978) and many authors have reported the effect of static MF on the metabolism and growth of different plants (Kato 1988; Kato et al. 1989; Peteiro-Cartelle and Cabezas-Cerato 1989). An extremely low MF (0.2–0.3 μT) stimulates the activity of Na and K-ATPases (Blank and Soo 1996), whereas a weak and moderate MF influences the redox

activity of cytochrome C oxidase (Nossol et al. 1993). A treatment of 30 mT increased the esterase activity in *Triticum aestivum* (Aksenov et al. 2000) and 1 mT influenced the activity of horseradish peroxidase (Portaccio et al. 2005). Strong MF (6 T) reduced L-glutamate dehydrogenase and catalase activity (Haberdtz 1967), but 2 T substantially enhanced the activity of carboxydismutase in *Spinacia oleracea* (Akoyunoglou 1964). The strong MF also enhanced the activity of trypsin (Cook and Smith 1964) and ornithine decarboxylase (Mullins et al. 1999); so that the changes in the enzyme activity may depend on strength, the frequency of the MF and the plant species.

A study on tomato plants showed that the irrigation water exposed to MF increases the nutrient uptake in plants (Duarte-Diaz et al. 1997). Radhakrishnan and Ranjitha-Kumari (2012) reported that the MF increases the Fe, Cu, Mn, Zn, Mg, K, and Na content and decreases the Ca content in soybean seedlings. Another study showed that the levels of N, K, Ca, Mg, Fe, Mn, and Zn significantly increased but Cu and Na remained unchanged in the leaves of MF treated strawberry plants (Esitken and Turan 2004). MF affects the membranes and Ca^{2+} signaling in plant cells, and many magnetic effects in living organisms are probably due to the alterations in membrane-associated Ca^{2+} flux (Galland and Pazur 2005). Na-channels are less affected than Ca^{2+} channels (Rosen 2003) and due to the changes of Ca^{2+} channels, the Ca content might be reduced in MF treated plants. However, MF treatment in seeds induces the changes in protein and lipid profile in harvested seeds (Radhakrishnan 2018).

Mitigation effect of MF on crops against unfavorable environments

The adverse environmental conditions including drought, salinity and heavy metal accumulation in soil, and light, temperature, insects, and pathogens affect the growth and yield of agricultural crops. MF induced changes in the metabolism of plants during those unfavorable environments are given in Fig. 2 and Table 1.

Drought

Drought is a very serious problem in agriculture. Few researchers have studied the application of MF to overcome the detrimental effect of drought stress (Vashisth and Nagarajan 2010; Javed et al. 2011; Selim and El-Nady 2011; Anand et al. 2012; Karimi et al. 2012; Sen and Alikamanoglu 2014). The drought-induced reduction in plant growth can be mitigated by the application of MF as it stimulates cambium differentiation activity to form more xylem and phloem tissues for improving the absorption and transport of water and nutrients to enhance plant growth

under drought condition (Selim and El-Nady 2011). The plant cell membrane permeability and free water flow are increased in MF pretreated seeds (Bondarenko et al. 1996). Owing to the variability in ionic flow through the cell membrane, the osmotic potential is changed under drought condition. In MF treated plants, Ca^{2+} enhancement is found to play a significant role in plant drought tolerance, it prevents the impairment of plasma membrane and photosynthetic apparatus and regulates the hormonal metabolism in drought affected plants (Blum 1993; Song et al. 2008, Selim and El-Nady 2011). MF enhanced the chlorophyll and carotenoid synthesis in leaves, which might be due to the increase in proline and GA_3 , which trigger the accumulation of Mg^{2+} for chlorophyll synthesis (Shaddad 1990) and K^+ to increase the number of chloroplasts (Garcia-Reina and Arza-Pascual 2001). This might eventually lead to increase in the thickness of mesophyll tissue (Selim and El-Nady 2011). In addition, it also increases stomatal conductance, sub-stomatal CO_2 concentration, and photochemical and non-photochemical reducing reactions to moderate the effect of drought in plants (Javed et al. 2011). MF prevents oxidative stress damage in drought affected plants by reducing H_2O_2 , SOD, POD and CAT activities and, the metabolic energy used for scavenging the free radicals and ultimately improves the plant growth (Anand et al. 2012; Sen and Alikamanoglu 2014).

Soil salinity

About one-third of the agricultural land is affected by salinity (Flowers and Yeo 1995) due to inappropriate irrigation practices and natural factors (Chinnusamy and Zhu 2003). A high salt content in soil disrupts the homeostasis in water potential and ion distribution in plant cells (Zhu 2001; Munns et al. 2002). An excessive accumulation of Na^+ and Cl^- ions changes the protein structures, which lead to the loss of turgidity of the cell (Chinnusamy and Zhu 2003). MF pretreatment enhances the water absorption in seeds and promotes the seed germination and growth of plants in saline or non-saline soil conditions (Cakmak et al. 2010; Radhakrishnan and Ranjitha-Kumari 2013; Karimi et al. 2017). In addition, α -amylase and protease activities are also increased in MF treated seeds due to the faster utilization of reserve materials required for a higher rate of germination (Kataria et al. 2017). MF treated seeds absorb water faster due to the electrophysiological changes in cells (Reina et al. 2001) and may help to alleviate the salt stress. Nevertheless, the photosynthetic rate, stomatal conductance, transpiration, and internal CO_2 concentrations were enhanced in salt affected plants pretreated with MF (Baghel et al. 2016; Rathod and Anand 2016). To achieve salt tolerance, plant cells have evolved several biochemical and physiological pathways, which include the exclusion of

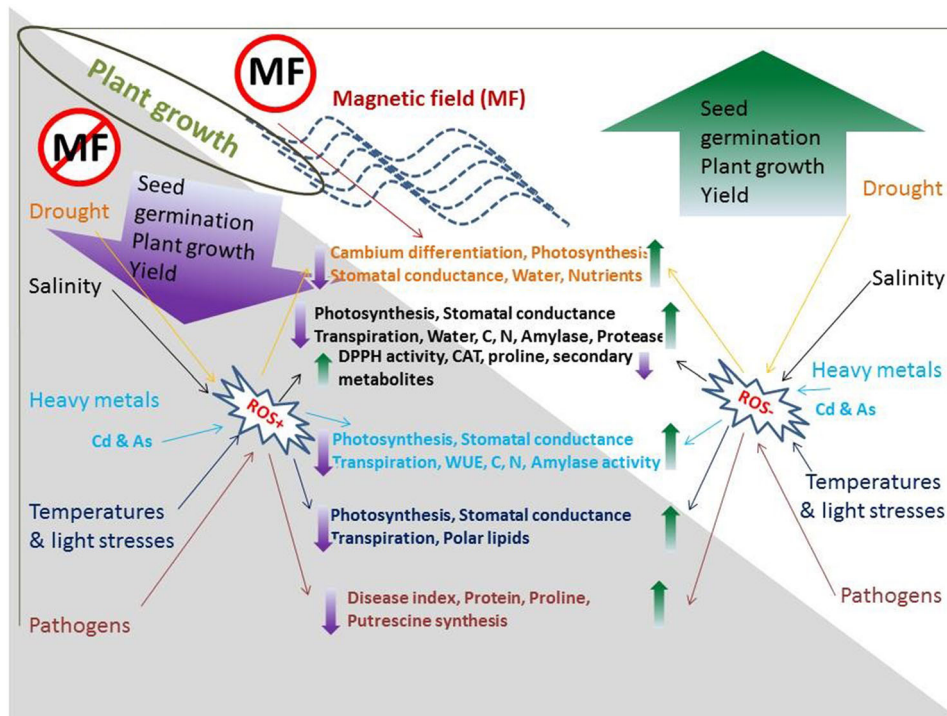


Fig. 2 Magnetic field induced metabolic alteration and tolerance of plants against adverse environmental conditions. Adverse stress conditions including drought, salinity, heavy metals, high/low temperatures, high/low light and pathogens infections reduce seed germination, plant growth and yield due to the molecular and physiological changes in plants. MF treatment reduces the ROS production in plants at stress conditions, and enhances cambium differentiation, photosynthesis, stomatal conductance, water and nutrient uptake in drought affected plants. MF induced salinity tolerance is achieved by an increase of photosynthesis, stomatal conductance, transpiration, water uptake, carbon, nitrogen, amylase

and protease activities and while reducing the DPPH activity, CAT, proline and some secondary metabolites. Cadmium (Cd) and Arsenic (As) affected plants are possibly recovered by promoting photosynthesis, stomatal conductance, transpiration, water use efficiency (WUE), carbon, nitrogen, amylase activities due to the treatment of MF. Whereas plants that suffered at temperature and light stresses are mitigated by MF treatment, which accelerate photosynthesis, stomatal conductance, transpiration and polar lipids. In addition, MF recovers the pathogen infected plants by increasing protein, proline, putrescine synthesis and disease index

Na⁺ and their trans-localization into vacuoles, and also the accumulation of compatible solutes such as proline, glycine, betaine, and polyols (Kameli and Losel 1996; Hasegawa et al. 2000; Chinnusamy and Zhu 2003; Parida and Das 2005). However, the precise mechanism underlying these effects has not yet been fully understood because salinity tolerance is a multigenic trait (Parida and Das 2005). MF exposure increases the sugar and protein content in salt affected calli to overcome the stress effects (Radhakrishnan et al. 2012). These compounds accumulate in high volumes in the cytoplasm of stressed cells without interfering with other macromolecules and act as osmoprotectants (Yancey 1994). It has been shown that proline plays a key role in stabilizing the cellular membrane and proteins (Rudolph et al. 1986; Yancey 1994). The higher proline accumulation in roots may be due to the increased rate of inhibition of proline dehydrogenase and proline oxidase (Veeranjaneyullu and Ranjitha-Kumari 1989). The production, along with accumulation, of proline in plant tissue during salt stress is an adaptive response and it has

been proposed as a stress-related metabolic marker (Burton 1991). The osmotic potential in the cytoplasm is adjusted by proline which acts as a compatible solute (Bartels and Sunkar 2006). It signals protein synthesis immediately after the salt stress that protects the plasma membrane (Santoro et al. 1992). Ahmad and Wyn Jones (1979) reported that during recovery period, tissue rehydration is associated with decline. Hence, subsequent to relief of stress, it acts as reserve of organic nitrogen for maintaining amino acid and protein synthesis (Trotel et al. 1996; Sairam and Tygai 2004). MF ameliorates the salt effects by reducing the overproduction of proline (Radhakrishnan et al. 2012).

According to Mittler (2002) high level of H₂O₂ accelerates the Haber–Weiss reaction and results in OH[•] formation and consequently lipid peroxidation. Several studies showed that the lipid peroxidation activity is enhanced during high salinity (Hernandez et al. 2000; Davenport et al. 2003). MF also increased lipid peroxidation in tobacco cell suspension cultures (Saheb Jamei et al. 2007). On the contrary, during a salt stress condition, MF

pretreatment resulted in the decline of lipid peroxidation in soybean callus culture (Radhakrishnan et al. 2012). Salt stress increases catalase (CAT) in plants (Manchandia et al. 1999), but MF pretreated seeds showed resistance toward the salinity and decreased the CAT and DPPH scavenging activity due to the reduction of oxidative stress (Radhakrishnan et al. 2012; Roshandel and Azimian 2015).

Alkaloids, saponins, flavonoids, flavones, and flavonols are generally increased in salt affected cells, while MF exposure reduced the accumulation of these secondary metabolites and alleviated the salt stress (Radhakrishnan et al. 2012). Saponins are glycosides occurring commonly in plants, which are derived from tri-terpenoids and exhibit a wide range of biological functions (Osborn 2003). The decrease in saponins at high Cu concentration provides an intrinsic defense to resist Cu-induced oxidative damage in *Panax ginseng* (Ali et al. 2006). Russo et al. (2002) reported that flavones and flavonols have antioxidant property, and isoflavones also possess antioxidant and antifungal activities that protect the plant against insect attack (Burden and Norris 1992). The salt stress induces the accumulation of isoflavones such as genistein and daidzein, while MF pretreatment resulted in the lowering of their levels. The high amount of total polyphenols increases the antioxidant potential in plants and MF results in the enhancement of total polyphenol in callus tissue grown under saline condition (Radhakrishnan et al. 2012).

Heavy metals

The heavy metals from the industry, fertilizers, and pesticides enter the water bodies and soil and subsequently reach to humans through the food chain (Wagner 1993; Pinto et al. 2014). The excessive deposition of heavy metals in soil limits the plant productivity. Recently, Chen et al. (2011) and Flores-Tavizon et al. (2012) reported that the toxic effects of cadmium (Cd) and arsenic (As) in plants were mitigated by an MF exposure. Due to the heavy metal toxicity, plants produce reactive oxygen species (ROS), which damage the cellular membranes and inhibit the photosynthesis and other metabolic processes (Prasad 1995). MF triggers nitric oxide (NO) signaling, which activates cell division, photosynthesis, and growth of Cd affected plants. The mung-bean seedlings treated with MF (600 mT) showed a lower level of ROS such as H_2O_2 , O_2^- , and malondialdehyde (MDA) but a higher level of total chlorophyll, photosynthetic rate, stomatal conductance, transpiration rate, intercellular CO_2 concentration, and water use efficiency in Cd stress conditions. In addition, MF increased the C and N concentrations in Cd-stressed plants (Chen et al. 2011). Another toxic metal, As is a non-essential metal for plant growth and inhibits enzyme activities in plants (Liu et al. 2005). MF pretreatment

increased resistance towards As toxicity in the plants by the regulation of ionic flow in plant cell membranes (Galland and Pazur 2005). The seed germination, growth, amyolytic activity, and As uptake was increased in As stressed plants treated with MF (Flores-Tavizon et al. 2012).

Temperature and light stresses

Crop productivity is affected by a wide range of temperature and light regimes. MF exposure alleviates the inhibitory effect of heat shock by eliciting heat shock proteins under thermal stress (Goodman and Blank 1998; Ruzic and Jerman 2002). Low temperature (cold) stress limits the yield and geographical distribution of several crops (Gai et al. 2008). Afzal et al. (2015) proved that chilling stress reduces the seed germination in maize, but MF treatment stabilizes the membrane permeability and regulates ion transport in stressed seeds to alleviate the chilling stress. In addition, MF accelerates the primary metabolic process such as photosynthesis, transpiration, and stomatal conductance during chilling injury in maize plants. The increased synthesis of chlorophylls and phenolics due to the effect of MF in stressed plants could be the reason for averting the ROS production. Similarly, the harvest index, weight, yield, and protein content in grains were significantly higher but the oil contents were lower in MF treated plants than untreated plants.

The role of MF against thermal stress varies under light or dark conditions. At low temperature, cell membranes change the lipid composition by promoting the conversion of unsaturated fatty acids to saturated ones (Kreps 1981). The fatty acids, especially erucic acid, are enhanced by 25% in light and dark grown plants pretreated with MF at 20 °C and declined at 10 °C in the light (Novitskaya et al. 2010). At 20 °C, MF decreased the synthesis of polar lipids (18%) in radish seedlings grown under the light but it was about 80% higher than non-treated seedlings. MF exposure increased the polar lipid content during chilling (10 °C) temperature and light but had no effects in the plants grown in dark plants. The breakdown process of lipids in germinating seeds is a critical element that provides energy for growing cells (Bewley and Black 1994). The MF treatment can modulate the lipid metabolism and synthesis in plants at the exposure of light and temperature (Novitskaya et al. 2010). The strong light enhances the singlet oxygen production in chloroplast by photosystem II (Telfer 2014) but disrupts the cellular activities and is harmful to plant growth. MF inhibits the formation of singlet oxygen, which reduces the metabolic energy available to the chloroplast (Hakala-Yatkin et al. 2011). The light wavelengths significantly influence the growth and flowering in plants, MF suppresses the flowering in white and blue light

but did not affect the flowering in the red light (Xu et al. 2015).

Biotic stresses

The application of MF can reduce the detrimental effect of pathogenic microbes and increase the growth and yield of plants (Galland and Pazur 2005). For example, citrus plants intermittently exposed to 10 Hz MF showed a substantial enhancement in fresh and dry leaf weight in healthy as well as *Phytoplasma aurantifolia* infected plants (Abdollahi et al. 2012). It proved that MF could also increase the resistance against pathogens. Biochemical analysis revealed that the accumulation of proteins was higher but carbohydrates were lesser in infected plants treated with MF. The synthesis of proline (a protective osmolyte) is notably activated by MF thus supporting cellular structures (Resenburg et al. 1993). The biotic stress alleviation mechanism of MF was determined by reduced H₂O₂ production in infected plants exposed to MF. On the other hand, scavenging enzymes control the free radicals, which alter membrane integrity and increase the resistance in plants against pathogen infection. However, Trebbi et al. (2007) studied the hypersensitive response (HR) in tobacco mosaic virus infected tobacco plants during the MF exposure and proved that MF treatment decreases the number and area of lesions in the diseased plants and it also regulates the calcium (Ca²⁺) signaling pathway in the cell. During the HR, the Ca²⁺ influx into the cytosol is stimulated that increases the resistance (Baureus-Koch et al. 2003). Similarly, MF influences the polyamine pathway enzymes such as ornithine decarboxylase (ODC) and phenylalanine ammonia lyase (PAL). The ODC and PAL activities enhanced by an MF exposure during infection suggest that putrescine synthesis helps the plant withstand the biotic stress (Trebbi et al. 2007).

Conclusion

Magnetic field (MF) therapy has been claimed to be effective for human ailments. Very few studies have been undertaken to understand the positive effect of MF on crop plants during environmental stress conditions. This review explores the current knowledge and future prospects of MF-induced physiological changes in plants toward enhancing the growth and yield under favorable and adverse conditions. The application of MF accelerates the seed germination, vegetative as well as reproductive growth in plants due to an increase in energy and its distribution to biomolecules in the cell. The enhancement of water and nutrient uptake, photosynthesis, carbohydrates, protein and enzyme metabolisms would impact the

promotion of plant growth and yield. Unfavorable environments such as drought, salinity, heavy metal contamination in soil, cold and/or hot conditions drastically decrease the crop productivity. MF exposed plants tolerate these adverse environments by reducing oxidative stresses. MF treatment can enhance plants drought tolerance by stimulating water and Ca²⁺ uptake, cell membrane permeability, cambial differentiation, pigment synthesis, stomatal conductance. Similarly, MF protects the plants against salinity by increasing water uptake, stomatal conductance, sugar, and protein synthesis, and also by regulating the antioxidants and defense metabolites. Heavy metals in soil suppress the plant growth but MF treatment alleviates these metal stresses through the increased water flow, nitrogen, carbon, endogenous NO accumulation, photosynthesis, stomatal conductance, transpiration, and cell division. In addition, the production of heat shock proteins in MF exposed plants confers protection against the hyperthermic stresses. During low temperature, MF triggers ion transport, membrane permeability, photosynthesis, stomatal conductance, and transpiration, and regulates the polar lipids and erucic acids, irrespective of the presence or absence of light conditions to enhance the plant tolerance against temperature stresses. However, a reduced area of infection in leaves showed the control of plant diseases by MF exposure and this resistance may be due to the accumulation of Ca²⁺, proteins, and proline in plants.

Future prospectus

The MF-induced changes in the fundamental physiological process of crop plants against adverse environmental conditions have been investigated by only few researchers. A comprehensive bio-stimulatory activity of MF in several cellular metabolisms and their subsequent effects on tissue proliferation and organization need to be elucidated to decipher the mitigation mechanism of MF and plant interaction under stress environments. The future studies are required to confirm the positive effects of MF on crop yield by answering the following: (1) Whether MF treatment influences the next generation of crop growth and yield? (2) Is there any toxicity due to the consumption of MF treated foods? (3) Does it affect the micro and macro flora of soil during plant growth? In addition, the comprehensive genomic and proteomic analyses in MF treated plants would also bridge the space between current understanding and future perspective of biological effects of the magnetic field in plants.

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Compliance with ethical standards

Conflict of interest The author has no conflict of interest to declare.

References

- Abdollahi F, Niknam V, Ghanati F, Masroor F, Noorbakhsh SN (2012) Biological effects of weak electromagnetic field on healthy and infected lime (*Citrus aurantifolia*) trees with phytoplasma. *Sci World J* 12:1–6
- Afzal I, Noor MA, Bakhtavar MA, Ahmad A, Haq Z (2015) Improvement of spring maize (*Zea mays*) performance through physical and physiological seed enhancements. *Seed Sci Technol* 43:1–12
- Ahmad N, Wyn Jones RG (1979) Glycinebetaine, proline and inorganic ion levels in barley seedlings following transient stress. *Plant Sci Lett* 15:231–237
- Akoyunoglou G (1964) Effect of a magnetic field on carboxydismutase. *Nature* 202:452–454
- Aksenov SI, Bulychiev AATI, Turovetskii VB (2000) Effect of a low-frequency magnetic field on esterase activity and change in pH in wheat germ during swelling of wheat seeds. *Biofizika* 45:737–745
- Aladjadjiyan A (2002) Study of the influence of magnetic field on some biological characteristics of *Zea mays*. *J Cent Eur Agric* 3:89–94
- Ali MB, Hahn EJ, Paek KY (2006) Copper-induced changes in the growth, oxidative metabolism and saponin production in suspension culture roots of *Panax ginseng* in bioreactors. *Plant Cell Rep* 25:1122–1132
- Anand A, Nagarajan S, Verma AP, Joshi DK, Pathak PC, Bhardwaj J (2012) Pre-treatment of seeds with static magnetic field ameliorates soil water stress in seedlings of maize (*Zea mays* L.). *Indian J Biochem Biophys* 49(1):63–70
- Asashima M, Shimada K, Pfeiffer CJ (1991) Magnetic shielding induces early developmental abnormalities in the newt, *Cynops pyrrhogaster*. *Bioelectromagnetics* 12:215–224
- Audus LJ (1960) Magnetotropism: a new plant growth response. *Nature* 185:132–134
- Azanza MJ, Del-Moral A (1994) A cell membrane biochemistry and neurobiological approach to biomagnetism. *Prog Neurobiol* 44:517–601
- Baghel L, Kataria S, Guruprasad KN (2016) Static magnetic field treatment of seeds improves carbon and nitrogen metabolism under salinity stress in soybean. *Bioelectromagnetics* 37:455–470
- Balcavage WX, Alvager T, Swez J, Goff CW, Fox MT, Abdullyava S, King MW (1996) A mechanism for action of extremely low frequency electromagnetic fields on biological systems. *Biochem Biophys Res Commun* 222:374–378
- Baluska F, Barlow PW, Baskin TI, Chen R, Feldman L, Forde BG, Geisler M, Jernstedt J, Menzel D, Muday GK (2005) What is apical and what is basal in plant root development? *Trends Plant Sci* 10:409–411
- Bartels D, Sunkar R (2006) Drought and salt tolerance in plants. *Crit Rev Plant Sci* 24:23–28
- Bathnagar D, Deb AR (1978) Some aspects of pregermination exposure of wheat seeds to magnetic field II. Effect on some physiological processes. *Seed Res* 6:14–22
- Baureus-Koch CLM, Sommarin M, Persson BRR, Salford LG, Eberhardt JL (2003) Interaction between low frequency magnetic fields and cell membranes. *Bioelectromagnetics* 24:395–402
- Beemster GTS, Baskin TI (1998) Analysis of cell division and elongation underlying the developmental acceleration of root growth in *Arabidopsis thaliana*. *Plant Physiol* 116:515–526
- Belyavskaya NA (2004) Biological effects due to weak magnetic field on plants. *Adv Space Res* 34:1566–1574
- Bewley JD, Black M (1994) Cellular events during germination and seedling growth. In: Bewley JD, Black M (eds) *Seeds physiology of development and germination*, 2nd edn. Plenum press, New York, pp 147–191
- Binhi VN (2001) Theoretical concepts in magnetobiology. *Electromagn Biol Med* 20:43–58
- Bitonti MB, Mazzuca S, Ting T, Innocenti AM (2006) Magnetic field affects meristem activity and cell differentiation in *Zea mays* roots. *Plant Biosyst* 140:87–93
- Blank M, Soo L (1996) The threshold for Na, K-ATPase stimulation by electromagnetic fields. *Bioelectrochem Bioenerg* 40:63–65
- Blank M, Khorkova O, Goodman R (1994) Changes in polypeptide distribution stimulated by different levels of electromagnetic and thermal stress. *Bioelectrochem Bioenerg* 33:109–114
- Blum A (1993) Selection for sustained production in water-deficit environment. *Int Crop Sci* 1:343–347
- Bondarenko NF, Rokhinson EE, Gakez Klygina LF (1996) Magnetic equipment in agriculture. *Russ Agric Sci* 2:30–34
- Boxer SG, Chidsey CED, Roelofs MG (1982) Magnetic field effects on reaction yields in the solid state an example from photosynthetic reaction centers. *J Am Chem Soc* 104:1452–1454
- Brown FA (1962) Responses of the *Planarium*, *Dugesia*, and the protozoan, *Paramecium*, to very weak horizontal magnetic fields. *Biol Bull* 123:264–281
- Burden BJ, Norris DM (1992) Role of isoflavonoid coumestrol in the constitutive antixenotic properties of soybean against an oligophagous insect, the Mexican Bean Beetle. *J Chem Ecol* 18:1069–1081
- Burton RS (1991) Regulation of proline synthesis during osmotic stress in the copepod *Tigriopus californicus*. *J Exp Zool* 259:166–173
- Cakmak T, Dumlupinar R, Erdal S (2010) Acceleration of germination and early growth of wheat and bean seedlings grown under various magnetic field and osmotic conditions. *Bioelectromagnetics* 31:120–129
- Carbonell MV, Martınez E, Amaya JM (2000) Stimulation of germination in rice (*Oryza sativa* L.) by a static magnetic field. *Electro Magnetobiol* 19(1):121–128
- Chen YP, Li R, He JM (2011) Magnetic field can alleviate toxicological effect induced by cadmium in mungbean seedlings. *Ecotoxicol* 20:760–769
- Chepts AD, Morozowa ZN, Tkacheva NA (1985) Wheat and sorghum yield and grain quality as affected by magnetic field, Monograph: methods for improved yields of winter wheat and spring barley, USSR
- Chinnusamy V, Zhu JK (2003) Plant salt tolerance. *Top Curr Gen* 4:241–270
- Commoner B, Townsend J, Pake GE (1954) Free radicals in biological materials. *Nature* 174(4432):689–691
- Cook ES, Smith MJ (1964) Increase of trypsin activity. In: Barnothy MF (ed) *Biological effects of magnetic fields*. Plenum Press, New York, pp 246–254
- Davenport SB, Gallego SM, Benavides MP, Tomaro ML (2003) Behaviour of antioxidant defense system in the adaptive response to salt stress in *Helianthus annuus* L. cells. *Plant Growth Regul* 40:81–88
- Davies MS (1996) Effect of 60 Hz electromagnetic fields on early growth in three plant species a replication of previous results. *Bioelectromagnetics* 17:154–161
- Dayal S, Singh RP (1986) Effect of seed exposure to magnetic field on the height of tomato plants. *Indian J Agric Sci* 56:483–486
- Dhiman SH, Galland P (2018) Effects of weak static magnetic fields on the gene expression of seedlings of *Arabidopsis thaliana*. *J Plant Physiol* 231:9–18

- 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. *Hortic Abstr* 69:494
- Esitken A, Turan M (2004) Alternating magnetic field effects on yield and plant nutrient element composition of strawberry (*Fragaria × ananassa* cv. *Camarosa*). *Acta Agric Scand Sect B Soil Plant Sci* 54:135–139
- Fischer G, Tausz M, Kock M, Grill D (2004) Effects of weak 16 2/3 Hz magnetic fields on growth parameters of young sunflower and wheat seedlings. *Bioelectromagnetics* 25(8):638–641
- Flores-Tavizon E, Mokgalaka-Matlala NS, Galindo JTE, Castillo-Michelle H, Peralta-Videa JR, Gardea-Torresdey JL (2012) Magnetic field effect on growth, arsenic uptake, and total amyolytic activity on mesquite (*Prosopis juliflora* × *P. velutina*) seeds. *J Appl Phys* 111:07B321
- 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
- Flowers TJ, Yeo AR (1995) Breeding for salinity resistance in crop plants: where next? *Aust J Plant Physiol* 22:875–884
- Gai YP, Li XZ, Ji XL, Wu CA, Yang GD, Zheng CC (2008) Chilling stress accelerates degradation of seed storage protein and photosynthetic protein during cotton seed germination. *J Agron Crop Sci* 194:278–288
- Galland P, Pazur A (2005) Magnetoreception in plants. *J Plant Res* 118:371–389
- Garcia-Reina F, Arza-Pascual L (2001) Influence of a stationary magnetic field on water relations in lettuce seeds. Part I: theoretical considerations. *Bioelectromagnetics* 22:589–595
- Goodman R, Blank M (1998) Magnetic field stress induces expression of hsp70. *Cell Stress Chaperones* 3(2):79–88
- Goodman EM, Greenebaum B, Marron MT (1994) Magnetic fields alter translation in *Escherichia coli*. *Bioelectromagnetics* 15:77–83
- Grabrielian S (1996) The sowing qualities of seeds and productivity of agricultural plants at action by magnetic fields. Ph.D thesis, The Stavropol agriculture academy, Stavropol
- Grissom CB (1995) Magnetic field effects in biology—a survey of possible mechanisms with emphasis on radical pair recombination. *Chem Rev* 95:3–24
- Gubbels GH (1982) Seedling growth and yield response of flax, buckwheat, sunflower and field pea after preseedling magnetic treatment. *Can J Plant Sci* 62:61–64
- Haberdtz W (1967) Enzyme activity in high magnetic fields. *Nature* 213:72–73
- Hakala-Yatkin M, Sarvikas P, Paturi P, Mantysaari M, Mattila H, Tyystjarvi T, Nedbal L, Tyystjarvi E (2011) Magnetic field protects plants against high light by slowing down production of singlet oxygen. *Physiol Plant* 142:26–34
- Hasegawa P, Bressan RA, Zhu JK, Bohnert HJ (2000) Plant cellular and molecular responses to high salinity. *Annu Plant Physiol Rev Plant Mol Biol* 51:463–499
- Hernandez JA, Jimenez A, Mullineaux PM, Sevilla F (2000) Tolerance of pea (*Pisum sativum* L.) to long term salt stress is associated with induction of antioxidant defenses. *Plant Cell Environ* 23:853–862
- Hirano M, Ohta A, Abe K (1998) Magnetic field effects on photosynthesis and growth of the cyanobacterium *Spirulina platensis*. *J Ferment Bioeng* 86:313–316
- Javed N, Ashraf M, Akram NA, Al-Qurainy F (2011) Alleviation of adverse effects of drought stress on growth and some potential physiological attributes in maize (*Zea mays* L.) by seed electro-magnetic treatment. *Photochem Photobiol* 87:1354–1362
- Jia-Ming Y (1988) Effects of high-voltage electrostatic field on growth in plants. In: Proceedings of international conference on modern electrostatics, Beijing, China, pp 140–143
- Kameli A, Losel DM (1996) Growth and sugar accumulation in Durum wheat plants under water stress. *New Phytol* 132:57–62
- Karimi S, Hojati S, Eshghi S, Moghaddam RN, Jandoust S (2012) Magnetic exposure improves tolerance of fig ‘Sabz’ explants to drought stress induced in vitro. *Sci Hortic* 137:95–99
- Karimi S, Eshghi S, Karimi S, Hasan-Nezhadian S (2017) Inducing salt tolerance in sweet corn by magnetic priming. *Acta Agric Slov* 109:89
- Kataria S, Baghel L, Guruprasad KN (2017) Pre-treatment of seeds with static magnetic field improves germination and early growth characteristics under salt stress in maize and soybean. *Biocatal Agric Biotechnol* 10:83–90
- Kato R (1988) Effects of magnetic fields on the growth of primary roots of *Zea mays*. *Plant Cell Physiol* 29:1215–1219
- Kato R, Kamada H, Asashima M (1989) Effects of high and very low magnetic fields on the growth of hairy roots of *Daucus carotta* and *Atropa belladonna*. *Plant Cell Physiol* 30:605–608
- Krebs EM (1981) *Lipidylketochnykh membran* (the lipids of the cell membranes). Nauka, Leningrad
- Kurinobu S, Okazaki Y (1995) Dielectric constant and conductivity of one seed in the germination process. In: Annual conference record of IEEE/IAS, pp 1329–1334
- Kuznetsov OA, Schwuchow J, Sack FD, Hasenstein KI (1999) Curvature induced by amyloplast magnetophoresis in protonemata of the moss *Ceratodon purpureus*. *Plant Physiol* 19:645–650
- Lawlor DW (2002) Limitation to photosynthesis in water stressed leaves: stomata vs. metabolism and the role of ATP. *Ann Bot* 89:1–15
- Leelapriya T, Dilip KS, Sanker-Narayan PV (2003) Effect of weak sinusoidal magnetic field on germination and yield of cotton (*Gossypium* sp.). *Electromagn Biol Med* 22:117–125
- Levedev SI, Baranskil PI, Limitrenko LG, Shiyun LT (1975) Physiobiochemical characteristics of plants after presowing treatment with a permanent magnetic field. *Sov Plant Physiol* 22:84–90
- Liboff AR, Cherng S, Jenrow KA, Bull A (2003) Calmodulin dependent cyclic nucleotide phosphodiesterase activity is altered by 20 μ T magnetostatic fields. *Bioelectromagnetics* 24:2–38
- Liu X, Zang S, Shan X, Zhu Y (2005) Toxicity of arsenate and arsenite on germination, seedling growth and amyolytic activity of wheat. *Chemosphere* 61:293
- Maffei ME (2014) Magnetic field effects on plant growth, development, and evolution. *Front Plant Sci* 5:445
- Manchandia AM, Banks SW, Gossett DR, Bellaire BA, Lucas MC, Millhollon EP (1999) The influence of α -amanitin on the NaCl induced up-regulation of antioxidant enzyme activity in cotton callus tissue. *Free Radic Res* 30:429–438
- Matsuda T, Asou H, Kobayashi M, Yonekura M (1993) Influences of magnetic fields on growth and fruit production of strawberry. *Acta Hortic* 348:378–380
- Mericle RP, Mericle LW, Smith AC, Campbell WF, Montgomery DJ (1964) Plant growth responses. In: Barnothy MF (ed) Biological effects of magnetic fields. Plenum Press, New York, pp 183–195
- Mitrov PP, Kroumova Z, Baidanova VD (1988) Auxin content of corn and tomato plants following magnetic field treatments. *Fiziol No Rasteniyata* 14:18–23
- Mittler R (2002) Oxidative stress, antioxidants and stress tolerance. *Trends Plant Sci* 7:405–410
- Morar R, Iluga A, Dascalescu L, Munteanu I (1993) Electric field influence on the biological processes of seeds. In: Proceedings of international symposium on high-voltage engineering, Yokohama, p 286
- Mullins JM, Penafiel LM, Juutilainen J, Litovitz TA (1999) Dose-response of electromagnetic field-enhanced ornithine decarboxylase activity. *Bioelectrochem Bioenerg* 48:193–199

- Munns R, Husain S, Rivelli AR, Richard A, James RA, Condon AGT, Lindsay MP, Lagudah ES, Daniel P, Schachtman DP, Hare RA (2002) Avenues for increasing salt tolerance of crops, and the role of physiologically based selection traits. *Plant Soil* 247:93–105
- Murphy JD (1942) The influence of magnetic fields on seed germination. *Am J Bot* 29:155
- Nossol B, Buse G, Silny J (1993) Influence of weak static and 50 Hz magnetic fields on the redox activity of cytochrome-C oxidase. *Bioelectromagnetics* 14:361–372
- Novitskaya GV, Molokanov DR, Kocheshkova TK, Novitskii YI (2010) Effect of weak constant magnetic field on the composition and content of lipids in radish seedlings at various temperatures. *Russ J Plant Physiol* 57(1):52–61
- Novitsky YI, Novitskaya GV, Kocheshkoiva TK, Nechiporenko GA, Dobrovolskii MV (2001) Growth of green onions in a weak permanent magnetic field. *Russ J Plant Physiol* 48:709–715
- Ogolnej K, Uprawy R, Rolnieza A (2002) The effect of magnetical-biostimulation of sowing material, spring wheat on its development and crops. *Folia Univ Agric Stetin Agric* 226:77–82
- Osborn AE (2003) Molecule of interest, saponins in cereals. *Phytochemistry* 62:1–4
- Parida AK, Das AB (2005) Salt tolerance and salinity effects on plants: a review. *Ecotox Environ Saf* 60:324–349
- Peteiro-Cartelle FJ, Cabezas-Cerato J (1989) Influence of static magnetic field on mitosis in meristematic cells of *Allium cepa*. *J Bioelectr* 8:167–178
- Phirke PS, Umbarkar SP (1998) Influence of magnetic treatment of oil seed on yield and dry matter. *PKV Res J* 22:130–132
- Pieturszewski S (1993) Effect of magnetic biostimulation on wheat. *Seeds Sci Technol* 21:621–626
- Pieturszewski S (1999) Effect of alternating magnetic field on germination, growth and yield of plant seeds. *Inzynieriarolnicza* 5:209–215
- Pinto E, Ana ARMA, Isabel MPLVOF (2014) Influence of soil chemistry and plant physiology in the phytoremediation of Cu, Mn, and zinc. *Crit Rev Plant Sci* 33:351–373
- Pittman UJ (1965) Magnetism and plant growth. II. Effect on germination and early growth of corn and beans. *Can J Plant Sci* 45:549–555
- Portaccio M, De-Luca P, Durante D, Grano V, Rossi S, Bencivenga U, Lepore M, Mita DG (2005) Modulation of the catalytic activity of free and immobilized peroxidase by extremely low frequency electromagnetic fields: dependence on frequency. *Bioelectromagnetics* 26:145–152
- Prasad MNV (1995) Cadmium toxicity and tolerance in vascular plants. *Environ Exp Bot* 35:525–545
- Radhakrishnan R (2018) See pretreatment with magnetic field alters the storage proteins and lipid profiles in harvested soybean seeds. *Physiol Mol Biol Plant* 24(2):343–347
- Radhakrishnan R, Lee IJ (2013) Regulation of salicylic acid, jasmonic acid and fatty acids in cucumber (*Cucumis sativus* L.) by spermidine promotes plant growth against salt stress. *Acta Physiol Plant* 35:3315–3322
- Radhakrishnan R, Ranjitha-Kumari BD (2012) Pulsed magnetic field: a contemporary approach offers to enhance plant growth and yield of soybean. *Plant Physiol Biochem* 51:139–144
- Radhakrishnan R, Ranjitha-Kumari BD (2013) Protective role of pulsed magnetic field against salt stress effects in soybean organ culture. *Plant Biosyst* 147(1):135–140
- Radhakrishnan R, Leelapriya T, Ranjitha-Kumari BD (2012) Effects of pulsed magnetic field treatment of soybean seeds on calli growth, cell damage, and biochemical changes under salt stress. *Bioelectromagnetics* 33:670–681
- Radhakrishnan R, Kang SM, Baek IY, Lee IJ (2014) Characterization of plant growth-promoting traits of *Penicillium* species against the effects of high soil salinity and root disease. *J Plant Interact* 9:754–762
- Radhakrishnan R, Khan AL, Kang SM, Lee IJ (2015) A comparative study of phosphate solubilization and the hostplant growth promotion ability of *Fusarium verticillioides* RK01 and *Humicola sp.* KNU01 under salt stress. *Ann Microbiol* 65:585–593
- Rathod GR, Anand A (2016) Effect of seed magneto-priming on growth, yield and Na/K ratio in wheat (*Triticum aestivum* L.) under salt stress. *Indian J Plant Physiol* 21:15–22
- 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
- Resenburg LV, Kruger GHJ, Kruger H (1993) Proline accumulation as drought tolerance selection criterion: its relationship to membrane integrity and chloroplast ultrastructure in *Nicotiana glauca* L. *J Plant Physiol* 141(2):188–194
- Rosen AD (2003) Mechanism of action of moderate intensity static magnetic fields on biological systems. *Cell Biochem Biophys* 39:163–174
- Roshandel P, Azimian F (2015) Effects of magnetic field on growth and antioxidant capacity of *Artemisia aucheri* in normal or saline conditions. *Biol Forum Int J* 7(2):1095–1103
- Rudolph AS, Crowe JH, Crowe LM (1986) Effects of three stabilizing agents: proline, betaine, and trehalose on membrane phospholipids. *Arch Biochem Biophys* 245:134–143
- Russo A, Longo R, Venella A (2002) Antioxidant activity of propolis: role of caffeic acid phenethyl ester and galangin. *Fitoterapia* 73(1):S21–S29
- Ruzic R, Jerman I (2002) Weak magnetic field decreases heat stress in cress seedlings. *Electromagnetobiology* 21(1):69–80
- Sahebjamei H, Abdolmaleki P, Ghanati F (2007) Effects of magnetic field on the antioxidant enzyme activities of suspension-cultured tobacco cells. *Bioelectromagnetics* 28:42–47
- Sairam RK, Tygai A (2004) Physiology and molecular biology of salinity stress tolerance in plants. *Curr Sci* 86:407–421
- Salikhov KM, Molin YN, Sagdeev RZ, Buchachenko AL (1984) Spin polarization and magnetic effects in radical reactions. Elsevier, Amsterdam
- Samy CG (1998) Magnetic seed treatment. I. Influence on flowering, siliques and seed characteristics of cauliflower. *Orissa J Hort* 26:68–69
- Santoro MM, Lau Y, Khan SMA, Hou L, Bolen DW (1992) Increased thermal stability of proteins in the presence of naturally occurring osmolytes. *Biochem* 31:5278–5283
- Savostin PW (1930) Magnetic growth relations in plants. *Planta* 12:327
- Selim AFH, El-Nady MF (2011) Physio-anatomical responses of drought stressed tomato plants to magnetic field. *Acta Astronaut* 69:387–396
- Sen A, Alikamanoglu S (2014) Effects of static magnetic field pretreatment with and without PEG 6000 or NaCl exposure on wheat biochemical parameters. *Russ J Plant Physiol* 61(5):646–655
- Shaddad MA (1990) The effect of proline application on physiology of *Raphanus sativus* plants grown under salinity stress. *Biol Plant* 32(2):104–112
- Shine MB, Guruprasad K, Anand A (2012) Effect of stationary magnetic field strengths of 150 and 200 mT on reactive oxygen species production in soybean. *Bioelectromagnetics* 33(5):428–437
- Smith EJ, Neugebauer M, Balogh A, Bame SJ, Erdös G, Forsyth RJ, Goldstein BE, Phillips JL, Tsurutani BT (1993) Disappearance of the heliospheric sector structure at Ulysses. *Geophys Res Lett* 20(21):2327–2330
- Song W, Zhang Z, Shao H, Guo X, Cao H, Zhao H, Fu Z, Hu X (2008) Relationship between calcium decoding elements and plant abiotic-stress resistance. *Int J BioSci* 4(2):116–125

- Souza-Torres E, Porras-Leon E, Casate-Fernandez R (1999) Effects of magnetic treatment of tomato (*Lycopersicon esculentum* Mill) seeds on germination and seedling growth. *Hortic Abstr* 70:6892
- Souza-Torres AD, Garcia D, Sueiro L, Gilart F, Porras E, Licea L (2006) Presowing agnetic treatments of tomato seeds increase the growth and yield of plants. *Bioelectromagnetics* 27:247–257
- Telfer A (2014) Singlet oxygen production by PSII under light stress: mechanism, detection and the protective role of β -carotene. *Plant Cell Physiol* 55(7):1216–1223
- Tican LR, Auror CM, Morariu VV (2005) Influence of near null magnetic field on *in vitro* growth of potato and wild solanum species. *Bioelectromagnetics* 26:548–557
- Trebbi G, Borghini F, Lazzarato L, Torrigiani P, Calzoni GL, Betti L (2007) Extremely low frequency weak magnetic fields enhance resistance of *nm* tobacco plants to tobacco mosaic virus and elicit stress-related biochemical activities. *Bioelectromagnetics* 28:214–223
- Trotel P, Bouchereau A, Niogret MF, Larher F (1996) The fate of osmoaccumulated proline in leaf discs of rape (*Brassica napus* L.) incubated in a medium of low osmolarity. *Plant Sci* 118:1–45
- Vaezzadeh M, Noruzifar E, Faezeh G, Salehkotahi M, Mehdian R (2006) Excitation of plant growth in dormant temperature by steady magnetic field. *J Magnet Mater* 302:105–108
- Vashisth A, Nagarajan S (2010) Characterization of water distribution and activities of enzymes during germination in magnetically-exposed maize (*Zea mays* L.) seeds. *Indian J Biochem Biophys* 47:311–318
- Vasilevski G (2003) Perspectives of the application of biophysical methods in sustainable agriculture. *Bulg J Plant Physiol* 2:179–186
- Veeranjaneyullu K, Ranjitha-Kumari BD (1989) Proline metabolism during water stress in mulberry. *J Exp Bot* 40:581–583
- Wagner GJ (1993) Accumulation of cadmium in crop plants and its consequences to human health. *Adv Agron* 51:173–212
- Wever R (1968) Einflußschwacher elektro-magnetischer Felder auf die Periodik des Menschen. *Naturwissenschaften* 55:29–32
- Xiao-ju MM, Guo YG (1999) Study on the effect of tomato seeds physiology and biochemistry with magnetic field treatment. *Bull Bot Res* 99:1–8
- Xu C, Li Y, Yu Y, Zhang Y, Wei S (2015) Suppression of *Arabidopsis* flowering by near-null magnetic field is affected by light. *Bioelectromagnetics* 36:476–479
- Yancey PH (1994) Compatible and counteracting solutes. In: Strange K (ed) *Cellular and molecular physiology of cell volume regulation*. CRC Press, Boca Raton, pp 81–109
- Yano A, Hidaka E, Fujiwara K, Limoto M (2001) Induction of primary root curvature in radish seedlings in a static magnetic field. *Bioelectromagnetics* 22:194–199
- Yinan L, Yuan L, Yongqing Y, Chunyang L (2005) Effect of seed pretreatment by magnetic field on the sensitivity of cucumber (*Cucumis sativum*) seedling to ultraviolet-B radiation. *Environ Exp Bot* 54:286–294
- Zhu JK (2001) Plant salt tolerance. *Trends Plant Sci* 6:66–71

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