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Review

Improvement in growth of plants under the effect of magnetized water

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Abstract: The magnetic field can change the polarity characteristics and hydrogen-bond structure of water; therefore, magnetized water can affect plant growth and development. Magnetized water is hexagonal water created by passing water through a specific magnet that can activate and ionize water molecules to change its structure. This review highlights the use of magnetized water in the agricultural sector to enhance plant growth and food productivity. We discussed the impact of magnetized water on seed germination, vegetative growth, fruit production, soil and pigments of treated plants. Plant growth and development can be improved both qualitatively and quantitatively via irrigation with magnetized water. It can promote seed germination, seedling early vegetative development, improvement of the mineral content of fruits and seeds, the enzyme activity of the soil, improved water use efficiency, higher nutrient content, and better transformation and consumption efficiency of nutrients; it can also mitigate soil salinity. Furthermore, magnetized water had a substantial good influence on the mobility and uptake of micronutrient concentrations, as well as promoted better growth criteria, all of which increased biomass and total yield. Also, irrigating plants with magnetized water resulted in a considerable increase in chloroplast pigments (carotenoids, chlorophyll a, and b) and photosynthetic activity. Magnetizing low-quality water (brackish water, saline water or water contaminated with metals) can be considered as an alternative tool to overcome the problem of scarcity and shortage of water resources. As a result, magnetic treatment of irrigation water could be a promising technique to boost agricultural production while also being environmentally beneficial in the future. The major challenge in using magnetized water in agriculture is creating pumps that are compatible with the technical and practical needs of magnetic systems while also effectively integrating irrigation components.

Keywords: magnetized water; magnetic field; plant growth; seed germination; yield; soil salinity

1. Introduction

Magnetic fields can help plants grow and develop in the agricultural sector, with magnetizing treated water being one method of magnetic field application. Irrigation using magnetized water can improve agricultural production, plant growth, seed germination, seedling vegetative growth and seed and fruit mineral content. As a result, using magnetized water to increase agricultural production in the future may be among the most promising ideas, while also being environmentally beneficial. Since then, the water magnetizing technique has seen rapid advancements in a variety of fields, including irrigation [1,2], plant growth [3], plant productivity [4], wastewater treatment [5], and animal use [6,7].

Magnetic water treatment techniques have become one of the most widely used methods for enhancing the agriculture sector [8–10]. With the water crisis influencing many countries, using modern technologies and practices in agriculture are important for increasing water efficiency. The use of magnetized water has been proposed as a means of conserving water and improving agricultural productivity and quality [11]. In regions where freshwater is scarce, irrigating plants with contaminated water containing metals and salts is common. The magnetization of water can be utilized as a new method to increase plant growth via improved absorption of essential metals from wastewater [12]. Water scarcity in agriculture can be alleviated by reducing agricultural water consumption. However, the demand for agricultural food production is at an all-time high, particularly in developing countries. Increasing food production to feed an expanding population is a severe challenge. The limited supply of freshwater and land is under increasing strain. Furthermore, inappropriate agriculture and irrigation can exacerbate the salinization of the soil and subsequent salinization and accumulation of salts, degrading farmland quality [13].

Magnetic water, also called magnetized water, magnetic field-treated water or magnetically treated water, is water exposed to a magnetic field of a specific flow rate and intensity [14]. The physical, chemical, biophysical and physicochemical properties of water can change after being treated with a magnetic field. Water can have an important role in determining how biological materials react to magnetic fields. Because water is thought to be the major medium in which diverse reactions take place, it is possible that exposure to magnetic fields could modulate cellular metabolism by employing the water in our body as a key magnetic field receptor. The formation of hydrogen bonds, conductivity, activation energy, surface tension, size of water molecules, evaporation, mobility of salts, dissolved gases, and structural regularity have all been highlighted as differences between magnetic and non-magnetized water [15].

Drought, a lack of freshwater supplies to irrigation regions, and soil salinization are all hazards to irrigation agriculture. Reduced salinity harm to plant growth, as well as improved irrigation water productivity with ionized brackish water, is critical for the region's agricultural production to continue [5]. In plants cultivated in heavy metal-contaminated soils, magnetized water significantly increased the most antioxidant activities [2]. Soil salinization could be avoided by using magnetic water irrigation technology. For many years, magnetically treated water has been used to leach certain ions from the soil, and it has shown promise [16]. Several studies revealed that irrigating crops with magnetic water improves plant growth and production [17].

This paper focuses on the impacts of magnetized water on the plant's growth and development, which could be useful in agriculture. Due to some contentious results, the direct application of magnetized water to agriculture requires more study.

2. Effect of magnetic fields on the growth of plants

Plants, like all other living things on Earth, are affected by the geomagnetic field [18]. External application of a magnetic field or an electromagnetic field, which are different from a geomagnetic field, affects plant growth and development both in vitro and in vivo. The application of a magnetic field and/or electromagnetic field influences seed germination [19–22], seedling development [23,24], flower production [25], the proportion of leaves [26], biomass yield [27] and soil water dynamics [28]. Moreover, it helps the plant to overcome difficult environmental conditions, such as high salinity [3,19,25].

In addition to the greenhouse and field investigations, in vitro growth of species such as medicinal plants, herbs, ornamentals and field crops have been examined when subjected to an external magnetic field. Experiments in an in vitro environment revealed that a magnetic field influenced the growth and development of cultured cells, tissues and organs, as well as stimulated axillary and adventitious organogenesis. The particular parameters of the magnetic field, such as polarity, intensity, exposure time and magnet type, have an impact on in vitro plant growth and development. Because the reported effects were always genotype-dependent, each magnetic field should be tested separately before being applied to a specific genotype [29,30].

In vitro systems, unlike pot experiments or greenhouse ex vitro trials, have the advantages of a standard and controlled environment, as well as being easy and fast and having reliable experiment reproducibility. Additionally, such systems require minimal space and material [31]. As a result, they are ideal as model systems or tools for investigating various physiological, biochemical or molecular changes and processes triggered by environmental factors like a magnetic field. The majority of these experiments, on the other hand, used a static magnet or magnetized water, which is the subject of this mini-review. Irrigation using magnetized water is another unique feature of using the magnetic field to improve agricultural growth and development.

3. Changes in properties of water after magnetization

The flow rate of passing water through the magnetic field, the position of the permanent magnets relative to the flow of water, magnet arrangement (Figure 1), magnetic strength, time of magnetization and temperature are considered important factors in magnetizing water [32–34]. The application of a magnetic field to water (Figure 2) changes the atomic, electronic and molecular structures of water (Figure 3), including changes to the intracluster and intercluster structure, the formation of clustering structures and magnetic interaction between them, boiling point and viscosity solidification, dielectric constant, hydrogen-bond chains of molecules and polarization influence of water molecules [35–37]. The properties of magnetized water change optically. The ultraviolet (UV) absorption intensity of magnetic water, which is higher than that of pure water, grows exponentially as the magnetization period increases and the wavelength of UV light reduces. As a direct outcome of magnetization, these alterations are related to molecular clustering, atomic polarization and changes in the transition dipole moment of electrons within molecules [14].

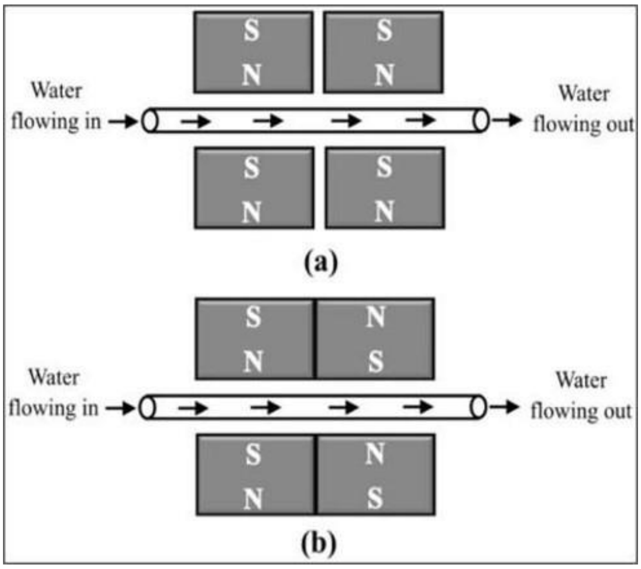

Figure 1. Arrangements of magnets through magnetizing water process: (a) non-reversed polarity and (b) reversed polarity [34].

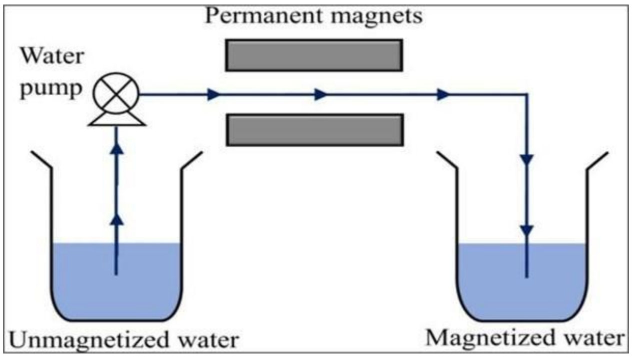

Figure 2. Magnetizing water by passing normal water through the magnetic field [34].

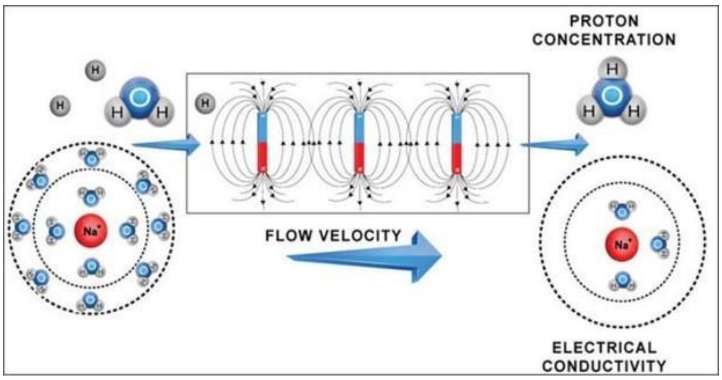

Figure 3. Changes in water and ion characteristics upon flow through magnetic field [36].

The properties of UV absorption and infrared, X-ray diffraction and Raman scattering of magnetized water are significantly changed as compared to untreated water. Also, the strengths of peaks are shifted and increased after magnetic field treatments [14,38]. Although some discrepancies may be due to differences in magnetizing apparatus, measuring instruments, water properties (impurities, dissolved gas content), magnetizing process, time of exposure to a magnetic field or variable conditions, applying a magnetic field reduced the surface tension and increased the pH of pure water [35]. Figure 4 summarizes the different factors which affect the properties of magnetized water produced after magnetization.

A saturation effect, a memory effect, temperature-dependent magnetization and changes in the surface tension forces are all key characteristics of magnetized water. The saturation effect implies that the characteristics of magnetized water can no longer be altered after reaching a maximum for both exposure length and field strength, regardless of whether the exposure period or field strength is increased [14]. According to a study of variations in infrared absorption of magnetically treated water, the magnetic impact decreased as the temperature increased due to a drop in the number of molecules in clustering structures, which was induced by an increase in the number of molecules with increasing thermal energy. Furthermore, the "memory effect" or "residual effect" of magnetized water refers to the fact that alterations generated by magnetic fields do not dissipate instantly once the magnetic field is removed. It has been observed that the magnetic field affects the memory time of magnetized water [39–41].

4. Studies on changes in plant growth using magnetized water

The biological effects of magnetic field treatments are determined by the strength of magnets, duration of water conditioning, especially the content of ions, volume and quality of water, flow rate and temperature [42,43]. Table 1 summarizes the latest studies carried out between the years 2022–2019 to investigate the impact of magnetized water on some plants.

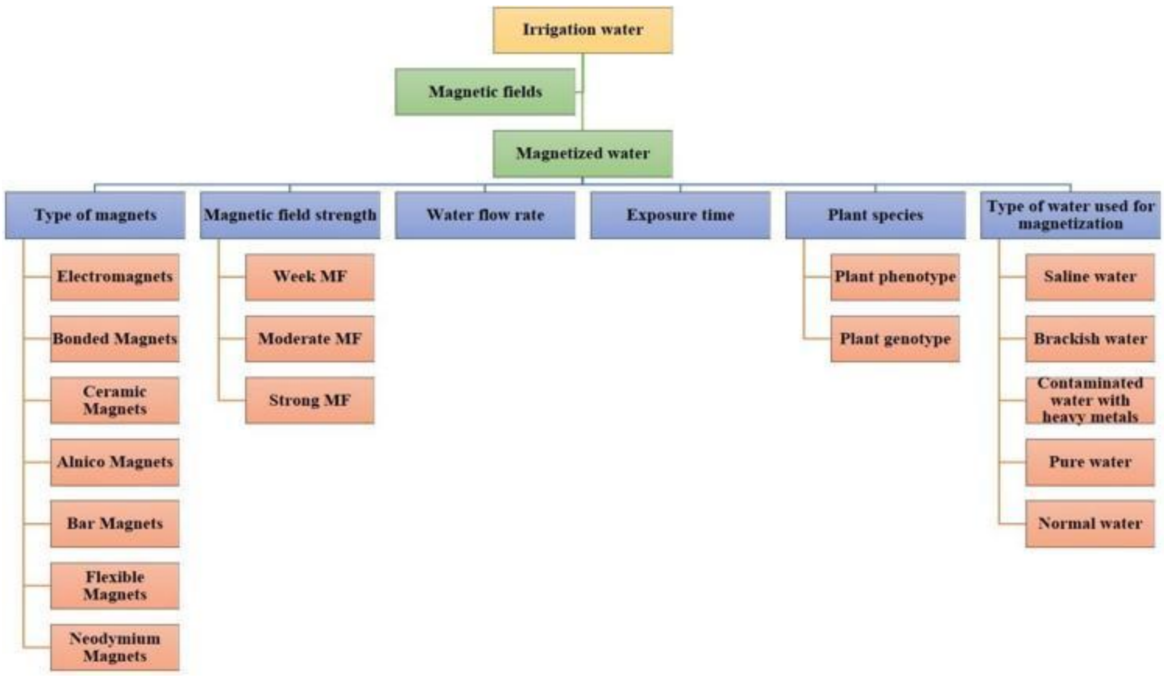

Figure 4. Factors which affect the properties of magnetized water produced after magnetization.

Table 1. Literature (2022–2019) showing the effects of magnetized water on different plant species.

Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Sunflower	Plants	The plants were watered with three different salinity levels which had electrical conductivities (ECs) of 0.7, 4 and 8 dS/m. The salinity of tap water is represented by the electrical conductivity's lower limit. Two magnetic intensities, 1000 and 3000 Gauss, were applied to the irrigation water treatment apparatus.	The salinity of untreated water has a significant negative impact on sunflower development. Irrigation with magnetized water (MW) can mitigate the negative impact of saline water and enhance sunflower growth. Depending on several factors (such as the part of the plant, the EC of water and the strength of magnetic field), magnetizing saline water can increase the root depth, germination, stem height and wet weight of the green part and root part of the sunflower plants.	[1]
Iceberg lettuce With two varieties: lemur iceberg lettuce and 077 iceberg lettuce	Plants	Four kinds of irrigation water were applied: ordinary irrigation water (IW1, EC = 0.96 dS/m), magnetized irrigation water (IW2, EC = 0.96 dS/m), saline water (IW3, EC = 4.56 dS/m) and magnetized saline water (IW4, EC = 4.56 dS/m). Three depletion ratios (DR) of field capacity (FC) (DR0 = 50%, DR1 = 60% and DR2 = 70%) and three slopes of hydroponic pipes (S1 = 0.0%, S2 = 0.025% and S3 = 0.075%).	Both varieties of iceberg lettuce had higher water productivity, total soluble solids and fresh weights after irrigation water had been magnetized. With the combinations of IW3DR2S3 and IW4DR1S3, both varieties recorded the highest fresh weight (3.10 kg/m) and water productivity values (39.15 kg/m^3). The combination of IW4DR1S3 yielded the maximum fresh weight (2.93 kg/m) and water productivity (36.15 kg/m^3) for iceberg lettuce 077. Saline irrigation of lettuce without magnetic treatment decreased its fresh yield by a factor of between 55% and 60%. While using normal water, the magnetic treatment had no effect on the weight of the lettuce when it was fresh.	[4]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Dry broad bean	Seeds and plants	Three magnetic treatments were used: magnetically treated seeds (MTS), magnetically treated irrigation water (MTIW) and no magnetic treatment of either the seeds or the irrigation water. Dry broad bean seeds were subjected to a 165-mT electromagnet-induced magnetic field for 2 and 4 min. A 165-mT magnetic field was applied to irrigation water.	Two-minute MTS and MTIW significantly increased plant growth and yield in broad bean plants. Compared to the control plants, the pods of the 2-min MTS and MTIW emerged 6 days earlier, whereas the pods of the 4-min MTS and MTIW emerged 5 days later. The quantity of seeds was the parameter most impacted, increasing by 21% for the 2-min MTS and MTIW in comparison to the control.	[8]
Maize	Plants	A brown coal and magnetization of Cu-contaminated water were applied to maize plants.	Water contaminated with copper sulfate or nitrate significantly increased shoot dry matter (distilled water) as compared to the control, which was irrigated with distilled water. MW caused significant increases in the concentration of Cu in plant tissues and phytoextraction efficiency (PE) of copper sulfate. On the other hand, the MW decreased the translocation efficiency, translocation factor and yield biomass of maize plants.	[12]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Barley (*Hordeum vulgare* L.)	Seeds and plants	At the center of magnets with variable gaps, the plates containing seeds were positioned vertically. Each magnet yielded 14–20, 32–42, 110–130 or 240–250 mT values. Two flat pole pieces (8 × 4.5 cm) were attached to each pole of the magnets to create a consistent magnetic field around the seeds.	Germination was enhanced by magnetic field treatment at lower strengths (≤125 mT). Cell membranes in roots were destroyed by the magnetic field, which can change the tissue's elemental composition. The concentration of macroelements (Ca, Mg, P and K) gradually decreased as the magnetic field strength increased, whereas the contents of microelements (Fe, B, Cu, Mn, Zn and Mo) increased in the roots. It appears that the magnetic moments' direction may have been affected by the magnetic field treatment at greater strengths (250 mT). Magnetic field application can improve germination, photosynthetic machinery and growth, as well as modify nutrient uptake and abundance in tissues.	[20]
Lettuce (*Lactuca sativa* L.)	Seeds and plants	The nutrient solution and water passed through magnetic fields. Lettuce seeds were divided into two groups and germinated under the effect of magnetized and non-magnetized water. The circulating hydroponic method was then used to cultivate each sprout group that was obtained from each water system by using magnetic and non-magnetized nutrient solutions.	The rate of seed germination was enhanced by the MW. The fresh weight (45.57%), dry weight (34.16%) and plant height (47.44%) were positively affected under the effect of the magnetized nutritional solution. The magnetized nutrient solution increased the quantity of chlorophyll a (16.43%) and b (26.30%), elements (such as N, Ca, P, K, Mg, etc.), vitamin C (2.87%) and carotenoid (13.01%).	[24]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Calendula officinalis	Plants	Two different types of soil additives (Fe_2SO_4 and peat moss) and three different types of water (tap water (TW), well water and magnetized well water) were used.	Saline well water had a negative impact on plant growth and flowering as compared to using TW. Plants irrigated with the MW exhibited a considerable improvement in all vegetative and blooming growth indices. Additionally, plants irrigated with the MW had higher mineral contents and higher survival rates than plants irrigated with TW. The levels of Na^+ and Cl^- in plant leaves were much lower after irrigation with the MW, demonstrating the significance of magnetization in reducing the negative effects of salinity.	[25]
Festuca arundinacea	Leaves	The amount of water was adjusted in accordance with the moisture of the soil. MW was prepared using a 20–2000mT electromagnetic field generator.	Both types of irrigation water caused plants to accumulate more Cd in their dead and senescent leaves than in other plant tissues. Senescent and dead leaf biomass increased after irrigation with MW, and a substantial amount of Cd (23.6%) was redistributed into dead leaves compared to the control. More Cd was removed from plants irrigated with MW by collecting their dead and senescent leaves. Magnetic fields were shown to lower the cost of disposing of harvested residue while increasing the phytoremediation efficacy of plants for Cd.	[26]
Celosia argentea	Seedlings	The seedlings received 3-day irrigation of double-deionized or MW during the cultivation process. The MW was created using a PEM-5005 P electromagnetic device, which has a 20–2000-mT magnetic field.	Root pruning increased the effectiveness of plants in phytoremediation, and this impact was improved when combined with irrigation with MW.	[27]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Barley (*Hordeum vulgare* L.; cv Giza-128)	Plants	Two factors were applied in the experiment: (1) water treatments (MW and non-magnetized water) and (2) five levels of salinity stress (320, 2000, 4000, 6000 and 8000 ppm). MW was prepared by passing water through a static magnetic field (0.35 T).	Irrigation of barley plants with magnetized saline water reduced the detrimental effects of salinity stress, increasing the grain yield by 14.75, 14.32, 16.06, 12.97 and 15.85% under 320-, 2000-, 4000-, 6000- and 8000-ppm salinity levels, respectively. Magnetized saline irrigation water boosted photosynthetic pigments and growth indices, even at high salinities, as compared to irrigation with non-magnetized saline water.	[43]
Festuca arundinacea	Seedlings	Two treatments were applied: MW and non-magnetized water.	MW alleviated oxidative damage, decreased the excreted Fe amount and increased the Cd excretion ability of *F. arundinacea*.	[44]
'Taifi' pomegranate (*Punica granatum* L.)	Shrubs	Water was subjected to a magnetic field device (strength = 14,500 Gauss and diameter = 2 in)	Enhanced chlorophyll content and nutritional status, decreased proline content, improved vegetative growth with minimum consumptive water use, promoted optimum water-use efficiency and reduced soil salinity.	[45]
Chickpea (*Cicer arietinum* L.)	Seeds and plants	Tubes surrounded by locally manufactured magnets with different overflows (0.2, 0.15 and 0.1 T).	MW increased the protein content in seeds and enhanced the contents of nitrogen, phosphorus, calcium and potassium in the leaves and seeds.	[46]
Corn	Seeds	Corn seeds were exposed to four irrigation treatments with MW, namely, magnetic induction of 0.28 T (T1), 0.229 T (T2), 0.029 T (T3) and 0 T (control).	The various percentages of germination in corn seeds were significantly influenced by the different magnetic induction conditions applied via seed treatment and irrigation water. No significant effect among the three treatments (T1, T2, T3) was observed on germination time, fresh mass, dry mass or seedling vigor.	[47]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Balkız bean (*Phaseolus vulgaris*)	Seeds and plants	Irrigation treatments were magnetized and non-magnetized, and water salinities were 0.38, 1.5, 4.5 and 7.0 dS/m^{-1}	Irrigation plants with MW had increased fresh yield (21.35%), water-use efficiency (23.00%) and irrigation water-use efficiency (14.8%) as compared to the non-magnetized water-treated plants. Saturated soil salinity was decreased by 20%. The green leaf area (13.4%), stomata (23.9%) and leaf succulence (3.3%) increased in the MW-treated plants as compared to the non-treated plants. Additionally, under magnetized saline water conditions, bean crops showed a capacity to defend water in tissue against salinity toxicity up to a 5.24 dS/m soil salinity level.	[48]
Tabasco pepper	Plants	The MW was prepared using a Quantum Biotek magnet, which produces a changeable magnetic field (0 to 156 mT). The MW was circulated five times through the magnet at a flow rate of 10 L/min. The irrigation levels were settled to 100% and 50% of FC. According to the kind of water and the amount of irrigation, it produced four treatments: MW at 100% FC (MTW100), MW at 50% FC (MTW50), control water at 100% FC (CON100) and control water at 50% FC (CON50).	At both irrigation levels, the fruit yield of plants watered with the MW exhibited a non-significant increase, whereas large- and medium-sized effects were found for the dry weight and fruits per plant. Quantum yield was the only photosynthetic measure to show a significant increase, despite increases in net assimilation and stomatal conductance of 17% and 28%, respectively. However, interestingly, the relative water content and electrolyte leakage in leaves were not significantly impacted at 50% FC.	[49]
Green pea (*Pisum sativum* L.)	Plants	Four treatments were used: full irrigation (FI) with non-magnetized water (W1) and three different irrigation levels (I1 = 100%, I2 = 80%, and I3 = 60%) with MW (W2).	A good technique to increase green pea plant yield, enhance quality traits and improve water-use efficiency is through irrigation with MW.	[50]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Cotton (*Gossypium hirsutum* L.)	Seeds and plants	An external permanent magnetizer of the CHQ type was used to prepare MW using two types of water: fresh and brackish. It was built of sintered Rufe-B and had an 8 × 10 cm^2 magnetic field with a 300-mT magnetic field strength. The magnetic time was set to 30 min while the water flow rate was 14.7 L/min when making MW.	Irrigation with magnetized fresh and magnetized brackish water increased the germination rates of cotton seeds by 13.14% and 41.86%, respectively. When cotton was irrigated with MW instead of non-MW, the stomatal limit value decreased and the net photosynthetic rate, transpiration rate, and instantaneous water usage efficiency were significantly enhanced. Under the condition of the magnetized brackish water, cotton had stronger effects on photosynthesis and water-use efficiency than under the magnetized freshwater condition.	[51]
Rice and wheat	Seedlings	Plants were irrigated with three types of activated water: magnetized distilled water, aerated distilled water and magnetized aerated distilled water with a total of four treatments for each species.	When wheat plants were irrigated with MW irrigation, their total root volume and root length increased by 7.7–8.6% and 17.2%, respectively. This resulted in a notable 13.6% increase in aboveground dry biomass. The growth of rice seedlings and roots was also enhanced by irrigation with MW and magnetized aerated water. The growth of wheat seedlings and roots, however, was inhibited by irrigation with magnetized aerated water.	[52]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Wheat	Plants	There were three different irrigation rates: 80% of the FC, 65% of the FC and 50% of the FC. TW, MW, oxygenated water (OW) and magnetized and oxygenated water (M&OW) were the four different forms of irrigation water. Tap water was magnetized repeatedly using a 3000-Gs magnetic field (magnetic ring, 3.0-cm inner diameter, 3.4-cm outer diameter, 3.2-cm height) to create MW.	Under various irrigation regimes, activated water enhanced wheat growth. The plant height, leaf area, aboveground biomass, special product analysis division (SPAD) value and photosynthetic indicators increased. With varying levels of irrigation, the yield and water usage efficiency changed. MW and OW outperformed TW in terms of yield and water usage efficiency at 80% FC. MW, OW and M&OW had a greater yield and water usage efficiency than TW with 65% FC. OW and M&OW exhibited noticeably greater yield and water usage efficiency than TW at 50% FC.	[53]
Sweet basil (*Ocimum basilicum* L.)	Plants	Arbuscular mycorrhizal fungi, magnetic solution and phosphorus concentrations of 0, 5, 10, 20 and 40 mg/L were used.	Both the magnetic solutions and arbuscular mycorrhizal fungi impacted the basil plant's growth, the shoots' nitrate content and the rhizosphere conditions.	[54]
Beta vulgaris L.	Plants	Two treatments were applied, including MW and non-MW treatments (Control, C). The MW was prepared by using a magnetic device (0.8–0.9 T).	Magnetic treatment caused increases in the dissolution of salts and EC in the water of the irrigated soil. Ca^{2+} (16.6%), K^{+} (9.7%) and Na^{+} (13.4%) contents in the MW-irrigated soil were decreased. The concentrations of Na^{+} (4.91%) and Fe^{2+} (126.3%) ions in the roots and leaves were increased in the plants irrigated with MW. The plants irrigated with MW had higher weights for the fresh leaf, dried leaf and root.	[55]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Populus × euramerican 'Neva'	Seedlings	Treatment of $Cd(NO_3)_2$ solutions (at 0 and 100 mML^{-1}) involved the application of a magnetic device with a 300-Gs field strength.	Under Cd stress, magnetization can enhance seedling growth and speed up the production of photosynthetic pigments at a concentration of 100 $\mu mol \cdot L^{-1}$. Additionally, it might support root growth, which was advantageous for the uptake and transfer of the mineral nutrient components. The activity of nitrate reductase and nitrite reductase in leaves was stimulated by tolerance to Cd, which appeared to lower the amount of nitrite present; otherwise, the accumulation of NH^{4+} in roots could provide an abundance of raw materials for the synthesis of amino acids triggered by irrigation with magnetically treated water. By promoting glutamine synthetase (GS) and glutamate synthase (GOGAT) activity, the magnetization's stimulation of the GS-GOGAT cycle may increase the effectiveness of nitrogen metabolism.	[56]
Strawberries	Plants	Four treatments were applied: (1) magnetic water level 1 = 3800 Gauss, (2) magnetic water level 2 = 5250 Gauss, (3) magnetic water level 3 (MWL 3) = 6300 Gauss and (4) normal water. Treatments of plants were in combination with three soilless culture systems (a nutrient film technique (NFT) hydroponics, tower aeroponics and pyramidal aeroponics).	The combination of the NFT system and MWL 3 produced the most leaves, the highest stem diameter and the largest leaf area in the strawberry plants when compared to the control. This combination outperformed all other treatments in terms of fruit yield, quality and other factors like titratable acidity, total soluble solids and fruit hardness.	[57]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Wheat (*Triticum Aestivum* L.) with three cultivars (Aksad 901, Karem and Gamina)	Seeds and plants	The magnetic treatment involved subjecting the seeds to various periods of magnetization (0, 15, 30 and 45 min) and the passing of seawater levels (0, 20, 50 and 80%) through a magnetic field (14500 Gauss or 1.45 T).	When compared to the three untreated wheat cultivars, either the magnetically stimulated seeds or irrigation with magnetized saltwater performed better. Magnetized irrigation water had no effect on the seed germination rate, but magnetic pre-sowing seed treatment increased the seed germination rate, especially under the conditions of 80% salinity and 45 min, compared to untreated seeds.	[58]
Date palm Hayany	Plants	Four levels of K-Humate and two kinds of water irrigation were used. MW was prepared by passing water through a field using a Magnolith permanently with a strength ranging between 2000–4000 Gauss.	Higher yield and bunch weight were obtained by treatment of K–Humate at 300 g/tree with magnetic water irrigation. In both seasons, this treatment resulted in the highest fruit weight, flesh weight, size and dimensions. By applying K-Humate and magnetic water irrigation, the total soluble solids, reducing sugar and nonreducing sugar contents in the fruits also increased. As compared to the control and other treatments, this treatment produced the highest values for the contents of N, P, K, Ca and Mg.	[59]
Maize cv. Maxima	Plants	The kind of irrigation water at two levels (crossed and without passing through a magnetic field) and the tape drip irrigation system at two levels (looping and no looping) were used as experimental treatments (looping and no looping). A magnetic field was produced using tube wires, an AC-to-DC converter and a looping arrangement made of three-way tubes.	MW increased the system's average discharge by 4.2% and reduced its coefficient of variation by 0.98%. Magnetic water irrigation increased the fresh weight (9%), water-use efficiency (9.5%), dry weight (1.4%) and leaf area (17%) as compared to irrigation with to non-MW.	[60]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Soybean	Seeds and plants	The major two factors (F1) were plots that had been bio-fertilized and those that had not. Three application rates (50%, 75% and 100%) of the three N, P and K fertilizers were the sub-factors (F2). Seeds that had been magnetically treated and those that had not been treated (NM) were the sub-sub-factors (F3). All factors were investigated for dry soybean seeds without soaking and soaking seeds in MW.	The soybean seed yield increased by 49.98% for the bio-fertilized magnetized seeds at 75% and 100% mineral N-P-K fertilization as compared to NM soaked seeds at 50% N-P-K without bio-fertilization. The protein increased by 41.69% after the 75% mineral fertilization, whereas the proline decreased by 46.68%. Before planting, treated seeds with the magnetic field and combined bio/mineral N-P-K fertilization decreased the proline that mitigates the stress conditions.	[61]
Sunflower (*Helianthus annuus* L.)	Plants	Along with three other salinity irrigation treatments, there were two separate magnetic (W1) and non-magnetic (W2) irrigation water treatments.	The effects of the W1 and W2 irrigation waters on stem height, stem diameter, head diameter and leaf fresh mass were significantly different. After irrigation with magnetic water, sunflower production (4064 kg/ha) increased. Additionally, salinity decreased grain yield. The productivity and effectiveness of irrigation water can be improved by irrigating with saline water that has been exposed to a magnetic field.	[62]
Artichoke (*Cynara scolymus* L.)	Plants	There were four levels of electromagnetic field intensity in the experimental treatments (0, 3000, 6000 and 10000 Gauss)	Irrigation with MW had a substantial impact on plant development, shoot weight, root weight, the efficiency of water consumption and chemical compounds. In samples that were irrigated with water magnified with 6000G, the maximum phenol concentration (3.99 mg/g) and antioxidant activity (66.74%) of plant extract were found.	[63]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Spinach (*Spinacias Oleracea* L.)	Plants	The spinach was irrigated using a surface drip irrigation system with three levels of irrigation water salinity (SL1=1.21, SL2=2.98 and SL3=4.54 dS/m), as well as four irrigation water stresses (IR100%, IR85%, IR70% and IR55%) under magnetic water treatment and non-magnetic water treatment.	The application of treatment SL1 and IR100% under the condition of MW for both seasons produced the greatest values for the yield and quality of spinach leaves. When treatment was applied at SL1 and IR55% with MW, the seasonal actual evapotranspiration of leaves was the lowest for both seasons. The application of treatment SL1 and IR70% with MW resulted in the greatest values for spinach leaf irrigation water-use efficiency and water-use efficiency.	[64]
Cowpea (*Vigna unguiculata* L. Walp.)	Plants	There were two treatment regimes: the first regime was irrigated with MW and the second regime was irrigated with non-MW.	The shoot height, number of leaves, leaf area and internode length of cowpea plants were enhanced with the use of MW. Plants treated with MW had significantly higher growth indices (net assimilation rate, crop growth rate, leaf area ratio, root-to-shoot ratio and tissue water content) than the plants in the control group. Biochemical parameters such as photosynthetic pigments and parameters related to the yield (number of fruits, seeds in pods and seed weight) were also significantly higher in plants treated with MW as compared to plants treated with TW.	[65]
Chickpea (*Cicer arietinum* L.)	Seeds and plants	Three tubes encircled by magnets with different overflows (0.2, 0.15, 0.1 T) were used to prepare MW. A 100-kg treatment of chemical fertilizer was applied to the soil in planting lines.	A significant effect of fertilizing and magnetization was observed on the height of plants, nutrient contents, the number of pods and dry vegetative weight as compared with the control.	[66]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Potato	Plants	There were two types of treatments: MW and normal water. To prepare the MW, a magnet device and an electromagnetic device were inserted together in the water's passage.	The total yield of potatoes treated with MW (25.4 tons per hectare) was higher than that of the potatoes treated with non-MW (19.4 tons per hectare). Magnetizing saline water significantly increased the size and weight of tubers, germination, yield, quality, freshness and the number of tubers per plant, as well as the reduction of weeds and crop pests.	[67]
Wheat (*Triticum aestivum* L.) Cultivar IPA 99	Seedlings	Two salinity levels of water were used to irrigate the plants and the water was magnetized using a magnetron (4000 Gauss). There were four types of treatments: M1 (plants irrigation with saline magnetize water; EC= 1.83 ds/m), M2 (plants irrigation with saline water; EC=2.728 ds/m), M3 (plants irrigation with saline magnetize water; EC=2.8ds/m), and M4 (plants irrigation with saline water; EC=3.17ds/m).	The magnetization of saline water decreased its harmful effects on plants. Superoxide dismutase, catalase and peroxidase enzyme levels increased for the magnetized saline water by 85%, 65% and 34%, respectively. The morphological features of the plants irrigated with magnetized saline water improved in terms of the thickness of mesophyll tissue, epidermal, leaf and vascular bundles.	[68]
Mentha piperita	Plants	The water was magnetized using alternating magnetic fields (M1: control, M2: 100 mT, M3: 200 mT and M4: 300 mT) and different salinity levels (S1: control, S2: 40 mM NaCl, S3: 80 mM NaCl and S4: 120 mM NaCl). The growth mediums were as follows: X1: coco peat, X2: palm, X3: coco peat + perlite and X4: palm + perlite.	At the greatest salinity levels, the application of magnetic treatments, particularly at the 100- and 200-mT levels, significantly increased plant concentrations of N (1.08%, S3M4X1), P (0.89%, S3M3X1), K (3.23%, S3M3X1), Ca (53.6 mg/kg, S4M4X4) and Mg (39.63 mg/kg, S3M3X2) compared to plants in the non-magnetized group. Under salt stress, MW increased the concentration of Fe and Zn in the plants. The MW may be more successful at reducing salt stress if combined with the organic and mineral media, as it improves nutrient uptake.	[69]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Eggplant (*Solanum Mebongena* L)	Seeds and plants	Three magnetized intensities were used (M0=0 Gs, M1=600 Gs, M2=1200 Gs) and two levels of bio-fertilization: level 1 (without bio-fertilizer) and level 2 (with bio-fertilizer).	The MW-treated plants had a significant increase in the length of the plant and yield characteristics. All growth characteristics were significantly impacted by the binary interference between MW and bio-fertilization.	[70]
Radish	Plants	Three treatments were applied: distilled water (control), distilled water magnetized for 30 min and distilled water magnetized for 1 h. The field intensity of the magnets was 0.6 T.	Magnetizing water for 1 h caused an increase in the tuber circumference (46%), leaf area (29%), fresh weight of shoot (19%), chlorophyll a (46%), carotenoid (43%), dry weight of the tuber (82%) and fresh weight of tubers (100%). The best treatment was the 1-h MW treatment.	[71]
Winter wheat	Plants	A tank for holding water, a pump, an exit pipe and a magnet make-up system were used to magnetize water. A permanent magnet with a 3000-G field intensity was used. To magnetize the water, the water was passed through the pipe where the permanent magnet was positioned on the pipe's outer wall. The eight irrigation treatments were: no irrigation, 0 mm; pure groundwater irrigation with a total irrigation amount of 180 mm; MW irrigation with total irrigation amounts of 60, 120 and 180 mm, respectively; and GD1, GD2 and GD3 (ionized water irrigation).	When compared to pure groundwater, MW had a 10.1% higher grain yield at 120 mm. The MW had the highest water-use efficiency for 120 mm at 28.0 kg $ha^{-1}mm^{-1}$. For irrigation using MW, water-use efficiency at 120 mm was 22.3 kg ha^{-1} mm^{-1}, i.e., 8.8% more than with pure groundwater. MW irrigation can enhance the growth, total yield and water-use effectiveness of wheat plants.	[72]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Velvet bean (*Mucuns pruriens*)	Seeds and plants	The structured water was produced by a bespoke water generator (a closed-loop water system) using two energy fields (magnetic and UV radiation). The treatments were as follows: magnetized seed, MW and water treated with a hydroxylated water generator. Three soil moisture levels were applied to the velvet bean plants.	Under conditions of low soil moisture, the combination of magnetic seed and structured water treatments increased water savings from 32 to 52% over the unstructured water treatments. The combined seed and water treatments significantly reduced irrigation water use by altering how drought-adapted plants respond to water stress circumstances.	[73]
Winter wheat	Seeds and plants	Winter wheat was grown hydroponically with the following treatments: a control group, oxidation, magnetization and a combination of magnetization and oxidation.	Plants watered with oxidized water (along with oxidized and subsequently magnetized water) displayed better grain yields and water-use efficiency than control plants under identical irrigation levels. Additionally, plants irrigated with magnetized and/or oxidized water showed significant increases in root vigor, root length density, root weight density and root surface area density. Cultivation with magnetized and/or oxidized water encourages root growth and increases the chlorophyll content of leaves and root/shoot ratio. Additionally, the plant's root vigor was enhanced by the magnetic and/or oxidation treatment of brackish water, which should have a positive effect on crop yield.	[74]
Jojoba (*Simmondsia chinensis*)	Seedlings	Four treatments were used: magnetized normal water (NW = 2.11 DSm^{-1}) and different concentrations of Red Sea water (RSWC1 = 5.61 DSm^{-1} and RSWC2 = 7.01 DSm^{-1}). MW was prepared using a magnetic field of 180 mT.	All magnetized concentrations of saline water exhibited significant enhancements in all characteristics compared with the controls, except membrane damage, proline and germination rate. Compared to RSWC1 and RSWC2, the response of all features was more substantial for the NW.	[75]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Raphanus sativus L.	Seeds and plants	Ten *R. sativus* seeds were put in petri dishes with Whatman No. 1 filter paper layered in two layers. The petri dishes were filled with 3 ml of water. Then, 3 ml of the treated liquid was added to each plate. Exactly the same amount of magnetic water was added to each petri dish.	The highest plant height, stem length, root length and fresh and dry weights of root and shoot systems were found in plants that were irrigated with MW. *Raphanus sativus* grown with MW had improved physical soil characteristics compared to the control.	[76]
Tobacco (*Nicotiana tabacum* var. Turkish)	Plants	In a hydroponic experiment, four magnetic treatments were used: distilled water, magnetized distilled water, TW and magnetized TW. The intensity of the magnetic field was about 0.07 T.	Shoot height and root length significantly increased in plants that were irrigated with magnetized distilled water. The photosynthetic rate and protein content followed the same trends; however, there were no significant differences in the stomatal conductance or transpiration rate. In contrast, plants that were irrigated with TW showed a substantial increase in total carbohydrates. Plants irrigated with TW and magnetized TW had distorted chloroplasts and damaged thylakoid membranes linked with plastoglobules.	[77]
Wheat, barley and lentil	Seeds and plants	Seeds of wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), trigonella (*Trigonella foenum-graecum*) and lentil (*Lens culinaris* M) plants were treated with fresh water (control), magnetized low-saline water and non-magnetized low-saline water.	When seeds were treated with MW, their water absorption rates were higher than those treated with non-MW. When compared to the control treatment, treating plant seeds with MW during germination improved the germination, seedling length, fresh weight, dry weight, vigor index and biomass accumulation in the wheat, barley, trigonella and lentil plants.	[78]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Grape (*Vitis vinifera* × V. labrusca cv. Summer Black)	Plants	Four treatments were applied: MW irrigation treatment (M0), non-MW irrigation (NM0), magnetized nitrogen (MN) and non-magnetized nitrogen (NMN).	MN had a marked impact on the ratio of root to crown, as well as on the biomass of the leaves, roots and whole plants as compared with NMN. In the MN treatments, a significant increase was observed in the stomatal conductance, pigment content of leaves, actual photochemical efficiency, photochemical quenching coefficient and net photosynthetic rate. In the contrast, intercellular CO_2 concentration, non-photochemical quenching coefficient, non-photochemical dissipation and excitation pressure were significantly decreased.	[79]
Winter wheat	Seeds and plants	The magnetic field was produced by using an electromagnet with an intensity of 0.2 T. Three treatments were applied: T1 (magnetized seeds + MW), T2 (normal seeds + MW) and T3 (normal seeds + non-MW).	MW boosted the growth of wheat and increased water-use efficiency, yield, plant height and leaf area index with different levels. Increases were also found in the effective panicle number, spikelet number and rate of the grain yield of the T1 and T2 treatments compared with the T3 control treatment.	[80]
Moringa (*Moringa oleifera* and *Moringa peregrina*)	Plants	Three irrigation regimes were applied: 100%, 50% and 20% FC and two water treatments (normal water and MW). The water was magnetized using a magnetic device with 30 mT of strength.	The physiological traits and growth parameters of the Moringa species were significantly impacted by drought stress. MW helped to mitigate the negative impacts of drought stress, the Fv/Fm ratio, chlorophyll content, leaf gas exchange and ion levels.	[81]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Tomato	Seeds and plants	Water was flowed through a magnetic flux density of 319 Gauss while tomato seeds were placed on a permanent magnet (1000 Gauss) for 24 h. There were four treatments: T1 [magnetized seed (MS) and MW (T1)], T2 [non-MS (NMS) and MW], T3 [MS and non-MW)] and T3 [NMS and non-MW].	Tomato yield increased by 27% when NMS and MW were combined relative to the 44% when the magnetized seed and water were combined. MW had more influence on tomato yield than just magnetizing the seed and irrigating with non-MW. All heavy metal concentrations in the tomato were within FAO/WHO permitted levels, and MW did not introduce any heavy metals that would be detrimental to humans.	[82]
Nitraria, Haloxylon and Atriplex	Plants	Plants were irrigated with two types of water: non-MW and MW.	Species irrigated with MW performed better on the growth metrics that were measured. The three species irrigated with MW showed increases in the leaf development of 121.74 (19.59%), leaf area index of 108.97 (17.5%) mm^2, special leaf area of 8.68%, relative water content of 9.81% and SPAD of 14.77% compared to plants irrigated with normal water.	[83]
Wheat	Seeds and plants	Magnetic fields (400, 500 and 600 mT) and different types of water (distilled and saline water) were applied to wheat plants.	Wheat seed germination and growth characteristics were significantly impacted by the strength of the magnetic field and the type of treated water. The morphological characteristics of the treated plants were improved. Groundwater-treated control seeds had a germination rate of 20%, while 400-mT-treated seeds had a germination rate of 53.3%. The root lengths that were impacted by distilled water in the 400-mT field and control groundwater were 155.3 and 20.0 mm, respectively. The amount of treated distilled water with a 600-mT magnetic field per kilogram of seedling fresh weight was the highest.	[84]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Parsley (*Petroselinum Crispum*)	Plants	Four different MW treatments were applied. The MW was passed through a magnetic funnel, once, three times, four times and six times compared with the TW as a control.	Parsley irrigated with MW showed an increase in germination, plant height, number of leaves, leaf area, chlorophyll content and certain components (K, Ca, Mg) as compared with the control. The outcomes showed that MW can be a potential method for a high parsley yield.	[85]
Spinach Matador (*Spinacia Oleracea* L)	Plants	Two salinity levels were used in the pot experiment: 0.2 g/L (TW) and 2.2 g/L (TW plus NaCl). A 13.5-mT magnetic treatment device was used to treat the irrigation waters.	With MW, the relative growth rate increased in response to irrigation, reaching 6.9% and 28.8% higher levels than the control salinity levels of 0.2 g/L and 2.2 g/L, respectively. In terms of the characteristics of the soil after harvest, irrigation with magnetized fluids raised the EC and moisture while decreasing the pH. In comparison to the soil at T0, the concentrations of all key elements (Ca, Na, Mg, K, Cl) were higher in the pots irrigated with magnetized fluids. The magnetic treatment increased the soil's ability to replace calcium with sodium by using 2.2 g/L of salty water.	[86]
Wheat (*Triticum aestivum*) (Three varieties: Sakha-94, Maser-2 and Gemiza-11)	Plants	In this study, there were two factors: 1) three water treatments for irrigating with brackish water, magnetized brackish water (BW 1) and magnetized brackish water (BW 2), along with three wheat varieties (Sakha-94, Maser-2 and Gemiza-11).	In all evaluated vegetative development parameters at 75 DAS (i.e., plant height, fresh and dry weight of wheat shoot, water contents and flag leaf area), irrigation with magnetically treated BW1 or magnetically treated BW2 surpassed irrigation with brackish wheat cultivars. The most significant crop yield was raised by irrigation using magnetic water.	[87]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Melon (*Cucumis melo* L.)	Plants	A total of two factors were used: the first involved two types of fertilizer treatment (urea 50 $kg \cdot N \cdot ha^{-1}$) with bio-fertilizer (*Azospirillum brasilense* and *Azotobacter chroococcum*) and chemical fertilizer (urea 100 $kg \cdot N \cdot ha^{-1}$), and the second involved MW and non-MW.	When compared to non-MW, MW showed considerable superiority in all study trait rates. The highest values of all study traits were found in the treatments that combined bio- and chemical fertilizers with MW, including the fruit yield (7.2 $kg \cdot plant^{-1}$), fruit weight (3.4 $kg \cdot replicate^{-1}$), total yield (28520.0 $kg \cdot ha^{-1}$), fruit length (27.6 cm), fructose sugar content in fruits after 24 days of storage (13.1%), fruit diameter from the outside and inside (16.8 and 5.1 cm, respectively) and fruit fiber content.	[88]
Corn (*Zea mays*)	Seeds and plants	Four treatments were used: a control, M1 (three magnets), M2 (six magnets) and M3 (nine magnets). Permanent magnets (70 mT) were used to produce MW.	MW increased the dry weight and enhanced the shoot length of treated plants. Magnetizing water with six magnets yielded the highest increase in the length of corn plants. MW had no effect on the size of the roots, the thickness of the stems or the fresh weight.	[89]
Chili pepper (*Capsicum annuum*)	Seeds and plants	Four treatments were used: a control, M1 (three magnets), M2 (six magnets) and M3 (nine magnets). Permanent magnets (70 mT) were used to produce MW.	The characteristics of plants changed when irrigated with MW. No significant differences in plant height or stem thickness was observed among the four treatments. Irrigating plants with MW had a substantial impact on the number of leaves, as the chili peppers in the M2 group had the highest number of leaves. The impact of MW depended on the number of magnets used for the magnetized irrigation water.	[90]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Bell pepper (*Capsicum annuum* L.)	Seeds and seedlings	To acquire water that had been magnetically treated, a Sylocimol Residence (Timol) magnetizer was employed. The device has a 1000-Gauss magnetic field and is made up of alternating magnets shielded by a stainless steel cylinder (16.5 cm in height and 10 cm in diameter). Two factors were adopted as follows: The first factor consisted of three water replacement depths based on crop evapotranspiration (50%, 75%, and 100% of ETc). The second factor was the application of irrigation water with or without magnetic treatment.	The application of MW to seeds enhanced germination one day prior to those irrigated with non-MW when cultivated with SS. With a 42% increase in SS cultivation with the application of magnetically treated water compared to the application of untreated water, there was a substantial interaction for chlorophyll A. When MW was applied, evaporation was significantly reduced and Su and SS cultivation showed higher gravimetric moisture levels.	[91]
Maize (*Zea mays* L.)	Seeds and plants	Two magneto-priming seed treatments [NMS and MS] were tested in the lab to investigate how they affected the germination of maize under four different salt stress levels (320, 1000, 2000 and 3000 ppm). Three factors were examined in the field experiments: (1) three salinity irrigation levels (1000, 2000 and 3000 ppm); (2) three magnetized irrigation water treatments (Un-MW (0 mT); MW1(0.75 mT) and MW2 (3.75 mT); and (3) two MS treatments.	Compared to NMS, seeds that had been magnetized and germinated under various salinity levels had a higher germination percentage. When magnetized maize seeds were sown and magnetized brackish water was used for irrigation, salt stress was reduced, which improved maize yield and water productivity. Under the condition of seeding with MS, the improvements in biological and grain yields were 13.30 and 19.37%, respectively.	[92]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Watermelon (*Citrullus lanatus*)	Seeds and plants	MW was prepared using a 319-Gauss magnetic flux density (31.9 mT). Water was used according to the treatments' water requirements of 100%, 80%, 60% and 50%. Watermelon seeds were planted and divided into two groups with 16 pots for MW and 16 pots for non-MW.	The yield of watermelon and water-use efficiency were improved by magnetic treatment of irrigation water. MW also enhanced the quality by increasing the contents of crude protein, ash, moisture content, fat, carbohydrate, crude fiber and oil in the watermelon.	[93]
Eggplant	Plants	Two treatments were applied: irrigation with non-MW and irrigation with MW. The MW treatment was performed with a magnetic device with a magnetic field intensity of 600 Gs.	The MW treatment significantly increased the soil nutrient levels, soil Proteobacteria abundance and soil enzyme activities, as well as the length, width and fresh weight of the leaves and fruits, as compared with the non-MW treatment. The MW treatment increased the vitamin C, organic acid and mineral contents of eggplant fruit as compared to the non-MW treatment.	[94]
Wheat	Plants	Two factors were applied: water type, i.e., magnetized and non-magnetized water) and three levels of water salinity stress (320, 3000 ppm and 6000 ppm).	When wheat plants were irrigated with magnetized saline water, the detrimental effect on grain yield per tiller under salinity levels of 3000 and 6000 ppm, respectively, was reduced from 66.12 to 25.96% and 87.68 to 69.30% as compared to those that were irrigated with the same levels dissolved in normal water.	[95]

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Plant species / cultivars	Plant organ	Magnet intensity / treatment	Effect	References
Populus× *euramericana* 'Neva'	Plants	Different salinities (0 and 4.0 g L^{-1} of NaCl) of irrigation water were used to irrigate the seedlings. Magnetic Technologies provided a magnetic treatment system with a permanent magnet (U300 Gs).	Improvements were found in the seedling height, basal diameter, leaf area and biomass of leaves and roots as compared to the non-magnetic treatment. The magnetic treatment group had a higher net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration and water usage efficiency. However, the magnetic treatment group had a lower transpiration rate and stomatal limiting value. MW irrigation promoted seedling growth, root formation, photosynthesis and mineral nutrient levels. Saline water's characteristics were enhanced by the magnetic treatment, suggesting that it can be used for irrigation.	[96]

4.1. Effect of magnetized water on seeds germination and seedlings growth

The effect of magnetic fields on plant growth has been investigated extensively, but not thoroughly enough. Many recent studies have found that applying a magnetic field to seeds or water improves the germination of treated seeds, reduces the time to germination and promotes the seedling growth of a variety of crop species. The germination of seeds and the growth and reproduction of the plant, as well as meristem cell proliferation, were improved when the seeds were magnetically treated. When irrigation water or planted seeds were subjected to a specific magnetic field, there was an increase in germination and growth in tomato (*Solanum lycopersicum*) [3,5], cucumber (*Cucumis sativus*) [9,10], sunflower (*Helianthus annuus*) [11], chili pepper (*Capsicum annuum*) [90], corn (*Zea mays*) [89], pepper (*Capsicum annuum*) [97] and potato (*Solanum tuberosum L.*) plants [98]. In addition, the height of the plant, dry weight and seedling vigor were all improved by magnetized water treatment.

In the study by de Almeida et al. [9], they investigated the effects of irrigation with magnetized water on the growth parameters (plant height and stem diameter) of cherry tomatoes. They concluded that tomato production irrigated with magnetically treated water resulted in superior stem development. In the study by El-Zawily et al. [99], they investigated the advantages and disadvantages of alternate tomato irrigation by using fresh and agricultural drainage water with or without the use of a magnetic field. They concluded that the plants irrigated with 100% freshwater and subjected to a magnetic field produced the maximum yield and economic efficiency. More recently, many studies [91,92,100–104] also found improvements in the growth of plants subjected to magnetized water.

Plant length increased after applying magnetically treated water to chickpea plants, with the plants watered with magnetically treated water being 2.67 cm taller 18 days after sowing than the plants given untreated tap water [105]. Magnetic treatment enhanced the amount and quality of sunflowers in other trials [106]. The magnetic field could react with ions in the seed embryo's cell membrane, enhancing water intake and causing alterations in the osmotic pressure and concentration of ions on both sides of the membrane. Therefore, the positive impact on the germination of seeds and speed of germination by magnetized water or seeds was more noticeable than that on the plants watered with untreated water.

The improvements in the growth of plants treated with magnetized water can be attributed to the fact that the application of a magnetic field has positive effects on soil characteristics, plant root architecture and cell membrane permeability, in addition to the chemical properties of the water. Surface tension, viscosity and evaporation rate were also changed under the effect of the magnetic field [37]. Furthermore, magnetized water has decreased hydrophobicity as a result of its reaction with released ions in soil solution, which increases the coupling of water molecules to soil particles. As a result, soil moisture content was found to be higher in the magnetized water irrigated group than in the control group [107].

It was reported that magnetized water affects the characteristics of soil features, such as the pH of the soil [108], precipitation of salts [109], stimulation of microbial activity in the soil [110], precipitation of carbonate [111] and P and K phyto-availability in the soil solution [108]. Magnetized water affects the cell membrane structure and permeability and enhances ion transportation through channels, which then leads to alterations in metabolic activities in cells [108]. Furthermore, using a magnetic field to purify irrigation water reduces the negative effects of saline soil or water on plant growth [108]. These effects of applying a magnetic field during watering plants resulted in increased nutrient uptake by plants and improved crop growth, development and productivity. When seeds were treated with magnetic water, increased root development rates were observed in a variety of species. The roots of treated plants grew higher and heavier than those of control plants, which corresponded to an increase in total fresh weight [109].

4.2. Effect of magnetized water on plant production

Water scarcity is a major limiting element and the main issue for most countries throughout the world, as it has a noxious impact on fruit yield and quantity. Magnetic treatments would be a reliable solution for overcoming the problem of water salinity and scarcity. The magnetization of ordinary or saline water is one of the approaches recommended to alter the water's properties to make it more suited for irrigation. The treatment of irrigated water with a magnetic field is considered a non-chemical, ecologically benign method of increasing agricultural yields without the use of pesticides [112].

Various studies have evaluated the ability of magnetized saline and non-saline water to improve the overall yield and productivity of a variety of crops, including strawberry, pea, eggplant, faba bean, tomato and maize plants. For example, Okasha et al. [4], Yusuf et al. [93] and Abdulraheem and Jameel [1] confirmed that magnetized water can increase the productivity of treated plants. Magnetic water treatments were used in a greenhouse to improve the growth characteristics and productivity of barley [43], snow peas [113] and wheat [114].

As compared to pure water, irrigation with magnetically treated water increased the production of peach (*Prunus persica*), apricot (*Prunus armeniaca*) and Thompson seedless grape (*Vitis vinifera*) plants [115]. The use of magnetic water improved the yield and yield characteristics of some plants. This rise is attributable to enhanced ion mobility or the improved uptake of various ions under the impact of the magnetic field, which leads to biochemical alterations or modulation of the activity of enzymes, which may have resulted in greater development of photosynthetic stimulation [116]. The use of magnetized water has been shown to increase various yield parameters, such as the total yield, fruit number, fruit quality, the number of flowers and total fruit yield of plants [117]; seeds could increase productivity for tomatoes under high-salinity conditions. In the study of Samarah et al. [118], they studied whether using a magnetic field to treat saline water or seeds could increase productivity in tomatoes under saline conditions. They found out that irrigating tomato plants with magnetically treated water increased the fruit yield per plant under saline conditions relative to the plants irrigated with non-magnetized water. They concluded that water magnetization can be a successful strategy for increasing crop yields when irrigated with salty water, as well as a method for reducing the harmful impact of salinity on crop productivity.

According to Taimourya et al. [119] strawberries (*Fragaria ananassa* Duch. cv. Camarosa) irrigated with magnetized water showed increases in the productivity, quality and quantity of flowers and fruits, as well as in the overall quantity for export. In the study by Cui et al. [94], they investigated the mechanisms of eggplant production and quality, as well as the soil properties, nutrient content and eggplant growth properties. The plants were treated with magnetized and non-magnetized water in a field experiment. They revealed that magnetized water treatment increased the fruit length, width and single fruit weight. With the magnetized water treatment, the level of vitamin C, organic acids and the contents of mineral elements in the eggplant fruit also increased relative to those of the non-magnetized group. Therefore, magnetized water promotes fruit quality and increases production.

4.3. Effect of magnetized water on soil

The salinity of the soil is considered to be one of the worst problems facing the agricultural sector around the world. The major cause is the accumulation of salts in soil capillaries, which results in a severe reduction in crop yield. Plants die as a result of high salt concentration in plant capillaries, combined with a shortage of nutrient elements. Various experts have studied the effects of magnetic fields on irrigation water and soil over the last decade, and interesting new applications have resulted from this research in the United States of America, Europe, the Middle East, Africa and Australia. The phenomenon of magnetized water has been recognized for a long time, and it is effective in several cases. The quality of irrigation water is a critical factor in protecting soil production and conserving the environment. In fact, the type of potentially exchangeable ions found in water affects the physical and chemical features of the soil, such as its permeability and structure (aggregate stabilization). The quality of irrigation water, organic matter contribution and tillage all play a role in agricultural soil protection [95]. According to Cui et al. [94], the soil nutrient content and enzyme activity were significantly higher in the magnetized water treatment group as compared to the control treatment group. As compared to the non-magnetized water treatment, the quantity of Proteobacteria in the soil increased dramatically after irrigation with magnetized water.

Magnetic water treatment has been proven in previous studies to raise the nutrient content of the soil, boost the activity of different enzymes and speed up the transformation and consumption efficiency of soil nutrients. As a result, it was proposed that magnetic treatment could influence microorganisms, particularly the bacterial composition and structure, as well as stimulate the activity of enzymes, resulting in favorable effects on the soil, including better nutrient cycling, structural improvements and improved quality of the produced fruit. It was reported that the pH scale is a crucial indicator of a soil's cation exchange capacity. In fact, for a given pH, the amount of cations that a soil can keep on its adsorbent complex varies. Water that has been magnetically treated has a considerable impact on the pH of the soil. In fact, the pH of the soil irrigated by magnetized water was shown to be lower [37]. Magnetized water causes changes in the solubility of several soil components, such as $CaCO_3$ and gypsum, which alter soil pH favorably and result in better nutrient uptakes, resulting in higher nutrient concentrations in plant tissues. After magnetic treatment, the physicochemical features of water change, resulting in better filtration and dissolvability.

In addition, water that has been magnetically treated affects the soil by increasing its moisture content. According to the findings of the latest studies, soil treated with magnetized water had more moisture than the soil irrigated with non-magnetized water. It was noticed that the cation exchange capacity is employed as a measure of the fertility of the soil by identifying a soil's nutrient retention capacity, which is then utilized to calculate soil moisture. As a result, if the magnetic treatment alters the properties of the water, the cation exchange capacity and soil moisture will be altered. It has been stated that employing magnetized water enhances soil moisture, reduces deep percolation and reduces irrigation intervals, resulting in increased irrigation efficiency [28]. It was also noted that magnetized water has an important effect on the soil by decreasing its conductivity [42]. The magnetization of water produces changes in its properties, most notably a decrease in its conductivity, which can affect soil properties and causes a reduction in the soil conductivity [37].

Surendran et al. [120] conducted a study to investigate the effects of magnetized water on the soil moisture, water characteristics and growth and yield metrics of cowpea and brinjal crops. According to the findings, magnetization treatment changed water parameters such as the pH, level of salts, electrical conductivity and total dissolved solids. The soil moisture with magnetized water was found to be higher than that with non-magnetized water. Additionally, employing magnetized water increased the crop development and yield parameters of cowpea plants in pot trials and the yield of brinjal plants in field experiments. More recently, Moussa et al. [121] conducted a study aimed to quantify the pore changes due to the magnetized water applied to cultivated soil. They examined the structure of soil taken from the surface layer by impregnating it with fluorescent glue and polishing horizontal sections horizontally. They pointed out that magnetized water had a significant impact on porosity, which increased on the macroscopic and microscopic scale on average throughout the depths. Al-Mana et al. [122] conducted a study to investigate how irrigation with magnetized water affected snapdragon (Antirrhinum majus L.) plant development and inflorescence production. Plants were irrigated with or without soil additions consisting of ferrous sulfate (Fe_2SO_4) and/or peat moss using three distinct water treatments: tap water, magnetic saline water and non-magnetized saline water. They found that magnetization improved the quality of irrigation water and increased plant competence to absorb water and nutrients from soil solutions.

4.4. Effect of magnetized water on pigments

Photosynthesis is considered to be the most important component of plant metabolism, and it is extremely sensitive to environmental modifications. Photosynthesis helps plants by providing substantial substances and the energy basis for the growth and development of plants. Photosynthesis is one of the most magnetic field-sensitive processes, as it can easily lead to changes in their concentration and efficiency. Researchers are becoming more interested in the effects of magnetic fields on plant photosynthesis. Under applied field conditions, the ability of photosynthetic machinery to handle light energy was increased in Zea mays [123]. Hozayn and Qados [124] showed that a magnetic field enhanced free-water molecules in chickpea seedlings and improved the levels of chlorophyll a and b and carotenoid pigments. Furthermore, such alterations improve photochemical reactions in the conversion of light energy and increase the intermolecular conversion rate [125]. It was reported that the magnetized water increased photosynthetic characteristics and total chlorophyll [126]. Alattar et al. [127] conducted a study to investigate the impact of magnetized water on the growth of corn (Zea mays) plants. They showed that using magnetized water to irrigate maize seedlings had a positive influence on the color of the leaves. Seedlings that were irrigated with magnetized water had greener leaves than those that were not. This variation could be attributed to different levels of pigments, including chlorophyll. Increased photosynthetic pigments, endogenous promoters (IAA) and increased protein production may all contribute to the stimulatory effect of magnetized water.

Hozayn et al. [43] found that watering barley plants with magnetized water resulted in considerable increases in chloroplast pigments (carotenoids and chlorophyll a and b) and photosynthetic activity. Hozayn et al. [128] found a similar favorable effect of magnetized water, with an increase in chlorophyll content and carotenoid content especially seen following treatment with magnetized water. Tombuloglu [129] studied the impact of an engineered magnetic nanoparticle on barley. They evaluated the physiological responses, as well as the expression of the photosystem marker genes of the treated plants. They found that magnetic nanoparticle treatment increased chlorophyll (a, b) pigments by 20% and carotenoid pigments by 22% relative to the untreated plants. More recently, Zareei et al. [113] studied the influence of a magnetized solution on the physiological and biochemical characteristics of hydroponically grown grapes. They found that some physiological and biochemical responses, including photosynthesis pigments, were positively enhanced, as magnetic treatments stimulated chlorophyll content.

In addition, magnetized saline water affects the photosynthetic pigments of plants, as it mitigates the harmful effect of saline water on the efficacy of pigments. More recently, it was reported that, when barley plants were irrigated with magnetized saline water instead of non-magnetized saline water, the values of photosynthetic pigments increased considerably [3,43,96,130,131]. As compared to non-magnetic treatment, the improvement owing to magnetized treatment reached 9.10% in chlorophyll a, 18.91% in chlorophyll b, 8.54% in carotenoids, and 11.12% in total pigments [43]. Several studies reported improvements in the plant chlorophyll a + b, total pigment and total phenol as a result of using magnetized water; the crops included cotton [3], lettuce [4,24] and rice [131]. The chlorophyll contents of the treated plants' leaves increased by 2.5 mg/g relative to the control plants' leaves [132]. Similarly, Al-Khazan et al. [133] and Hozayn et al. [134] found that, when treated plants were compared to untreated plants, the chlorophyll content increased dramatically, with average chlorophyll concentrations of 10 mg/g and 7.5 mg/g, respectively. This is attributed to the fact that magnetized water has a higher nutrient uptake through the roots than untreated water. Plant metabolism [135], including the balance of enzyme activity and photosynthesis, as well as secondary metabolites [23], may be stimulated by irrigation with magnetized water [135]. Similarly, in Celosia argentea plants irrigated with magnetized water [27], and in the cultivation of lupine [136], a considerable increase in pigment fractions was observed in water relative to the control treatment.

5. Conclusions

Magnetized water could be one of the most promising ways to use a magnetic field to improve agricultural production in the future, while also being environmentally beneficial. Irrigating plants using magnetized water can improve agricultural production, seed germination, seedling vegetative growth, seed and fruit mineral content and photosynthesis pigments. Magnetic water treatment increases soil nutrient content, enhances the activity of enzymes in soil and enhances the transformation and consumption efficiency of soil nutrients. Magnetized water can also influence microorganisms, particularly the bacterial structure and composition, as well as boost different enzyme activities, resulting in significant effects on the soil, including better nutrient cycling, structural improvements and higher-quality produced fruit. In addition, magnetized saline water affects the photosynthetic pigments of plants, as it mitigates the harmful effect of saline water on the efficacy of pigments.

Challenges and prospects for the future

As reviewed above, magnetized water has demonstrated its advantages and potential in the applications of agriculture as a result of being applied to different plants. However, it is still facing many challenges. The major challenge in using magnetized water in agriculture is creating pumps that are compatible with the technical and practical needs of magnetic systems while also effectively integrating irrigation components. It is necessary to conduct controlled laboratory and field studies to investigate the precise mechanism through which magnetized water affects various plant cultivars, particularly common crops, and to determine the standard level of salts in saline water used for magnetization as an important alternative tool for using saline water and brackish water in irrigation and overcome water shortages. In this regard, many studies have been carried out on the effects of the magnetic treatment of irrigation water on plant development and crop and water productivity; however, few studies focus on the use of low-quality water after magnetization in irrigation. Some countries face a significant problem of the increase in water demand from other sectors; therefore, water has become scarce and limited for the agriculture sector. Therefore, magnetizing low-quality water (brackish water, saline water or water contaminated with metals) can be considered as an alternative tool to overcome this challenge, as magnetizing low-quality water is an effective approach to mitigate its harmful effects on plants. To overcome the field difficulties and learn more about the mechanism of magnetized water, additional field and laboratory studies are urgently needed.

Conflict of interest

All authors declare no conflict of interest regarding this paper.

Author contribution

All authors contributed to the conception and design of the manuscript. All authors critically revised the manuscript and approved the final manuscript. Etimad Alattar led the conceptualization, analysis, interpretation and writing of the manuscript. Eqbal Radwan contributed to writing the first draft of the manuscript, prepared the tables and analyzed the data. Khitam Elwasife contributed to the revision and editing of the manuscript.

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