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Review

From mystery to reality: Magnetized water to tackle the challenges of climate change and for cleaner agricultural production

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ABSTRACT

Water magnetization is a cutting-edge technology, a physical water treatment, which contributes to a more sustainable supply of clean fresh water, and gives tool for mitigating some effects of the climate change in the plant production, and remediating pollution of soil and water. The mechanism of action of water magnetization, the quantum physical and chemical reasons behind it leading to enhanced structural order by hydrogen-bonded networks of water molecules are presented. Practical application possibilities of magnetized water in agriculture, water management and remediation of water and soil are reviewed based on latest researches. This review also provides an outlook of future research directions and an overview of opportunities for its practical use. The major effects of magnetized water with practical importance are the following: 1) Magnetized water enhances plant growth and development. 2) Irrigation with magnetized water alleviates abiotic stresses intensified due to the climate change, such as drought and salt stresses. 3) Magnetized water can be used for saving irrigation water; the saving of water produced is greater than 10% while achieving or exceeding the same yield both in quantity and quality. Using salty water magnetization as one of the alternative solutions for resolving the shortage in fresh water is also discussed. These effects also contribute to the mitigation of water shortage caused by the climate change. 4) Water magnetization may be a promising physical treatment that can be used in phytoremediation technologies for cleaning up heavy metal polluted water and soil.

1. Introduction

The amazing and fascinating property of lodestones, i.e. noticing that magnetite can attract the iron, has been known since ancient times to the Greeks; the name magnetism is also of Greek origin. The magnetism was used by the Chinese as a compass even as early as the 4th century BC (Du Trémolet de Lacheisserie et al., 2005). The application of magnetism, including both the magnetic field (MF) and electromagnetic field (EMF), is today already the part of our everyday life when used in the computer technology, communications, transportation, medical imaging and treatments, or even in the household machines. In this century, however, there has been an increasing interest in the agricultural usability of magnetism.

Geomagnetic field (GMF) on the Earth's surface originates mainly from the dynamo mechanism in the inner of our globe due to the motion of its outer core consisting of molten iron and nickel (Glatzmaiers and Roberts, 1995). The average of GMF is 5×10^{-5} T (T), but it is geographically asymmetric and variable between 25 and 65 μT. Therefore, every living being on earth exists immersed in a magnetic field (MF) (Roberts, 2015). During the evolution, the different living beings, among them plants, as well, developed different mechanism to detect the GMF and its variations and to respond to them (Galland and Pazur, 2005; Minorsky, 2007; Maffei, 2014).

Recently there are an increasing number of studies and reviews proving that MF or EMF affects the metabolism, growth and development of plants. The results achieved are well-summarized in some recent reviews (Maffei, 2014; Teixeira da Silva and Dobránszki, 2016; Sarraf et al., 2020). MF, from super-week (near 0 T) to very strong MF (> 15 T), acts on germination rate, seed vigour, modifies the photosynthetic efficiency, nitrogen assimilation and fixation, the plant height, root length, leaf area and biomass, may alleviate abiotic stresses, and thereby is able to affect the growth and yield of different crops. The actual effects of MF depended on the properties of the MF applied, such as the exposure time, polarity, orientation and intensity of the MF. Furthermore, species- and genotype-dependence were also detected in the responses of plants to MF. MF has morphogenetic effects, as well, which can be used under *in vitro* conditions to manipulate the plant growth and development *in vitro* (Teixeira da Silva and Dobránszki, 2015).

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In the above-mentioned studies, either static MF or EMF was applied to the plants or their tissues or organs directly. A special and promising possibility for application of magnetism in agriculture is the use of magnetized water (MW) when the irrigation water is treated by magnetic force. In this review, the mechanism and effects of water magnetization performed with static magnets, as well as its applicability and perspectives are discussed drawing emphatically on the latest basic and applied research findings over the past decade.

2. Changes in water properties due to magnetization

2.1. Mechanism and basics of water magnetization: how a magnetic field acts on water

When water is magnetized, the magnetic force acts externally on the water for a while, usually in practice on the flowing water, by using a stationary magnet. If electromagnet was used for water magnetization (Mghaiouini et al. 2020a, 2020b) then also the effects of electric force should be considered, which might modify the effects of the conditioned, i.e. electro-magnetized, water on living beings.

Magnetic water treatment is based on the structure of the water molecules and the architecture of networks formed from them. Water is dihydrogen oxide with a dipole character. The dipole character and the bent structure of the water molecule due to the repulsive effect of the two lone electron pairs of the oxygen atom, are critically necessary in the formation of hydrogen bonds between the water molecules. The lone electron pair of the oxygen atom can hydrogen bond to a hydrogen atom from another water molecule, theoretically allowing a tetrahedral motif to form around each oxygen atom. However, based on the string theory of water (Wernet et al., 2004; Ball, 2008), one water molecule binds to only two others, and thereby chains or rings are formed. At present, the theory of 'two-state model' seems to be the most possible. According to this, both structures are present in the fluid water simultaneously, i.e. clusters with tetrahedral structure and strong hydrogen bonds and the less hydrogen bonded string structures, like 'microscopic iceberg in a fluid sea' (Ludwig, 2001; Ball, 2008) (Fig. 1).

The water molecule exists in two nuclear-spin isomers, the *ortho-* and *para*-isomers as the relative orientation of the nuclear spins of the two hydrogen atoms can be different: antiparallel (S = 0) in *para*-water or parallel (S = 1) in *ortho*-water (Kravchuk et al., 2011; Kilaj et al., 2018). Their chemical reactivities are different because of their different energy profile, molecular conformation, and molecular quantum state. Based on the different rotational states of the *para-* and *ortho*-isomers, the number of H bonds can be formed by the different isomers of the water molecule is different due to energy efficiency reasons (Kilaj et al., 2018).

In response to magnetization only physical changes occur in the water, i.e. the distribution and states of water molecules vary while the molecular structure of the water does not change (Pang, 2006). The ice, a typical system with hydrogen bonds was used as model system to study the magnetization on water by Pang (2006). Based on that, they identified that a "molecular current" as a "small magnets" occurs in closed hydrogen bonded molecular chains, where proton transfer, a "ring proton-current" befalls in response to external magnetic field. Thereby water molecules arrange in an orderly manner. External MF changes the ratio of *para/ortho*-isomers in the fluid water towards the conversion of isomer with higher physical and chemical activity. MF basically acts on the interconversion of nuclear spin isomers of water, accelerating the interconversion towards the *ortho*-isomer (ratio of *ortho: para* is 3:1) (Vaskina et al., 2020). External MF directly affects the formation of clusters from ring and linear chains of hydrogen-bonded molecules, the atomic polarization of water molecules, and raises the transition dipole-moment of electrons within the molecules (Pang and Deng, 2008). Thereby clustering and size of clusters from water molecules may be governed by external MF (Chang and Weng, 2006). Using a flowing-circulated system with a low rate of 1 m s^{-1} and magnetic induction of 0.5 T, Cai et al. (2009) proved that the activation energy of the water molecules increases when external MF is applied, which affects the formation and re-orientation of hydrogen bonds between water molecules. With increasing the magnetization time the proportion of hydrogen-bonded molecules increased. Simultaneously, the rotational motion of the water molecules slowed down and inter-cluster hydrogen bonds became stronger.

The water orientation or reorientation affected by the hydrogen bonds, may act on the functionality of metal complexes, like Co(II) complex (Su et al., 2021), and thereby may be essentially necessary in biological processes, as well. Water reorientation is widespread in biological processes of living beings and accompanied by restructuring the network built from hydrogen bonds (Laage and Hynes, 2006). Quantum

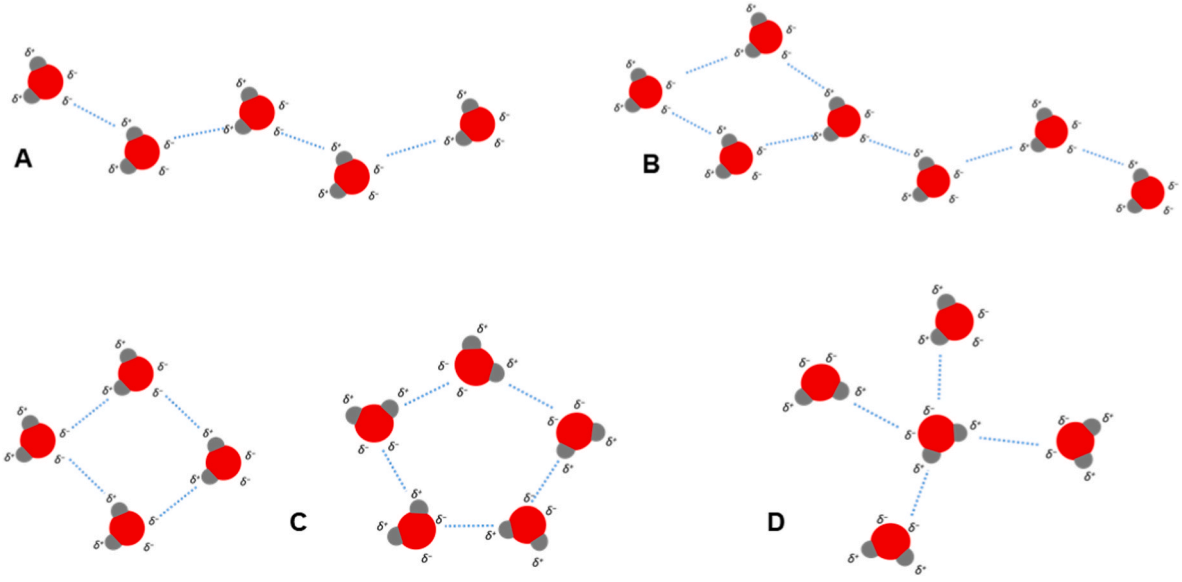


Fig. 1. Some possible basic configurations (architecture) of molecules in liquid water. (A) Chain, (B) loop or lasso, (C) ring of different number of molecules, and (D) tetrahedral configuration. Red circle indicates the oxygen atom while grey circles the hydrogen atoms in the water molecule. δ−: partial negative charge, δ+: partial positive charge of the water molecule; dashed blue line: hydrogen-bond between the water molecules. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

dynamics of water is modulated by *ortho*-water and nuclear spins may affect chemical reactions (Fisher and Radzihovsky, 2018; White, 2020). Thus, theoretically it can be hypothesized that the predominance of *ortho*-isomers and subsequently the altered network of hydrogen bonds in the magnetized water might be one of the basic reasons that affect the biochemical processes of plants.

The effect of magnetization on the water structure depends on the force and exposure time of magnetic induction, and the flow and temperature of the water, moreover, in aqueous solutions on the dissolved substance content of the water, as well. The most often applied magnetic induction ranged between 0.1 and 0.8 T (Lin and Yotvat, 1990; Pang and Deng, 2008; Cai et al., 2009; Teixeira da Silva and Dobránszki, 2014), however, in some cases higher force was also applied, up to 10 T (Chang and Weng, 2006).

2.2. Changes in the physicochemical properties of magnetized water

Since the orientation of water molecules having dipole moment changes under the influence of an external magnetic field, the effect of MF on water can be considered as a paramagnetic effect. Magnetization also causes modifications in the macroscopic and physicochemical properties of the water due to physical changes that occurred. These changes are directly attributable to the atomic polarization, the transition dipole-moment changes and shift of interconversion of nuclear spin isomers towards the *ortho*-isomer, leading to the architectural alterations in the water as the proportion and size of molecule clusters increase and networks of clusters form.

Boiling and solidifying points, electric conductivity, dielectric constant, magneto conductivity and self-diffusion coefficient of water changed after magnetization compared to the pure water (Chang and Weng, 2006; Pang and Deng, 2008; Cai et al., 2009). External MF altered some optical features of the water. It enhances the absorption of the water in UV light, and with increasing exposure time the intensity of the absorption increases. Infrared absorption increased with the exposure time and strength of MF, but there was no change in the localization of the absorption peak since molecular changes did not occur in response to the magnetization (Pang and Deng, 2008). Viscosity increased while the surface tension decreased as the clustering structure of the water changed in response to MF (Pang and Deng, 2008; Cai et al., 2009). As the intramolecular energy decreased in the magnetized water with the increasing magnetization time, the activation energy of the water molecules increased (Cai et al., 2009).

2.3. Features of magnetized water that are important from a practical point of view

When applying magnetized water in practice, for example in agriculture, we need to keep in mind some of its features that derive from the mechanism of water magnetization and that determine its effective usability. These main features are saturation, memory effect and temperature dependence.

Saturation effect of water magnetization means, that the water magnetization can reach a maximum level when water is exposed to static MF, i.e. there is an upper limit of magnetization. This maximum level depends on both the strength and exposure time of MF, but after reaching this maximum level, no more changes in the properties of the magnetized water could be achieved by further magnetic treatment (Deng and Pang, 2007; Pang and Deng, 2008). Considering the mechanism of water magnetization, this saturation effect is self-evident property of the magnetized water.

Studies have shown (Pang, 2006; Pang and Deng, 2008) that the magnetized water preserves the physicochemical properties that were triggered by the MF for a period of time even after the removal of MF. This features that the water is able temporarily to store the magnetic energy is called the *memory effect* of MW. The properties evoked by the MF then gradually disappear. The duration of the memory effect depends on the intensity of the applied MF, as the intensity of the MF increases, the time of memory increases. When MF applied to water of 25 °C was increased from 600 G up to 4000 G, the period of the memory time of MW increased from 35 min to 60 min (Pang and Deng, 2008).

High *temperature* is the "enemy" of water magnetization, as is evident when we consider the mechanism that leads to water magnetization. Disorder-effect of the rising temperature on the water molecules is even contrary of the magnetic effect that promotes the formation of the magnetic order and thus clustering. With increasing temperature, as the thermal energy and non-linear vibration of the water molecules and thereby their kinetic energy increase, the number and proportion of the hydrogen-bonded clusters in the fluid decrease. Experimental studies showed that with each 10 °C increase decreased the strength of the magnetization by 5–8% (Pang, 2006; Pang and Deng, 2008; Cai et al., 2009; Mghaiouini et al., 2020a).

Therefore, based on the memory effect of the MW, the demagnetization of the MW occurs spontaneously after a period of time, or can be triggered by increasing the water temperature.

In the case of *aqueous solutions*, also the dissolved substances (ions, colloids) in the water affect the structural changes caused by magnetization. This fact is very important when it comes to the practical application of MW, since in reality we always work with aqueous solutions. The various source of the water leads to various dissolved substance content and thus to different levels of magnetization and can affect the biological effects achievable in plants (Lin and Yotvat, 1990).

3. Current achievements and applications of magnetized water

3.1. Amendment of plant growth and development

Several, both beneficial and negative effects of irrigation with MW on plants were reported. The plant growth and developmental responses to MW depended on the species and even on the cultivars, as described and reviewed elsewhere earlier (Teixeira da Silva and Dobránszki, 2014; Ali et al., 2014; Krawiec et al., 2018; Faridvand et al., 2021), which was confirmed by recent research findings as summarized in Table 1. Similarly, the strength and exposure time of the MF applied to the water and the quality, mainly the ion content of the water affects the effects of MW on plants (Tables 1–2). Priming effect of MW on seed germination and seedling growth and even on the yield was evinced in several plant species leading to quick and uniform germination, increased vigour, enhanced growth and improved yield (Table 1). Growth parameters of different plant species, like shoot and root length, number and area of leaves and biomass (fresh and dry weight) can be improved (Table 1). A series of physiological, biochemical and metabolic processes of the plant were studied in response to the irrigation with MW and they were proved to be affected by MW. Irrigation with MW affects the antioxidant system of the plants leading to the reduction of ROS production (Tables 1–2, Azimi et al., 2018; Sutiyanti and Rachmawati, 2021). The chlorophyll content (both chlorophyll *a* and chlorophyll *b*) and the carotenoid content in plants can be increased. The activity of the photosynthesis, the stomatal conductance and even the intracellular concentration of CO_2 were improved (Tables 1–2). However, in some cases the decrease in the chlorophyll content was detected (Mostafa, 2020). Besides enhancing the uptake of some nutrients (f.e. N, P, K, Ca, Mg, Fe, Zn), MW could affect their distribution as well. Nitrogen uptake and distribution within the plants were changed in response to irrigation with MW in poplar (*Populus x euramericana*). The total nitrogen uptake of the plants increased and the ammonium-N uptake and content was higher in the leaves than in the roots (Liu et al., 2019a, 2019b, Table 2). When MW was combined with other bio-stimulants, like chemical or bio-fertilizers, or mycorrhyzal fungi, its priming effect on plant growth and development could be further enhanced in various plant species (Table 1, Shabani et al., 2019; Ali et al. 2019a, 2019b; Mostafa, 2020; Al-Mana et al., 2021). It should be noted, however, that excessive uptake of some microelements, f.e. heavy metals, may have even some harmful

Table 1
Effect of MW on the metabolism, growth and development of plants.

Plant	Magnetization method[a]	Response of the plant	Reference
pea (*Pisum sativum* L.)	Device: 2 lines of 26 magnets of MF: 88–211 mT (along the centre line)	MW reduced the germination time of seeds from 3.72 to 2.92 days, just like T_{50} (decreased from 2.86 days to 2.38 days). Germination energy increased from 75% to 95% as well as the germination index from 4.32 to 5.38, the final germination percentage from 92% to 100%, and the seedling length from 2.91 to 3.18 cm. Total soluble sugars were increased by MW (from 67.83 mg g^{-1} DW to 112.46 mg g^{-1} DW). Similarly, the α-amylase activity almost doubled by MW (from 35.230 IU $mg^{-1}_{protein}$ to 65.380 IU $mg^{-1}_{protein}$). If MW was combined with 3% *Moringa* leaf extract, the priming effects of MW can be enhanced further inT_{50} (2.45 d), root and shoot length (12.96 cm and 3.65 cm, respectively), root to shoot length ratio (from 3.29 to 3.56), α-amylase activity (71.830 IU $mg^{-1}_{protein}$) and total soluble sugar content (124.82 mg g^{-1} DW).	Noor et al. (2016)
rice (*Oryza sativa* L. var. Hashemi)	MF: 110 mT device was produced by Iranians Technology & Research Co.	Seed germination increased with 8.34% in response to MW. Furthermore, plant height and root length increased in average with 2.4 cm and 1 cm, respectively as well as leaf area with 102.67 mm^2. MW increased the chlorophyll *a*, chlorophyll *b* and carotenoid content, as well; the increase was 0.008, 0.002 and 1.07 mg g^{-1} FW, respectively. Total available carbohydrate and total protein content of leaves increased with 2.06 μg g^{-1} FW and 0.129 μg g^{-1} FW, respectively.	Babaloo et al. (2018)
sweet basil (*Ocimum basilicum* L. cv. Mobarakeh)	$Ca(H_2PO_4)_2$ H_2O solutions were treated by MF of 110 mT; flow rate: 3 dm^3 min^{-1}.	P use efficiency was investigated by using magnetized solution of $Ca(H_2PO_4)_2$ H_2O with the concentration of P of 0, 5, 10, 20 and 40 mg l^{-1}. The highest P use efficiency (18.9% higher than in control) was achieved with magnetized Ca $(H_2PO_4)_2$ H_2O solution of 10 mg l^{-1} P. Leaf number, leaf area, harvest index in response to magnetization of the solution as well as chlorophyll *a* and chlorophyll *b* content increased. When plants were inoculated with arbuscular mycorrhyzal fungi (*Divesispora versiformis*), and combined with magnetized Ca $(H_2PO_4)_2$ H_2O solution, the P use efficiency further increased (by 23.5% compared to the control).	Shabani et al. (2019)
butternut squash (*Cucurbita moschata* Duchesne)	MF: 1500 G drip irrigation	Two fertilizers were investigated in combination with MW: chemical fertilizer (CF) (urea 100 kg N ha-1) and bio-fertilizer (BCF) (in 1:1 ratio of chemical fertilizer and the mix of *Azotobacter chroococcum* and *Azospirillum brasilense)*. The fruit weight was the highest when BCF was applied. MW increased the fruit yield. When MW and BCF was combined, further increased could be detected in the fruit yield at the first harvest; at the 2nd and 3rd harvest the same tendency could seen. Total yield/plant thereby increased by MW (18% increase compared to the control) and it was further increased when BCF was combined with MW (45% increase). Total soluble solid content of the fruits increased with 12.7% in response to MW, after 65 days. However, there was no difference between the effect of non MW and MW on total	Ali et al. (2019a)

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Table 1 (*continued*)

Plant	Magnetization method[a]	Response of the plant	Reference
		soluble solids after 95 days. MW reduced the chlorophyll content to 57.7 μmol m^{-2} from 83.8 μmol m^{-2} while chlorophyll content was the highest (90 μmol m^{-2}) when BCF with non-MW was applied. Fructose content and fiber content were not modified by MW.	
melon (*Cucumis melo* L. cv. Piel de sapo)	MF: 1500 G drip irrigation	The same water magnetization and CF, and BCF treatments as was described in Ali et al. (2019a). MF was superior to non-MW on fruit yield, fructose and fibers contents of fruits and total soluble solids at all harvesting and storage times studied. When MW was applied in combination with BCF the results could be further improved.	Ali et al. (2019b)
maize (*Zea mays* L.)	ring magnet of MF: 125 mT The water was 7-times re-passed through the funnel.	Length of seedlings, the thickness of the stem, leaf number was increased by MW. Leaf morphology was modified by MW.	Alattar et al. (2019)
potato (*Solanum tuberosum* L. Spunta)	permanent magnet of MF: 0.16 T	When MW was applied in combination with fertiliser applied after magnetization, the productivity of potato increased with 40.5% compared to the control as well as the plant height (with 24.66%), leaf number (with 21.7%). Similarly at the combined treatment developed the most and largest (considering the length, width and thickness of the tubers) tubers. However, before harvest the chlorophyll content was the lowest in response to MW and combined treatments.	Mostafa (2020)
tobacco (*Nicotiana tabacum* L. var. Turkish)	2 types of water were magnetized: distilled and tap water. MF: 0.07 T	Shoot height, root length, shoot/root DW increased after magnetization of distilled water. The tendency was similar for photosynthetic rate and protein content, but the differences were not proved to be significant. If tap water was magnetized, MW increased the total carbohydrate content. Chloroplasts were deformed and thylakoid membranes were damaged after irrigation with tap water, both for magnetized and non-magnetized water.	Alkhatib et al. (2020)
chilli pepper (*Capsicum annuum* L.).	3 treatments: 3, 6 or 9 nickel-plated elliptical (30 mm × 15 mm) neodymium magnets were used for water magnetization; each had an MF of 70 mT	Shoot length and stem thickness were tendentiously but not statistically significantly while and leaf number was significantly affected by MW. The effects of MW depended on the number of the magnets; shoot length and leaf number were the highest after applying 6 magnets, while thickness of the stem was the highest when 9 magnets were used.	Alattar et al. (2021)
fennel (*Foeniculum vulgare* Mill.) 5 landraces: Qaziantep, Hamadan, Urmia, Yazd, Shiraz	Russian SIB8 water magnetization device. MF: 200 mT; U050 mg, 0.5 inch, output: 4–6 cm h^{-1}.	Foliar application of MW affected both vegetative and reproductive growth and development, and chlorophyll content of the fennel, but its effects depended on the landraces. The highest biological and seed yield, chlorophyll *a* and *b* contents, moreover N, P and K content was achieved in Qaziantep landraces after application of MW while highest essential oil yield was detected in Urmia landrace.	Faridvand et al. (2021)
coriander (*Coriandrum sativum* L.)	2 types of magnets: Neodymium (NdFeB) and ceramic magnets; bar, cube, disc and sphere NdFeB, and bar ceramic magnets. two exposure times: 10 min, 20 min	Germination rate of coriander seeds were significantly not different in response to different treatments, except if water was magnetized by NdFeB sphere magnet for 20 min, which ssignificantly decreased the germination rate. In tendency it could be seen that as MF increased, the germination rate increased to a certain point, and then it fallen.	Tzib and Daniels (2022)

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Table 1 (*continued*)

Plant	Magnetization method[a]	Response of the plant	Reference
		Growth rate of seedling could be enhanced by MW. The optimal MF of MW for growth rate was 5.75×10^{-2} T, achieved by the ceramic bar magnet.	
Rasha grapevine (*Vitis vinfera* L.)	1) magnetized nutrient solution (MNS) 2) magnetized nutrient solution + pre-magnetizes water (MW + MNS) MF: 0.1 and 0.2 T	MNS at 0.2 T caused changes in the FW and DW, moreover in the shape and size of leaves.increased the contents of photosynthetic pigments, soluble carbohydrates and protein and increased the activity of antioxidant enzymes (POD, PPO). MW + MNS at 0.2 T increased the N, K, P, Fe and Cu content.	Zareei et al. (2022)

[a] Tap water was magnetized unless otherwise described. DW, dry weight; FW, fresh weight; POD, peroxidase; PPO, polyphenol oxidase; T_{50}, time to gain 50% germination of seeds.

effects (Table 2; Mohrazi et al. 2021a, 2021b; Hu et al., 2022).

3.2. Stress mitigation and priming effect

It has been reported that some damages in growth and productivity of plants caused by different abiotic stresses could be alleviated by applying MW for irrigation. This alleviating effect of MW can be particularly useful in the case of abiotic stresses exacerbated by climate change and discussed below. Stress mitigation effect of MW may be related to its effect on antioxidant system. In lentil (*Lens culinaris* Medik.), Azimi et al. (2018) detected that after MW (at 110 mT) treatment the activities of enzymes that are members of the glutathione-ascorbate antioxidant pathway changed significantly; activity of ascorbate peroxidase (APX) increased while the activity of superoxide dismutase (SOD) decreased. In the experiments of Hu et al. (2022) the activity of APX, SOD and CAT increased in *Festuca arundinacea* Schred. leaves by 64.1%, 22.0% and 21.5%, respectively, while the malondialdehyde content decreased by 25.6% in response to the MW. Sutiyanti and Rachmawati (2021) described the response of the antioxidant system of rice (*Oryza sativa* L. cvs. IR64 and Inpari 35), as well, as they detected the decrease in the contents of anthocyanin, malondialdehyde, H_2O_2 and SOD after magnetization of the seawater.

Drought. In the experiments of Hasan et al. (2019, 2020) two moringa species (*Moringa oleifera* Lam. and *Moringa peregrina* (Forssk.) Fiori) were drought stressed and irrigated by MW (with a magnetic induction of 300Gs, or 30 mT). Drought stress was applied as 50% (mild stress) and 20% (severe stress) of field capacity and compared to the control of 100% field capacity. Plants were irrigated either by normal (as a control) or MW treated water, respectively. Drought stress caused significant decrease in the growth parameters (plant height, leaflet number, length of the internodes), which could be significantly improved when MW was applied for irrigation. Irrigation with MW increased the fresh and dry weight and the leaf area, as well. Root and shoot fresh and dry weight after MW irrigation and under mild stress reached the level of the control, i.e. non-stressed plants, while the fresh weight of the leaves exceeded the levels of the control. Chlorophyll contents (both chlorophyll *a* and *b*) under mild stress was the same or higher (chlorophyll *a* and thus total chlorophyll content) than in non-stressed plants irrigated with normal water. Under severe stress conditions, MW was able to improve the fresh and dry weights of shoots and leaves and carotenoid content was also the same as in non-stressed plants. Drought decreased the relative water content of the plants (RWC), while MW treatment was able to restore it. Moreover, MW improved the water use efficiency and the water pressure deficit, and increased the assimilation and transpiration rates, and the stomatal conductance. Increasing chlorophyll-a and chlorophyll-b content, and thereby cessation of chlorosis and improving photosynthetic rate were also detected after irrigation by MW. MW affected the ion-content of leaves, shoots and roots, as well, increased the Na^+/K^+ ratio in them due to lower accumulation of Na^+.

Salt stress. As magnetization affects the hydrogen bonds in an aqueous solution (Chang and Weng, 2006; Cai et al., 2009) hereby, the treatment of saline water with MF can be expected to cause changes in it affecting its quality. As expected, as magnetization cause changes in hydrogen bonds, an increase in the mobility of different ions and thereby solubility of different salts, as well as an enhancement in the sedimentation of electrolytic materials and colloids occur (Lin and Yotvat, 1990; Surendran et al., 2016). Studies on the magnetization of saline and hard water support this theoretical expectation and they are summarized in Table 2. The pH of magnetized water increased while its electric conductivity decreased as well as decreased its salinity level. Decrease was detected in the total dissolved solids, as well.

Use of magnetized saline water for irrigation caused favorable changes in soil properties as summarized in Table 2. Soil pH decreased but electric conductivity increased. The available N and P content of the soil, soil humidity, and organic matter content increased, as well. As the magnetization mitigated the salt stress of saline water, seed germination, biomass, yield and crop quality can be improved in different plant species, as well as the inside content of the yield, f.e. its carbohydrate, protein and nitrogen content. Recent studies proved the irrigation with magnetized saline water, even at high salinity level, resulted in increases not only in growth parameters and yields, but in some micronutrient content (Fe, Cu, Zn), photosynthetic pigment content and photosynthetic activity compared to the use of non-magnetized, normal (i.e. non-saline) irrigation water (Table 2). Magnetization of saline water led to a decrease in the Na^+ content, an increase in the K^+/Na^+ ratio, as well as an increase in the Ca^{2+} and total nitrogen content in poplar plants compared to plants irrigated with non-magnetized saline water, promoting the adaptation of plants to the saline environment (Liu et al., 2019a, 2019b, Table 2). Nutrient uptake (N, P, K, Ca, Mg, Fe and Zn) from different nutrient media can be improved by using magnetized saline water even if not static, but an alternating magnetic field was used (Table 2; Alavi et al., 2021).

In addition to the alleviating the effect of saline water caused by Na-overweight, water magnetization was proved to be suitable also to decrease the water hardness (Table 2; Surendran et al., 2016). In magnetized water the earlier lime deposits became redissolved, and were mobilized, furthermore more micro crystals form which move in suspension with the water as it flows through the magnetizing device. Scanning electron-microscopic study proved that while the water hardness decreases the crystal structuring of calcium carbonate shifts from disc shape towards the needles of aragonite in response to MF (1800–2000 G).

Seawater availability is practically unlimited in term of agricultural demand, considering that the availability of the seawater is about 97% of the water stock on Earth. However, it cannot be directly used for irrigation due to its high salinity content. Taken in consideration that magnetization of the water is able to decrease its salinity level, the thought may come to mind to use magnetized seawater for irrigation of agricultural fields as an alternative solution for resolving the shortage in fresh water, which is an increasing problem due to climate change. Sutiyanti and Rachmawati (2020) used successfully the mix of magnetized seawater and freshwater (salinity levels of 0 and 10 dS m^{-1}) to irrigate rice cultivars (*Oryza sativa* L. cvs. IR64 and Inpari 35). Using the mix of magnetized seawater and freshwater, the plant height as well as

Table 2
Effects of MW on the properties of water and soil and the plant growth and development when using saline water.

Type and properties of the water	Magnetization method	Plant	Responses to soil and water properties and plant growth and development	References
normal water saline water: 500, 1000 and 2000 ppm sodium chloride hard water: 150 and 300 ppm calcium carbonate	MF: 1800–2000 G; (2 magnets ($SrO{\cdot}6Fe_2O_3$) with 120 mm length, 130 mm width and a distance of 30 mm between them.) Water flow: between the magnets in 1 cycle for 10 min; flow rate of 2 l s^{-1},	cowpea (*Vigna unguiculata* (L.) Walp.)	*Plant.* Growth parameters (plant height, weight of shoots and roots) and yield were improved in response to magnetization of irrigation water, they were significantly higher when hard and saline water were treated by MF compared to the control irrigation water. *Soil.* If MW was used for irrigation, the decrease in the soil surface moisture between the 3rd and 1st days was lower than after using non-magnetized water. Soil moisture at surface increased after irrigation with MW in all water types (solutions). Increasing saline concentration increased the soil moisture. *Water.* Magnetization increased the pH of all types of water significantly; in saline water, depending on the level of salinity from 6.0 to 6.1 to 6.4–7.0, in hard water from 3.52 to 4.0 to 4.52–5.0, while in normal (control) water from 6.5 to 7.70. On the contrary, the EC was decreased in all water types after magnetization. This effect of water magnetization lasted for 108 h. The total dissolved solid content decreased after magnetization as well as the Ca and Na content in hard and saline water, respectively. Crystal structure of calcium carbonate varied in the hard water in response to the magnetization; Aragonite needles longer than in non-magnetized hard water were formed according to the SEM studies.	Surendran et al. (2016)
water with different salinity levels: (S1):0.5 (tap water), (S2):2, (S3):4, (S4):6 dS m^{-1}	MF: 1500 mT, 5 circulations, with a water flow rate of 3 l min^{-1}, (neodymium bock magnets with 45 mm length and 5 mm height, and 35 mm width; 4 pairs, with a distance of 25 mm between the pairs	maize (*Zea mays* L.)	*Plant.* Germination of seeds occurred 1–2 days earlier after MW treatment at all salinity levels, and the germination rate was higher (FEP was 70% compared to the 40% of the control at S4). Irrigation with MW enhanced the ERI at all salinity levels; it increased to 10.2, 11.1, 13.3, and 13.3 at S1, S2, S3 and S4, respectively compared to the controls of 7.6, 9.1, 10.3, and 11.8, respectively. MW treatment reduced the MET from 5.7 to 5.3, 6.6 to 5.9, 8.3 to 7.6 and 8.4 to 7.2 for S1, S2, S3, and S4, respectively. 15-day old seedlings was higher and their FW (the detected increase was 7.2%, 1.85%, 1.68% and 2.48%, respectively) and DW (increase of 13.95%, 10.61%, 9.76% and 9.33%, respectively) increased at all salinity levels (S1, S2, S3, S4) when they were irrigated by MW. *Soil.* pH of the soil decreased after MW slightly and depending on the salinity level, but EC increased. MW increased the available N and P content of the soil.	Abedinpour and Rohani (2017)
salinity levels: 2.1 g l^{-1} and 4.2 g l^{-1}	Device: "Delta Water Technology", 13,500 G, irrigation: each 3 day until 800% of the soil capacity	tomato (*Solanum lycopersicon* L.)	*Plant.* MW increased the germination rate of seeds, the length, FW and DW of seedlings and harvested plants. Proline content was lower after MW treatment indicating stress mitigation effect of the MW. *Soil.* Soil humidity, EC and organic matter content were higher after irrigation with MW compared to non-magnetized water while the soil pH was lower. *Water.* Its pH increased while EC decreased immediately after magnetization.	Fakhri et al. (2018)
SW (700 mg l^{-1} Na^{+})	Details of the magnetizing device was not described; drip irrigation method	eggplant (*Solanum melomgena* L. cv. Florida High Bush); faba bean (*Vicia faba* L. cv. Isban); tomato (*Solanum*	*Plant.* Yield of the crops examined increased (to 34.05 t/ha from 23.23 t/ha, to 6.92 t/ha from 4.25 t/ha, and to 77.5 t/ha from 50. 76 t/ha, in eggplants, faba been and tomato, respectively) as well as the fruit weight and fruit number of eggplant. In eggplant	Kareem (2018)

(*continued on next page*)

Table 2 (*continued*)

Type and properties of the water	Magnetization method	Plant	Responses to soil and water properties and plant growth and development	References
		lycopersicon L. cv. Logaen)	carbohydrate, protein and nitrogen contents increased as well in response to MW. Salinity decreased the fruit weight. In faba bean, number of pods, root weight and root nodes per plant increased, yield quality improved and the total P in the seeds significantly increased. In tomato, both the carbohydrate and protein contents of the fruits increased and acidity decreased in response to MW. *Soil.* pH of the soil decreased as irrigated with MW.	
Hoagland solution (Hoagland and Snyder, 1933) with 0 (non-saline) or 4 g l^{-1} (saline) NaCl	magnetic device (U050 mg, 0.5 inch) output: 4–6 m^3 h^{-1}	poplar (*Populus x euramericana* cv. Neva)	*Plant.* After a 30-day-long treatment when irrigation occurred with magnetized saline water in field, biomass accumulation, DW of shoots and roots were improved as well as the morphology of roots. Total N content increased, in roots more nitrate-N was detected than in leaves, moreover, nitrate reductase was activated and the efflux of nitrate ion was higher compared to plants irrigated with non-magnetized water. The total and oxidized glutathione content of the leaves increased as well as the activities of glutamine and glutamate synthases and glutamate dehydrogenase, but they were decreased in roots. Na^+ content of plants irrigated with magnetized saline water decreased, Ca^{2+} content and K^+/Na^+ ratio increased. Furthermore, in pot experiments, biomass of roots and leaves increased, but stem biomass decreased when irrigation occurred with magnetized saline water. Higher content of Cu, Fe and Zn and lower content of Mn could be detected in response to magnetization of saline water, in leaves and roots. C and P content of the leaves and C/N ratio in them increased, as well. After irrigation with magnetized water also the net photosynthetic rate, stomatal conductance increased, as well as intracellular concentration of CO_2.	Liu et al. (2019a, 2019b)
3 levels of salinity: 320, 3000 and 6000 ppm, salt mixture components: 10% $MgSO_4$, 1% $CaSO_4$, 78% NaCl, 2% $MgCl_2$ and 9% $CaCO_3$	the magnetization details are not described	wheat (the exact species was not described)	*Plant.* Magnetization of irrigation saline water reduced the harmful effects of saline water; grain yield decreases was improved from 66.12% to 25.96% and from 87.68% to 69.30% at salinity levels of 3000 ppm and 6000 ppm, respectively. Similarly, magnetization of saline water increased the FW and DW, grain number, grain weight, number, length and weight of spike and leaf area. It was proved by using Bayesian network modelling, that MF affected positively the studied growth and yield parameters of wheat at any salinity level studied.	Hassen et al. (2020)
3 water types: tap water (EC: 0.74 dS m^{-1}), saline (3-fold sodium and chlorine content of the tap water, EC: 3.7–4.0 dS m^{-1}) non-MW, and saline MW	Magnetic Fluid Conditioner 8000 GMX (GMX Coorporation, Chino, CA): 1500G, 3-unit magnetization system	snapdragon (*Anthirrhinum majus* L. cv. Montago Pink)	*Plant.* Vegetative growth (high, stem diameter, number of branches and leaves, leaf are and shott DW) was significantly higher when irrigated with tap water. Magnetization of saline water, however, was able to alleviate the harmful effect of saline water (non-MW), increasing the vegetative growth compared to the irrigation with non-magnetized water. MW significantly interacted with soil amendments (peatmoss, Fe_2SO_4, and their combination) and resulted in better vegetative growth than non-MW with amendments. MW enhanced the flowering, as well, mainly if applied with the combined soil amendment.	Al-Mana et al. (2021)
5 levels of salinity: 320, 2000, 4000, 6000 and 8000 ppm	static magnetic unit, diameter: 0.5 inch, MF: 0.35 T	barley (*Hordeum vulgare* L. cv.Giza-128)	*Plant.* Magnetization of saline water at any salinity levels alleviated the harmful effects of saline water on the grain yield; the mitigating effect depended on the salinity level and varied between 12.97 and 16.06%.	Hozayn et al. (2021)

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Table 2 (*continued*)

Type and properties of the water	Magnetization method	Plant	Responses to soil and water properties and plant growth and development	References
			Similar salt stress alleviating effect of MW could be detected on all measured growth parameters (plant height, leaf number, FW and DW of shoots) and on the content of photosynthetic pigments (Chlorophyll *a* and *b* and carotenoids).	
Salinity levels: control, 40, 80, 120 mM NaCl	MF: 0, 100, 200 and 300 mT (alternating MF); for 5 min	peppermint (*Mentha x piperita* L.)	*Plant.* Nutrient uptake was measured by using different growth media: coco-peat, palm, coco-peat + perlite, palm + perlite. N and Fe uptake were increased from magnetized (300 mT) saline (80 mM NaCl) water, from coco-peat nutrient medium, as well as P, and K uptake when MF was 200 mT. Mg uptake increased from palm nutrient medium after saline water of 80 mM NaCl was magnetized with MF of 200 mT. Magnetization with MF of 300 mT of saline water with 120 mM NaCl resulted in increased uptake of Ca and Zn from palm + perlite and coco + perlite nutrient media, respectively.	Alavi et al. (2021)
Salinity levels: 0, 3 and 6 g l^{-1} (S_0, S_3 and S_6) by NaCl dissolved in tap water	MF: 0, 1000, 2000, 3000, 4000, 5000, 6000 and 7000 G. CHQ type device with permanent magnets (Baotou Xinda Magnetic Material Factory, China)	soil columns were used; soil samples from top soil of 0–50 cm (pH: 8.14)	*Soil.* At all depths of the soil, the pH decreased and pH decreasing was parallel with increasing salinity with 8.44, 8.28 and 8.27%, respectively. With increasing MF, the soil pH decreased at the same depth depending on the salinity level; the decrease was 1.4%, 2.6% a zero, at S_0, S_3 and S_6, respectively. The pH in the deepest soil layer was with 3.6% lower than in the uppermost layer. As MF increased, the pH decreased at the same soil depth. The lowest pH occurred at the 30–37 cm depth at S_6 and MF 7000 G. However, the highest MFs (6000–7000 G) in the upper soil part (0–5 cm) resulted in the highest pH of 8.8–8.9 at S_6. Soil EC decreased as the depth increased (by 10–35%). Sodium adsorption ratio, Cation ratio of structural stability and Soluble sodium percentage of the soil were the highest without MF, in control, while they were the lowest at S_6 and 3000 G. *Leachate.* EC value halved at S_0; and it was 12.4% lower at S_3 in response to magnetization. If MF was increased, the Sodium adsorption ratio, Cation ratio of structural stability and Soluble sodium percentage also increased at S_3 and S_6.	Abdelghany et al. (2022)

DW, dry weight; EI, emergence index; EC, electric conductivity; ERI, emergence rate index; MET, mean emergence time; FW, fresh weight; MF, magnetic field; MW, magnetized water.

the chlorophyll and carotenoid contents of the plants increased and exceeded the values of the control plants, in both cultivars and at all salinity levels. Furthermore, fresh and dry weight of plants were increased after using magnetized seawater. If the cycles of magnetic treatment increased from 1 to 3 cycles the growth parameters of both cultivars were further increased as the salinity of the water decreased more and more after more and more magnetization cycles (Sutiyanti and Rachmawati, 2021). Similarly, the diluted and magnetized seawater was successfully applied for irrigation of North Indian rosewood (*Dalbergia sissoo* Roxb.) (Sarhan et al., 2021). The rosewood seedlings could tolerate high salinity level (4000 mg l^{-1} prepared from the seawater (35, 000 mg l^{-1}) of Mediterranean Sea). The application of water magnetization (250 mT, Magnetic Technologies Ltd, Germany) and a biofertilizer (mixture of Cyanobacteria) improved both the growth parameters (height, stem diameter, leaf area, root length, fresh and dry weights of seedlings) and chemical constituents (chlorophyll, carbohydrate and prolin content, N, P, K) while decreased the Na content within the plant.

Heavy metal stress. Increasing industrial and mining development and activity is increasingly leading to soil and water contamination with heavy metals. Copper (Cu) contaminated water was magnetized (MF: 0.21 T; flow rate: 0.66 l min^{-1}) and used for irrigation in the experiments of Mohrazi et al. (2021a) to study its effect on the growth and production of maize (*Zea mays* L. cv. 89MAY70). The fresh weight of the maize shoots and the biomass, up to 180 mg Cu/soil kg were increased by irrigation with Cu-contaminated magnetized water as well as the Cu content in the plant tissues, however the yield and translocation efficiency, i.e. the Cu uptake of shoots per that of roots, were decreased. When broan coal was added to the soil, the Cu concentration in the roots decreased. The phytoextraction efficiency, i.e. the Cu uptake of shoots/root dry weight, increased by 12% if the copper sulfate-polluted water was magnetized compared to non-magnetized water, but simultaneously the Cu content did not increase in the shoots. Therefore, the detected increase in the phytoextraction efficiency was due to the decrease of root dry weight. When maize produced on calcareous soil was irrigated with magnetized water polluted with zinc (Zn) of up to 1200 mg kg^{-1} Zn, MW improved the uptake of Zn and increased the dry matter of maize shoots (Mohrazi et al., 2021b). Irrigation with MW (100

mT, three-times within 10 s, at a constant flow rate of 5 ml s^{-1}) significantly increased the dry weight and Cd content of *Festuca arundinacea* Schred. shoots by 13.6% and 52.8%, respectively, compared to irrigation with non-magnetized water. Thereby, Cd removal from the soil increased by 109.7%. Moreover, as the ferritin content of leaves increased by 91.3%, the Fe sequestration and detoxification capacity of the *Festuca* was increased, as well, when irrigated by MW excreting less Fe by 38.1% (Hu et al., 2022).

3.3. Saving irrigation water by increasing the water productivity

Water productivity means the total amount of the water that is necessary to achieve a certain yield. There are some investigations where the effect of MW on the water productivity was studied in different plant species (Maheshwari and Grewal, 2009; Sadeghipour and Aghaei, 2013; Kareem, 2018). Based on those, MW was able to increase the water productivity of 6 out of 7 plant species examined; however, it varied between 7.5 and 88% depending not only on the plant species but on the type of water which was magnetized, as well (Table 3). The study of Maheshwari and Grewal (2009) showed that water productivity increase was the highest when saline water was magnetized in snow pea and celery. Similarly water productivity significantly increased in three other plant species when saline water was magnetized (Kareem, 2018, Table 3). The reported water saving depended on the species and varied between 11 and 14.2% (Table 3). However, it depends also on the quality of water that is used for magnetization. The water use efficiency in cowpea was improved by 22% by applying MW to normal, i.e. non-saline water (Table 3). Moreover, we should consider also the type of the magnetization device; however, it is very hard sometimes because the details of the devices were not always described.

Water productivity is a metric of increasing economic importance, just like the water saving percentage, due to the water shortage caused by the climate change and small proportion of irrigation water of adequate quality.

4. Concluding remarks and future perspectives

In present review, the recent studies of mainly the last half-century on water and its interaction with MF were evaluated, and the concept of mechanism of action when water is magnetized was described. This knowledge can lead us to understand the mechanism of action of water magnetization treatment and thereby to see how much potential this technology has to grow from the mystery to a real and practical possibility. Furthermore, the recent practical applications of MW in modifying plant growth and development, alleviating some abiotic stresses on plants, and improving irrigation water management have been evaluated. The main effects of MW on water, plant and soil, which may affect the plant growth and development, are summarized in Fig. 2.

Although the beneficial effects of the technology of irrigation with MW on plants and crops have been reported decades ago, the mechanism of water magnetization and the quantum physical and chemical reasons behind it are beginning to emerge from recent researches (Ludwig, 2001; Ball, 2008; Kravchuk et al., 2011; Kilaj et al., 2018; Vaskina et al., 2020). The mechanism how MW achieves its effects in biological systems, and thus in plants, whether at the molecular or biochemical level, is currently unknown or based only on theoretical hypotheses. One of those hypotheses that are described in this review paper based on the present studies relates to the *ortho* nuclear spin isomer enrichment in the MW (Laage and Hynes, 2006; Fisher and Radzihovsky, 2018; Kilaj et al., 2018; Vaskina et al., 2020; White, 2020), and thereby increased structural-architectural order formed by the network of hydrogen bonds (Chang and Weng, 2006). Nevertheless, there are still some outstanding questions regarding how the predominance of *ortho* nuclear spin isomers in magnetized water can affect plant growth and development by modulating the ion-channels located in the plasmalemma, exactly how it can act on macromolecules and affect biochemical reactions within the plant cells. Therefore, further targeted investigations are necessary to discover how this magnetically conditioned water affects the water orientation and macromolecules participating in the biochemical processes of living beings. First of all, whether and how it affects the molecular and biochemical processes of plant cells. In addition, we need to study how different aqueous solutions with various mineral content can change the magnetizing effects and what parameters of the magnetic treatment, among them magnetic induction, field strength, exposure time or water flow rate and the water temperature, need to change in a targeted way.

Priming effect of MW on abiotic stress mitigation has been detected and proven also for several types of abiotic stresses, which can be exploited for overcoming the challenges of climate change. Water shortage is increasingly becoming a global problem due to the climate change. Therefore increasing the drought tolerance of crops is of food safety and economic importance. Out of different strategies, like nutritional management, mycorrhizal applications, using biosensors etc., the application of MW is one of the cheapest and most environmentally

Table 3
Effect of MW on water productivity in different plant species when magnetization occurred on different types of water.

Plant species	Water type	Magnetization	Effects on water productivity and water saving	Reference
celery (*Apium graveolens* subsp. *dulce* (Mill.) Schübl. & G. Martens)	potable water (PW) recycled water (RcW)	Magnetic device with MF range was 3.5–136 mT; pipe section was 100 mm with internal diameter of 22 mm; Water flow rate was 10 ml s^{-1}	Water productivity increased by 12% and 24% when RcW and SW (3000 ppm) were magnetized, respectively.	Maheshwari and Grewal, 2009
pea (*Pisum sativum* L.)	Saline water (SW, 1500, and 3000 ppm NaCl)	Water passed 2-times through the magnetizing device	No effect was detected.	
snow pea (*Pisum sativum* var. *saccharatum*)	PW, RcW, SW (500, and 1000 ppm NaCl)		Water productivity increased by 12%, 7.5% and 13%, in response to magnetized TW, RcW and SW (1000 ppm), respectively.	
cowpea (*Vigna unguiculata* L. Walp. cv.Kamran)	normal tap water	Details of the magnetizing device was not described.	Water use efficiency, I.e. total dry weight per consumed water, increased by 22% (from 114.8 g m^{-3} to 139.87 g m^{-3})	Sadeghipour and Aghaei, 2013
eggplant (*Solanum melomgena* L. cv. Florida High Bush)	SW (700 mg l^{-1} Na^{+}), drip irrigation method	Details of the magnetizing device was not described.	Water productivity increased by 65% (6.42 kg m^{-3} when irrigation occurred with MW and it was 3.90 kg m^{-3} in control). 11% water saving occurred.	Kareem, 2018
faba bean (*Vicia faba* L. cv. Isban)			Water productivity increased by 88% (1.43 kg m^{-3} when irrigation occurred with MW and it was 0.76 kg m^{-3} in control). 13.5% water saving occurred.	
tomato (*Solanum lycopersicon* L. cv. Logaen)			Water productivity increased by 78% (15.52 kg m^{-3} when irrigation occurred with MW and it was 8.73 kg m^{-3} in control). 14.2% water saving occurred.	

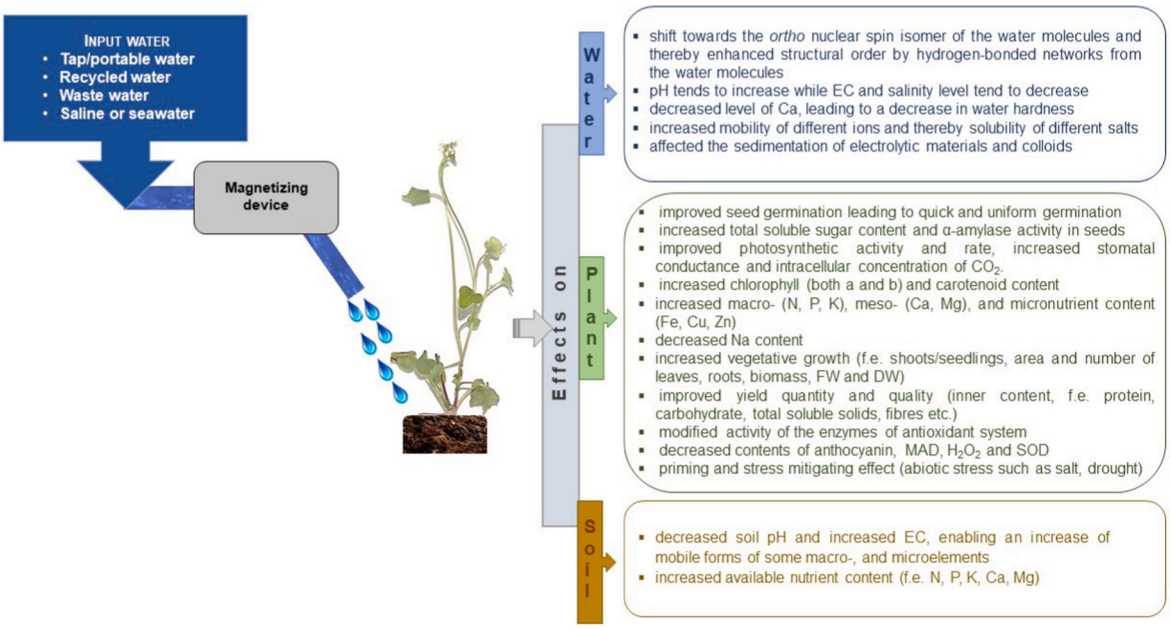


Fig. 2. Main effects of magnetized water (MW) on water, plant and soil, affecting plant growth and development (DW, dry weight; EC, electric conductivity; FW, fresh weight; H_2O_2, hydrogen peroxide; MAD, malondialdehyde; SOD, superoxide dismutase).

sound solutions to alleviate drought (Ali et al., 2014). Salt stress mitigating effect of MW enables another solution for attenuating and alleviating the problem of water shortage. Since the application of water magnetization is able to improve the water quality of salty as well as hard water, thereby makes them suitable for use as irrigation water. In addition, water magnetization is an ecofriendly solution for improving the low quality irrigation water. Furthermore, considering that water saving of 11–22% was reported depending on the type of water and plant species, the use of MW for irrigation may be of increasing economic importance in the future.

Based on our recent empirical knowledge, MW has the potential to enhance and improve both vegetative and reproductive growth and development of plants. However, as described here and earlier (Tables 1–2; Teixeira da Silva and Dobránszki, 2014; Ali et al., 2014), its effect can be not only supportive but also harmful on plant growth and development. Thereby, the appropriate magnetizing device and treatment must always be fit to the needs of the plant species and even varieties and taking into account the quality of the water available, as well. MW can act even harmful for plant growth and development, for example by modulating and enhancing the uptake of some nutrients, among them heavy metals, as well. Some heavy metals, like Cu, Zn, or even cobalt (Co), are necessary for the processes of living beings to some extent, but beyond a certain concentration, they can be harmful. Other heavy metals, like lead (Pb), mercury (Hg) or cadmium (Cd) affects the organism negatively. Heavy metal pollution can not only hinder or decrease the plant production but through the food chain they can cause diseases in animals and humans. Currently there is a lack in studies regarding heavy metal stress mitigating effect of MW. However, considering the effect of magnetization to enhance the ion mobilization in water and from soil, there is a theoretical opportunity to do so. A similar possibility in the case of Cd phytoremediation was recently suggested by Hu et al. (2022) study. There is a need for detailed and extensive investigations how magnetized heavy metal-contaminated water, or irrigation with MW on heavy metal contaminated soil can affect the uptake and translocation of different heavy metals in various crops, and how they can alter the production of those crops. An interesting question for future research may be whether the MW may be used as one of the technologic components of phytoremediation processes.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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