Journal of King Saud University – Science 35 (2023) 102890

HOSTED BY

Contents lists available at ScienceDirect

Journal of King Saud University – Science

journal homepage: www.sciencedirect.com

Original article

Influence of magnetic field on the physicochemical properties of water molecule under growing of cucumber plant in an arid region

M.A. Abu-Saied [a], Eman A. El Desouky [b], Mohamed E. Abou Kamer [c], Mohamed Hafez [d,]*, Mohamed Rashad [d]

[a] Polymeric Materials Research Department, Advanced Technology and New Materials Research Institute, City of Scientific Research and Technological Applications (SRTA-City), New Borg El-Arab City, Alexandria, 21934, Egypt
[b] Chemistry Department, Faculty of Science, Alexandria University, Alexandria, Egypt
[c] Cross-Pollination Vegetable Dept., Horticulture Research Institute, A.R.C., Egypt
[d] Land and Water Technologies Department, Arid Lands Cultivation Research Institute, City of Scientific Research and Technological Applications (SRTA-City), New Borg El-Arab City, Alexandria, 21934, Egypt

ARTICLE INFO

Article history:
Received 26 November 2022
Revised 1 March 2023
Accepted 3 September 2023
Available online 9 September 2023

Keywords:
Magnetizer
pH
TDS
Alkalinity
Surface tension
Hardness

ABSTRACT

This study highlights the potential impact of magnetic fields on water quality, which could have implications for plant growth and development. Theoretical estimates of changes in surface tension, pH, and some other properties due to passing water through a magnetic field for a certain period were experimentally validated in this study. Overall, the results revealed changes in the physicochemical properties of water after magnetic field application. In accordance, pH significantly ($p < 0.05$) increased from 2 to 2.25, from 4 to 4.5, from 6 to 6.45, from 7.3 to 7.8, and from 8 to 8.7 and except at $pH_{10,}$ which decreased from 10 to 9.7. In addition, the model developed in this study indicated that the change of electrical conductivity (EC) decreased from 9 to 6.11 dS m^{-1} with an increasing number of run flow through the magnetic field. The decline in EC can be described as follows: magnetically treated water contains fine colloidal molecules and electrolytic chemicals that respond to a magnetic field by enhancing their ability for precipitation, resulting in a fall in EC. Moreover, the Hardness values of recirculated water were decreased after magnetic field application. This corroborates the decline of calcium carbonate adhesion and surface tension values as increases in hydrogen bonding between protons and water molecules and changes in the distribution of molecules in magnetized water. As the internal electrical field grew and the hydration shells surrounding the constituent ions weakened, EC decreased. Lastly, by using an electronic microscope, observing the water in regular, such as regular hexagonal tree shape instead of random irregular shapes after magnetic field application, confirming that the magnetic field had a significant effect on the physical properties of water molecules. In conclusion, magnetic behavior may improve water quality, resulting in increased development and plant growth.

1. Introduction

Water chemistry modification is critical in the treatment of wastewater. More work has been undertaken on implementing such changes that consume less material and energy to minimize treatment costs and enhance task performance. Water that has been put through a magnetic field before usage is known as magnetically treated water (MTW). There are numerous advantages to using such treated water, though there is an ongoing debate about its effectiveness. Biological advantages provide a rise in yield, enhanced crop maturity, improved sugar, vitamin C, and total acid content (Taha et al., 2022) and improved fruit set and flowering (Taha et al., 2020). MTW has a wide range of industrial applications. It is used to block leveling on the interior walls of fluid-transporting pipes, most notably water, according to (Abu-Saied & Taha, 2020). Taha et al. (2019) notes that the oil industry recently succeeded in avoiding calcium carbonate levelling in the Auk field, illustrating how magnetic treatment of fluids on offshore rigs has a considerable benefit. In other well-documented cases, the applied field has also been utilized to avoid hydrocarbon deposits in pipes.(See Scheme 1)

Anti-scale magnetic therapy (AMT) is strengthened by extended or repeated magnetic exposure, is more effective beyond a thresh-

---

* Corresponding author.
E-mail addresses: mouhamedabdelrehem@yahoo.com (M.A. Abu-Saied), mhafez290@yahoo.com (M. Hafez), marashad2@gmail.com (M. Rashad).

Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.jksus.2023.102890
1018-3647/

$$\text{During titration: } H_2Y^{-2}(aq) + Ca^{+2}(aq) \longrightarrow CaY^{-2}(aq) + 2H^{+}(aq)$$

$$H_2Y^{-2}(aq) + Mg^{+2}(aq) \longrightarrow MgY^{-2}(aq) + 2H^{+}(aq)$$

$$\text{At end point } \quad H_2Y^{-2}(aq) + MgIn^{-}(aq) \longrightarrow MgY^{-2}(aq) + HIn^{-2}(aq) + H^{+}$$

Wine-red Sky-blue

Scheme 1. Chemical analysis to determine the hardness of samples.

old magnetic field contact duration, and is more effective in flowing systems, according to several studies (Cho & Lee, 2005; Selim & El-Nady, 2011). Numerous theories and mechanisms explain how insufficient magnetic fields can affect other fluids and water to decrease the formation of scale. Review of the main components of ion hydration in water, fine structure, and the property of the hydrocarbon bond (Herzog et al., 1989; Kronenberg, 1985). He develops a model of proposed pathways for how particularly weak fields can affect the number of hydrogen bonds between water molecules due to triplet-singlet transitions in the water molecule's Zeeman electron–proton multiplets and its immediate surroundings. Baker and Judd list additional mechanisms as intramolecular / intraionic interaction, Lorentz force effects, contaminant dissolution, and interfacial effects (Deng & Pang, 2007; Pang & Deng, 2008). Enhanced magnetic field density causes a higher percentage of salt removed because water molecules are charged with electricity and have a small dipole, resulting in a low dielectric constant. Exogenous electric and magnetic fields may affect this dipole. It is well established that exposing water to a weak magnetic field can alter its dielectric constant. Changes in the electric dipole moment of water can alter its physical properties. TDS, EC, and pH are included in those physical properties. The purpose of this study was to determine the effect of commercial magnetizers on the TDS and pH of various types of water using a magnetizer designed specifically for each type of water. (Pang & Shen, 2013). Cucumber (*cucumis sativus* L.) is a popular crop belonging to the family Cucurbitaceae which has 118 genera and 825 species. Cucumber has chromosome number (2n = 2x = 14). cucumber is initially from India but has developed in most areas. Conferring to the United States department of agriculture (USDA), A 100-gram portion of fresh cucumber (with peel) has 16 calories. It contains 95 percent water, low in cholesterol and sodium, so eating cucumber in a hot summer helps the body to stay hydrated. Cucumber supplies low content of essential nutrients; vitamin K at 16%; calcium at 2%; iron at 2 %; magnesium at 4%; potassium at 3%; and zinc at 2% of the daily value (Hachicha et al., 2018).

Many studies show that if adequate management practices are used, these water resources that were previously classed as unsuitable for irrigation may be effectively utilized to grow crops without long-term harmful implications to crops and soils with and without humic substances to achieve agriculture sustainability (Rashad et al., 2022). These techniques include using sophisticated irrigation technology, selecting salt-tolerant crops, and leaching salts below the crop root zone (Wan et al., 2010). Drought and competing water sources have hindered water resource utilization in several Middle Eastern locations (Gleick, 2014). It is crucial to improve irrigation water using proper procedures in quantitative and qualitative terms. As a result, one of the potential alternatives for reducing total water usage in the agricultural sector is to apply technologies that enhance crop yield per unit volume of water (water use efficiency, WUE).

Research indicates that utilizing magnetically treated water improves agricultural production and water productivity due to chemical and physical changes in irrigation water quality (Adeniran et al., 2020; Liu et al., 2019). Pang and Deng (2008) examined the water magnetism mechanism and suggested a proposal based on water molecule structure. MW is produced when water passes through the magnetic field of a permanent magnetic device or electromagnetic one installed on a feed pipeline, where all water and salt molecules have internal vibration (Babu, 2010).

Hasaani et al. (2015) investigate the interaction of flowing water with magnetic fields, measuring TDS, pH, EC, viscosity, absorbance, thermal conductivity, and surface tension for ordinary tap water before and after applying magnetic fields of strength 6560G created by properly arranging permanent magnet pieces around the pipe accommodating the flowing water (Hasaani et al., 2015). They discovered that the physical characteristics of magnetized water were examined using precision measurement techniques. These include a rise in pH of 12% and decreases in TDS and EC of 33% and 36%, respectively. Mechanical properties such as viscosity and surface tension are also reduced by 23 and 18%, respectively. Even the heat conductivity was reduced by 16%.

This study presents a scientific breakthrough by demonstrating the potential effects of magnetic fields on the physicochemical properties of water, such as changes in pH, electrical conductivity, hardness, and the formation of hexagonal structures. The research suggests that magnetically treated water may contain colloidal molecules and electrolytic chemicals that improve their precipitation ability, leading to a decrease in electrical conductivity. These novel findings could have significant implications for enhancing water quality and plant growth, thus opening up new avenues for the practical applications of magnetic fields.

The aim of this study was to examine the effects of magnetic field treatment on cucumber vegetative characteristics, yield, and components. Magnetic water treatment generates an anti-scale effect by varying a variety of variables, including the composition of the water, the strength of the magnetic field, the speed at which it flows, and the amount of time it spends in the magnetic field.

2. Materials and experimental

2.1. Materials

Sodium chloride and magnesium sulphate were purchased from United Company, (Egypt), Hydrochloric acid 99% from Sigma Aldrich (USA), sulfuric acid and Ammonium ions 25% were purchased from United Co., Egypt. Ethylenediaminetetraacetic acid (EDTA), indicators (Erio-chrome Black T& Phenolphthalein) were from United Company, (Egypt).

2.2. Solution preparation

In this study, we investigated the effect of a variable magnetic field intensity with exposure times changing. Tap water and sodium chloride were utilized as solutions. The salt solutions were made by dissolving a certain quantity of NaCl in 200 ml of distilled and tap water and stirring it with a magnetic stirrer for various periods at room temperature to ensure full dissolution.

2.3. Experimental setup

The magnetic source device (Fig. S1) was from Delta water Co. for water treatment (Japan), with a magnet strength of 14,500 Gauss with 316 magnetic field number. This device is composed of an inner magnet surrounded by a copper housing and an outer magnet protected by a steel shield from the outside within and out one-way openings for water current.

2.4. Cation exchange capacity (CEC)

Cation exchange capacity (CEC) evaluates a soil's ability to support replaceable cations that neutralize the negative charge of the soil. The cation sites are exchanged with ammonium (NH_4^+) ions, and the exchangeable NH_4^+ions are leached with protons from HCl acid. (Dontsova, 1998; Horneck et al., 1989). This method has undergone many adaptations. In this experiment, prepared tap water samples of different TDS from 1000 to 8000 ppm depending on NaCl and $MgSO_4$ salts were used before and after magnetic treatment to pass on 100 g of a representative soil sample, then NH_4OAc was added, and the concentration of exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+ ions are subsequently analyzed before and after magnetic treatment of water using ICP-OES.

2.5. Physical and chemical analysis of water samples

The total dissolved solids, pH, hardness values, surface tension, and alkalinity are all measured with the selected instrumentation setup (Fig. 1).

pH is assessed with a high-precision pen-type pH meter with a sensitivity of 0.01 and ± 0.1 accuracy. EC and TDS are detected using a TDS meter with ± 2% f.s. accuracy (Dunstan, 1994).

The EDTA titration technique is used to determine hardness. These titrations are dependent on bases and acids, with an indicator that color turns in a different medium (basic or acidic). The chelating substance ethylene diamine tetra acetic acid (EDTA) can be used to quantify magnesium and calcium ions. On a cation like Ca^{2+}, the EDTA molecule can form a compound with six sites. Because both Ca^{2+} solutions and EDTA are colorless, an indicator is required to indicate the completion of the reaction. Eriochrome Black T, which forms a wine-red compound with Mg^{2+}, is the preferred indication. During the majority of the titration, a small quantity of Mg^{2+} will be bound to the indicator. The Mg^{2+} in the indicator will react with EDTA once all of the Ca^{2+} has interacted with it. The indicator then returns to its acidic state, which has a sky-blue color, indicating that the process is complete. The reactions that occur throughout the titration are listed below, with H3 being the generic formula for Erio-chrome Black T (Alkhazan & Saddiq, 2010; Szcześ et al., 2011).

The water capacity to neutralize acids is measured by alkalinity. Bicarbonates, carbonates, and hydroxides are alkaline chemicals in the water that remove H^+ ions and reduce the acidity of the water (which means increased pH). Titration is used in the total alkalinity analysis. In this test, titration is the addition of 0.02 N sulfuric acid (the reagent) to the sample, which contain a small quantity of Phenolphthalein Indicator until the pink color disappears (V1), then add a few drops of mixed indicator in which the color turn to blue due to presence of carbonate in the water sample. Titrate till the solution become red(V2).

$$Totalalkalinity = \frac{V1 \times N \times 50 \times 1000}{Volumeofsampletaken} \quad (1)$$

Surface tension is the physical property of liquids that results from an imbalance of attractive intermolecular forces in which the exposed surface tendency to contract to the smallest possible area. It is measured by Rame- heart instrument, as shown in the Figure S2 (Qu et al., 2004).

2.6. Coefficient of soil permeability and soil leaching

Soil permeability was measured using the constant head test ASTM-D2434 and the Darcy equation, and it was observed that soil permeability enhanced by around $4x10^{-5}$ cm/s after magnetic treatment, which might be due to increased ion solubility and decreased ion association as mentioned earlier. The soil leaching percent was also determined for 100 g of soil with total dissolved salts of 2100 ppm using salinized water ranging from 1000 to

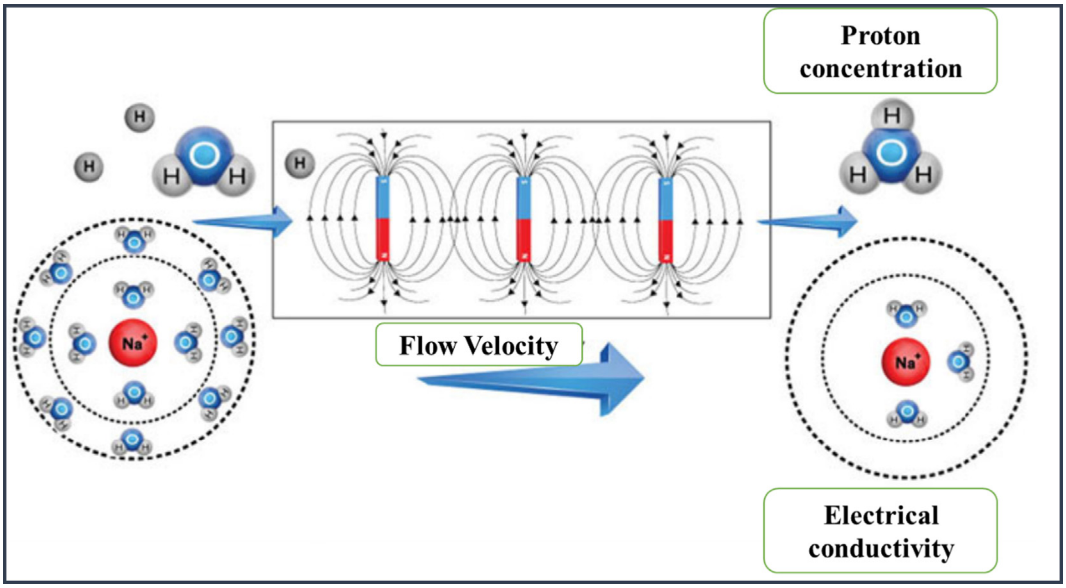


Fig. 1. Changing of water characteristics upon magnetic treatment (Wu & Brant, 2020).

5000 ppm. It was discovered that the salts content in magnetic treated water increased significantly after washing compared to non-magnetic treated water, implying that the salts content of soil decreases when using magnetically treated water. For all forms of flow issues in soil when laminar flow conditions occur, the permeability coefficient is utilized to calculate the quantity of flow (Iwasaka & Ueno, 1999; Joshi, 1996). It can be calculated according to Darcy's law by the constant head method:

$$q = -K \cdot i = K \cdot \frac{\partial H}{\partial Z} \tag{2}$$

where t is the time required for flow, K is the permeability coefficient through a volume, V. q is the flux (flow density), and Q is the flow rate (V/t). The flux (q) is proportional to the water level difference h.

$$\frac{dV}{dt} = -K \cdot h \cdot \frac{A}{L} \tag{3}$$

By integration both sides:

$$K = \frac{a \cdot L}{A(t_2 - t_1)} \cdot \ln h1/h2 \tag{4}$$

where h1 and h2 represent water level differences inside and outside the ring holder at the start (t1) and finish (t2), respectively, a represents the ring holder's cross-section surface, and t represents the duration of time-lapse.

2.7. Vibrating sample Magnetometer (VSM)

A vibrating Sample Magnetometer (VSM) system monitors the magnetic characteristics of materials as they change with the magnetic field, time, and temperature. Modern commercial VSMs have practically automated operations with data acquisition/control and analysis software that runs on a personal computer, making the VSM accessible to non-specialists.

2.8. Morphological analysis (SEM) & (TEM)

The morphological features and microstructure of the polymeric materials and their membranes were examined using SEM & TEM, JEOL JSM-6360LA, Japan (Abu-Saied et al., 2017; Moustafa et al., 2021; Moustafa et al., 2022).

2.9. Field experiment under growing cucumber plant

The field experiment was conducted at El-Sabaheya Horticultural Research Station farm (Hort. Res. Inst., Agric. Res. Cen.) at Alex., Egypt., during the summer seasons of 2021 and 2022. This experiment was conducted on cucumber inbred line (1–26-27–19 KAHA), which was kindly provided by the improvement of the main vegetable and Hybrids Production Project, Vegetables branch, Horticulture Research Institute. The recommended production of commercial cucumber was done. Five salt concentrations of irrigation water were used with total soluble salts of 500 (tap water as a control), 1000, 1500, 2000, 2500, and 3000 mg/L. The saline water was prepared by mixing tap water electrical conductivity (EC) 0.78 dS/m with seawater to obtain 1.57, 2.35, 3.13, 3.91, and 4.69 dS/m at specific ratios equal to 500, 1000, 1500, 2000, 2500 and 3000 mg/L, respectively. The experiment was designed as a split plot with three replicates. The combination of two factors formed treatments. Five salt levels of saline water irrigation (500, 1500, 2000, 2500, and 3000 mg/L) were assigned in the main plots, and two water treatments (MTW and NMTW) were random and distributed in the subplots. Irrigation treatments started during early vegetative growth 30 days after transplanting, keeping the soil moisture content near the field capacity (28%).

Seeds were sown in 209 cells tray at16th April and 20th March of 2021 and 2022, respectively. Seedlings were transplanted in to field 21 days after sowing when the second true leaf was fully expanded, and then, seedlings were thinned to one plant/hill of three plants/m^2. Irrigation, fertilization, weeding, and pest controls were practiced as recommended by Ministry of Agriculture and land Reclamation (MALR). The experiments included 270 plastic pots of 28 cm for upper and lower diameters, respectively, and a height of 30 cm. The pots were arranged in three lines, with nine pots for each line. Each line represented a specific treatment with three replications. The first treatment (T1) was the control 500 mg/L, which was irrigated with tap water, and the (T2) was tap water treated with a magnetic field. The (T3) and (T4) treatments were 1000 mg/L ones without magnetic treatment and ones with magnetic treatment; the (T5) and (T6) were1500 mg/L ones without magnetic treatment and ones with magnetic treatment. The (T7) and (T8) were 2000 mg/L, ones without magnetic treatment and ones with magnetic treatment. The (T9) and (T10) were 2500 mg/L, ones without magnetic treatment and ones with magnetic treatment. Concerning the concentration of 3000 mg/l, the cucumber plants did not tolerate this high concentration of water salinity, and it prompted dwarfing, lack of growth, and burning of the vegetative system, and then died.

Measurements were recorded for vegetative growth characteristics there were; days to first female flower (days), days to first male flower (days), days to first fruit harvest (days), plant length (cm), number of nodes/ plants, number of female flowers per node. For yield and yield components, total fruit yield/plant (kg), number of fruits/plants, and average fruit weight/plant (gm).

2.10. Statistical analysis

The analysis of variance (ANOVA) was used to compare the means with a significance level of 0.05, followed by Duncan's multiple comparisons test was used to determine the differences among treatments and to classify the treatments according to their performance. The costate software program was used to conduct this statistical test after checking the normality and homogeneity of variance among treatments.

3. Results & discussion

3.1. pH, TDS & EC

The pH, EC, and TDS values of water before and after magnetic treatment are depicted in Fig. 2. Magnetic treatment of solutions tends to increase pH except for alkaline water, additionally reducing the EC of all the solutions. Nevertheless, after 24 h, this factor variation is neutralized, and the solutions revert to their original values (Cai et al., 2009). The decrease in EC, TDS, and increase in pH in magnetically treated solutions might be a result of hydrogen bonding alterations and improved ion mobility (Tables 1 and 2). The drop in EC may be described as follows: magnetically treated water contains fine colloidal molecules and electrolytic chemicals that respond to magnetic treatment by enhancing their ability to sediment, resulting in a fall in EC (Pang et al., 2012).

3.2. Hardness measurement

Table S1 presents the hardness measurements of recirculated water vs the circulation numbers, with the base line data clearly defined as 168 ppm before circulation. After five cycles of circulation, it is inferred that the hardness of the water is reduced. This corroborates the discovery of reduced calcium carbonate adhesion to surfaces as a result of the MWT. Magnetic water hardness has

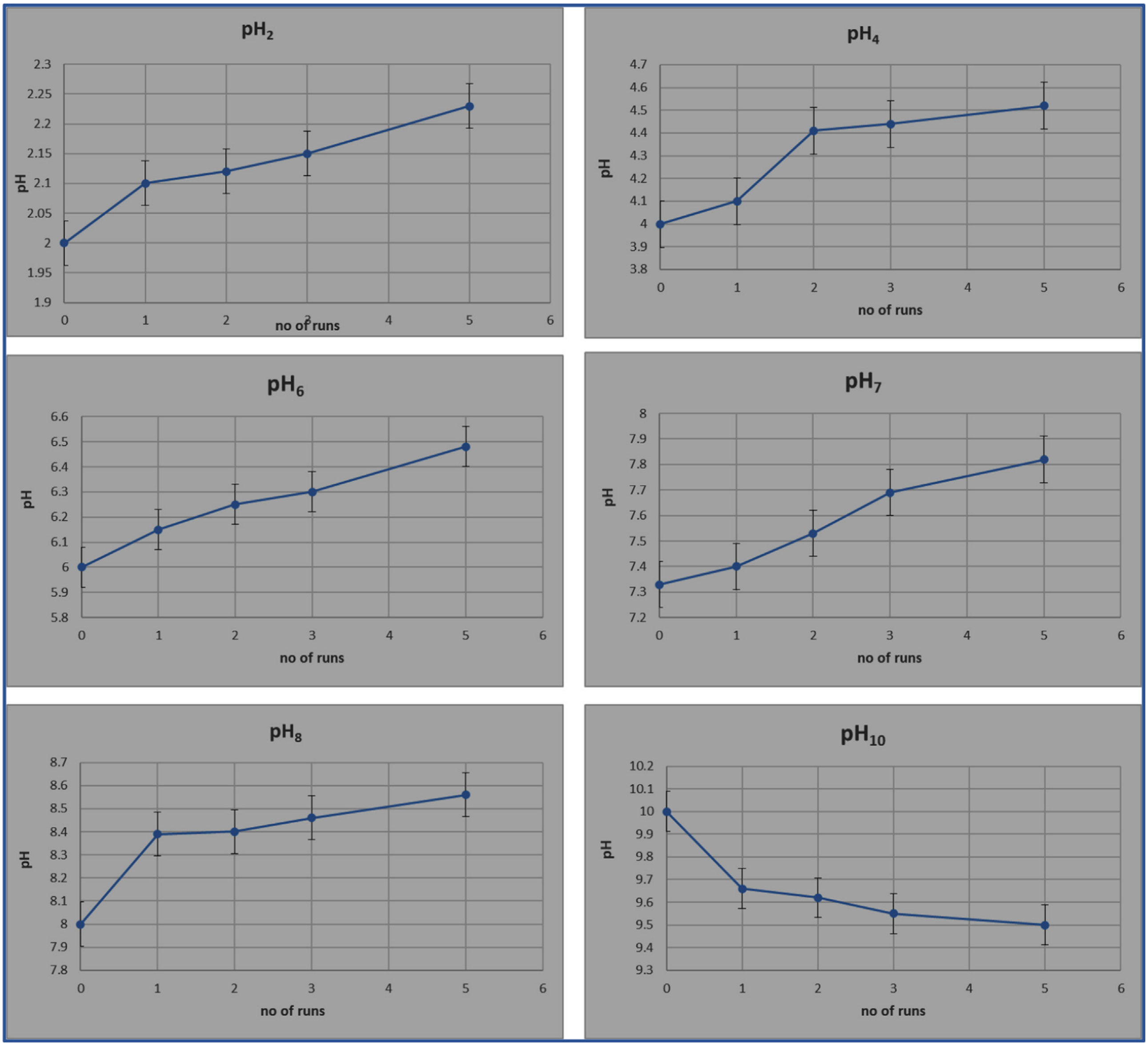


Fig. 2. Influence of magnetic field on water pH.

Table 1
Effect of magnetic field on TDS of water.

no of runs	TDS_1 (ppt)	TDS_2 (ppt)	TDS_3 (ppt)	TDS_4 (ppt)	TDS_5 (ppt)	TDS_6 (ppt)	TDS_7 (ppt)	TDS_8 (ppt)
	1	2	3	4	5	6	7	8
1	0.99 ± 0.08	**1.99** ± 0.1	2.98 ± 0.12	3.98 ± 0.15	5.98 ± 0.20	5.96 ± 0.25	6.98 ± 0.35	7.94 ± 0.5
2	0.99 ± 0.05	1.99 ± 0.09	2.98 ± 0.14	3.98 ± 0.17	5.98 ± 0.22	5.96 ± 0.30	6.98 ± 0.33	7.94 ± 0.51
3	0.98 ± 0.06	1.98 ± 0.07	2.96 ± 0.13	3.95 ± 0.15	5.96 ± 0.24	5.95 ± 0.33	6.97 ± 0.37	7.92 ± 0.53
5	0.98 ± 0.08	1.98 ± 0.1	2.96 ± 0.15	3.94 ± 0.19	5.95 ± 0.22	5.95 ± 0.32	6.95 ± 0.33	7.92 ± 0.57

Table 2
Effect of magnetic field on EC of water.

no of runs	EC_1 (ms)	EC_2 (ms)	EC_2 (ms)	EC_3 (ms)	EC_4 (ms)	EC_6 (ms)	EC_7 (ms)	EC_8 (ms)
	2	4	6	8	10	12	14	16
1	1.98 ± 0.10	3.98 ± 0.24	5.96 ± 0.31	7.96 ± 0.34	9.96 ± 0.42	11.92 ± 0.62	13.94 ± 0.80	15.94 ± 0.88
2	1.98 ± 0.11	3.98 ± 0.25	5.96 ± 0.32	7.96 ± 0.38	9.96 ± 0.50	11.92 ± 0.60	13.94 ± 0.84	15.88 ± 0.84
3	1.97 ± 0.14	3.96 ± 0.22	5.92 ± 0.34	7.9 ± 0.32	9.92 ± 0.45	11.9 ± 0.64	13.92 ± 0.87	15.8 ± 0.88
5	1.97 ± 0.11	3.96 ± 0.28	5.92 ± 0.37	6.88 ± 0.33	9.9 ± 0.50	11.9 ± 0.61	13.9 ± 0.88	15.8 ± 0.9

gained significant relevance in agriculture, particularly in regions where water quality concerns and a lack of access to high-quality water are prevalent. In response to these challenges, modern agricultural practices are increasingly focused on developing efficient and eco-friendly production methods that can boost crop yields while minimizing environmental impact. To achieve this goal, researchers have been exploring the potential of magnetic water treatment to improve soil and water quality, enhance nutrient uptake by crops, and increase overall agricultural productivity. According to (Pang & Jalbout, 2004), this approach holds great promise as a sustainable solution to the pressing challenges facing the agricultural industry.

3.3. Alkalinity

In practice, alkalinity is defined as the sum of the CO_3^{-2}, HCO_3, and OH ions. Because fluctuations in pH affect alkalinity. As seen in (Fig. S3), the water's alkalinity reduces with each run-in compared to the entering water. Thus, it is clear that differences in OH-ion concentrations result in variances when comparing measured hardness and alkalinity together (Ali, Samaneh, Zohre, & Mostafa, 2014).

3.4. Surface tension

Surface tension values drop, as indicated in Fig. 3, owing to the attractive attraction between water molecules caused by the applied magnetics field's changes in the distribution of molecules and increased polarization effect in magnetized water consequently, decrease the surface tension value of water molecules (Pohlmeier et al., 2010).

3.5. Soil permeability coefficient

Soil permeability Fig. 4 is critical for predicting optimal nutrient utilization and washing away excess salts and toxic elements; it was discovered that soil permeability increased by approximately $4x10^{-5}$ cm/s following magnetic treatment, which may be due to greater ion solubility and decreased ion association, as previously mentioned (Mohamed & Ebead, 2013).

3.6. Cation exchange capacity

From Table 3, leaching of soil with magnetic treated saline water is accompanied by a decrease in CEC of soil than untreated equivalent. This may be due to the breakdown of water clusters which increases the solubility of salts, and also the effect of Lorentz forces which increase ionic mobility and decrease ion association. The soil CEC decrease is significantly noticeable for TDS of 1000 and 8000 ppm. The diminution of soil CEC results in the reduction of salt buildup and promotes uniform soil infiltration. Alternatively, the soil's texture is influenced by the ratio of Ca^{2+} and Mg^{2+} ions, which determines its compactness. An increase in Ca ions leads to a looser soil structure, whereas an increase in Mg ions results in a tighter soil. Consequently, soils with high calcium content tend to have better oxygenation, improved drainage, and greater potential for aerobic decomposition of organic matter. In contrast, soil with a high magnesium content will have less oxygen, would drain slowly, and organic matter will degrade poorly. In agriculture, the soil must not be more loosely or more tightly, but it should have a lower Mg ion content than Ca ion to support aeration of the soil, and hence; using of magnetic treated water will be useful to get rid of excess Mg ions without affecting negatively on water retention capacity.

3.7. Vibrating sample Magnetometer (VSM)

Magnetized water exhibits magnetism, as seen in Figure S4. Its lower magnetism is owing to the tiny amount of protons and water molecules involved in this conductivity in the closed hydrogen-bonded chains, which account for just a fraction of the protons and water molecules in water. This provides more evidence for the existence of closed hydrogen-bonded chains.

3.8. Scanning electron microscope (SEM) & transmission electron microscope (TEM)

Under the electronic microscope, it is obvious from Figs. 5a and 5b that water develops in a random irregular pattern amid the salt deposits prior to magnetic treatment. Following treatment, regular forms of water occur in the salt deposits, such as regular hexagonal ice crystals, indicating that the hexagonal tree shape resulted in more well-formed crystals. Confirmation of the magnetic field's influence on the rearrangement and arrangement of water crystals, as well as enhancement of the quality of water used in medical treatment (Abdel Tawab et al., 2011; Ghauri & Ansari, 2006; Lewis & Sjöstrom, 2010). Among the most common properties of water is float of ice in it. When other substances move from the liquid to the solid state, the density of the molecules and atoms that form the solid increases, and the substance becomes relatively heavier.(See Fig. 5c.).

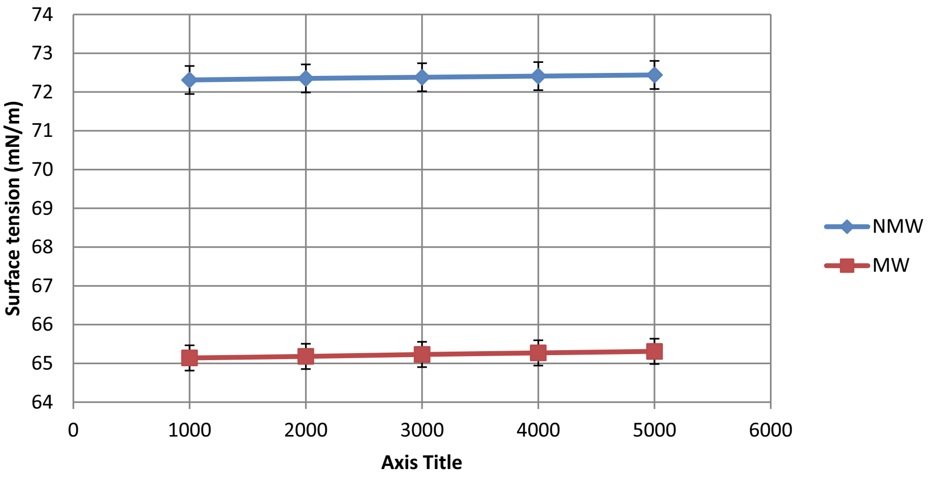


Fig. 3. Surface tension (mN/m) versus TDS (ppm).

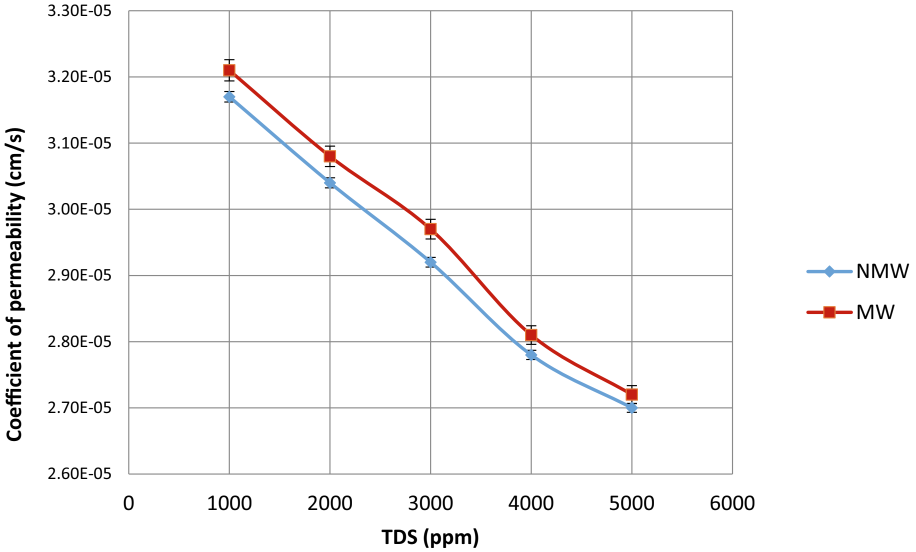


Fig. 4. Coefficient of permeability (cm/s) versus TDS (ppm).

Table 3
CEC and concentration of Na$^+$, K$^+$, Ca^{+2}, and Mg^{+2} ions.

TDS (ppm)	**CEC (meq/100 g)**				
		Na	K	Ca	Mg
1000	NMT	15.21 ± 0.80	0.74 ± 0.08	3.84 ± 0.01	7.45 ± 0.06
	MT	8.16 ± 0.50	0.62 ± 0.07	0.34 ± 0.03	3.35 ± 0.04
2000	NMT	17.92 ± 0.17	0.82 ± 0.05	4.12 ± 0.08	11.19 ± 0.14
	MT	16.09 ± 0.12	0.63 ± 0.08	0.46 ± 0.08	11.02 ± 0.10
3000	NMT	26.02 ± 0.51	0.84 ± 0.04	4.85 ± 0.05	27.58 ± 0.14
	MT	23.77 ± 0.74	0.73 ± 0.07	0.39 ± 0.04	26.58 ± 0.17
4000	NMT	42.12 ± 0.97	1.32 ± 0.02	5.14 ± 0.09	31.47 ± 0.20
	MT	40.58 ± 0.90	1.11 ± 0.03	0.60 ± 0.07	31.29 ± 0.22
5000	NMT	61.97 ± 1.1	1.37 ± 0.04	6.02 ± 0.02	32.33 ± 0.12
	MT	57.39 ± 1.1	1.14 ± 0.02	0.69 ± 0.04	31.84 ± 0.13
6000	NMT	71.25 ± 1.25	1.51 ± 0.05	6.15 ± 0.04	33.30 ± 0.17
	MT	58.48 ± 1.5	1.17 ± 0.07	1.58 ± 0.03	29.77 ± 0.18
7000	NMT	98.03 ± 1.1	1.60 ± 0.06	6.26 ± 0.07	41.77 ± 0.12
	MT	86.24 ± 1.2	1.17 ± 0.05	2.18 ± 0.01	38.15 ± 0.20
8000	NMT	101.56 ± 1.33	1.67 ± 0.07	6.61 ± 0.04	44.09 ± 0.24
	MT	80.49 ± 1.24	1.19 ± 0.06	3.07 ± 0.04	36.49 ± 0.30

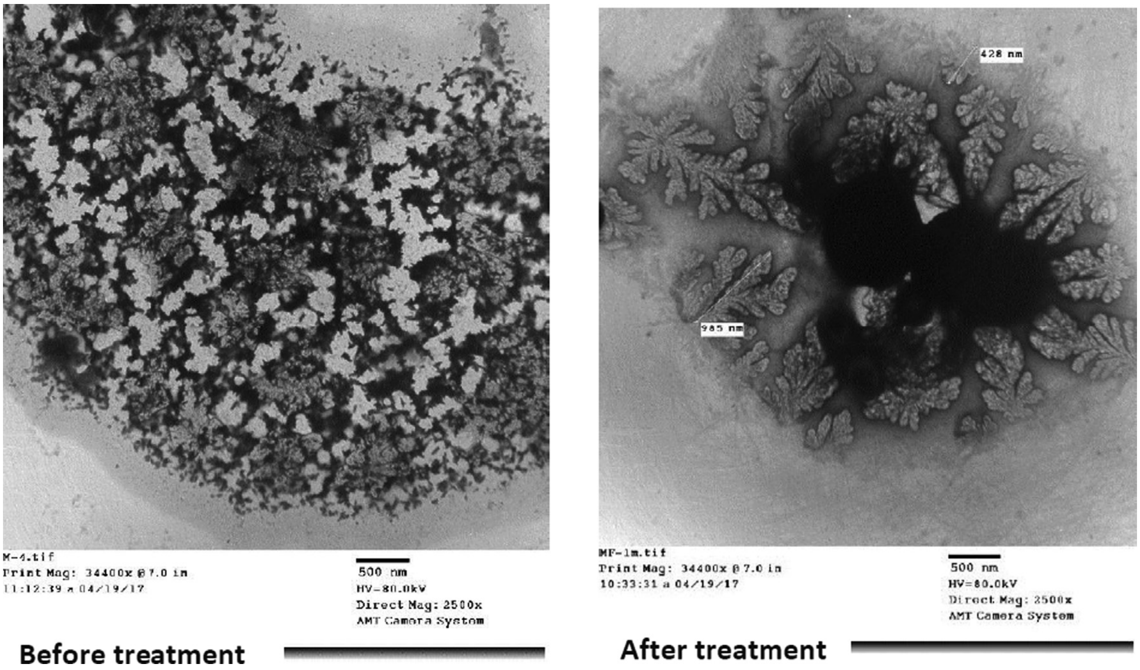
On the other hand, water particles align in a very controlled manner, with several huge voids between them. When ice melts and returns to water, the particles become more active. As the particles become more active, the gaps between them close, resulting in a heavier and denser liquid form of water than the solid version. TEM images illustrate that water crystals formed from the distilled water were deformed and incomplete before magnetic treatment, but the water formed complete crystals. So, SEM and TEM indicates that the magnetic treatment is more powerful and has a more significant influence. A magnetic field tends to be more active energy. When a full geometric crystal forms, we might guess that water is in harmony with nature, and the water particles merge to form the crystal nucleus. When the nucleus develops into a stable hexagonal shape, a visible water crystal forms, as a consequence, magnetic therapy may increase the quality and intake of water, the value of feed, ruminal fermentation, blood profile, and antioxidant status, and hence milk and labneh production.

3.9. Effects of magnetic water on growth and productivity of cucumber plant

This experiment was conducted to evaluate the effect of magnetic treatment of salt and fresh irrigation water on the growth and productivity of cucumber plants. Table 4 the analysis variance values show that there are no significant differences within the blocks except for the trait average fruit weight; this can be attributed to the difference in the fertility of the soil between the places of cultivation of the different repeaters, which leads to a variation in productivity one another.

Also, the analysis of variance values showed that there are significant differences in all the studied traits in each of the concentrations of saline water and magnetic treatment, which shows that cucumber plants are affected by their growth and productivity by different concentrations of saline water as well as the use of magnetic treatment of water. On the other side, the obtained data showed non-significant differences in the interaction values between saline water concentrations and magnetic treatment, except for the traits number of days to the first female flower, number of days to harvest the first fruit, and the average fruit weight (gm).

Table S2 In this section, we are interested in studying the characteristics of vegetative traits of cucumber plants, their impact on different levels of saline irrigation water and magnetic water treatment, and the interaction between these two factors. The results of the vegetative characteristics illustrate significant differences in all the studied traits except for the number of days to first fruit har-



Before treatment

After treatment

Fig. 5a. TEM of well water (TDS = 1000 ppm) before and after magnetic treatment.

vest when we used the magnetic water treatment and not magnetic treatment, where the magnetic treatment recorded the highest values. The highest values of magnetic treatment of salt and fresh irrigation water are due to the high solubility of magnetically treated water compared to non-magnetically treated water decompose and spread.

Regarding the trait number of days to the first female and male flower, the obtained data indicate significant differences between irrigation water with a salinity of 500 mg/L and irrigation water with a salinity of 500, 2000, and 2500 mg/L. The highest values of decrease (days) were in irrigation water with a salinity of 2500 mg; this is due to the accumulation of salts around the plant root system and, thus, the occurrence of salt stress, which prompts the plant to flower early. For the number of days to harvest the first fruit, the data showed no significant differences between the salinity concentrations of irrigation water except for the concentration of 1500 mg/L.

Concerning the trait plant height, the obtained data showed that there were no significant differences between water salinity at 500 mg/L and 1000 mg/L, while significant differences were found with the others concentrations of irrigation water salinity, where there was a decrease in plant height by 19.6% and by 28% At a concentration of 2000 and 2500 mg /L respectively, which indicates that, with the increase in the salinity of the irrigation water there is a decrease in the growth of cucumber plants. For the number of nods/plants, the obtained results showed no significant differences between the two concentrations of water salinity at 500 mg /L and 1000 mg/L. On the other hand, significant differences were found between the concentrations of irrigation water salinity, where the saline irrigation water at 2500 mg /L recorded the lowest value. Zhao et al. (2021) discovered that magnetic or ionized irrigation water was beneficial for plant absorption of soil water, which was reflected in the development of winter wheat, resulting in improved growth metrics. According to Maheshwari and Grewal (2009), water's physical and chemical properties completely altered following magnetic treatment, making water more helpful for plant systems, resulting in better cell activity and crop development (Maheshwari & Grewal, 2009). All of these changes result in changed plant development metrics, such as changes in height and mass, as well as an increase in the plant's capacity to absorb more water, which boosts nutrient absorption owing to the tiny water molecules of magnetized water, increasing agricultural yield (Maheshwari & Grewal, 2009; Abdelraouf et al., 2020; Zhao et al., 2021; Rashad et al., 2021).

Regarding to the total yield /plant (kg), significant differences were found between all concentrations of salinity irrigation water, and the data showed a decrease in the values of the yield by 12% with an increase in water salinity from 1000 mg /L to 1500 mg /L and 34.5% with an increase in water salinity from 1500 to 2000 mg /L and 48% with an increase in the water salinity from 2000 mg/L to 2500 mg /L, while the values showed a decrease of 74% when the salinity water increased from 500 mg/L to 2500 mg/L. The same results were found by Shahin *et al*,0.2016) on cucumber illustrate that Magnetic seeds were germinated and flooded with magnetised water (40.0mT) to evaluate and analyze the growth characteristics, yield output, and certain nutrients (N, P, K, Fe, Mn, Zn, and Cu) content of cucumber crop (Khatab et al., 2016; Shahin et al., 2016; Hafez et al., 2019, 2020a). The results showed that magnetic treatments boosted cucumber plant height, yield (kg/m^2), fruit length, fruit diameter, and leaf dry matter % when compared to the control treatment. Anmar et al, 2022 found that magnetically treating the seeds for 2 min before planting and irrigating them with magnetically treated water had a good influence on all broad bean growth and yield indices.

Referring to the traits number of fruits/plant, the obtained results showed the effects of increasing the saline irrigation water on the number of fruits/plants, where significant differences appeared between the concentrations of 1500, 2000, and 2500 mg/L, the lowest values were recorded by the concentration 2000 and 2500 mg /L, respectively. Concerning to the trait average fruit weight (gm), the recorded data showed that there are significant differences between the concentration of 500 mg /L and the other concentrations. Still, no significant differences appeared between the concentration 1000 mg /L and 1500 mg /L with significant differences between the concentration 2000 mg/L and 2500 mg/L. At the same time, the lowest value for the average fruit

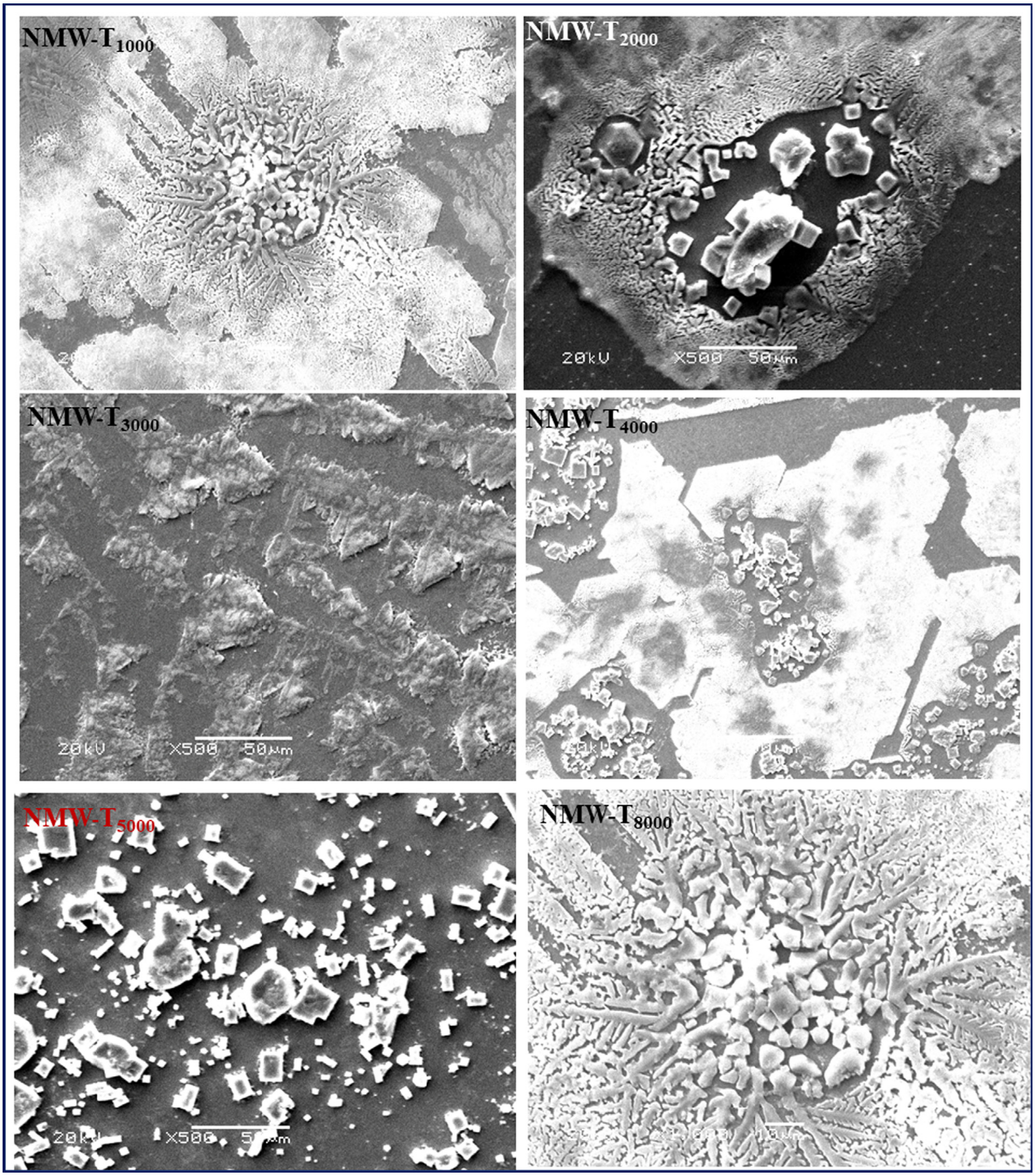


Fig. 5b. SEM of well water before magnetic treatment.

weight was recorded by the saline irrigation water at 2500 mg /L. As shown in Table 4, the interactions between water salinity concentrations × magnetic treatment and non-magnetic treatment for vegetative growth traits, as well as the yield and its components. With regard to the trait number of days to the first female flower, the obtained data showed that the highest values were recorded at water salinity 500 mg / L without magnetic water treatment, with no significant differences between them and the concentration of irrigation water salinity 1000 mg /L with magnetic water treatment, the concentration 2500 mg /L was the lowest value with no significant differences between it and the concentration of 2000 mg /L without magnetic water treatment and 2000 and 2500 mg/L with magnetic water treatment.

For the trait number of days to the first male flower, the obtained results showed that, the highest value was recorded by the saline water irrigation at 2500 mg/L with no significant differences between it and the concentration of 2500 mg/L in the presence of magnetic treatment, while less values were recorded with a concentration of 2000 mg/L without magnetic treatment.

The data on days to first harvest showed that the highest values were observed at a water salinity concentration of 500 mg/L. However, there were no significant differences between this concentration and the one at 2500 mg/L. In contrast, all other concentrations, with or without magnetic water treatment, exhibited significant differences from one another. Regarding plant height, the most favorable outcomes were obtained at salinity levels of 500 and

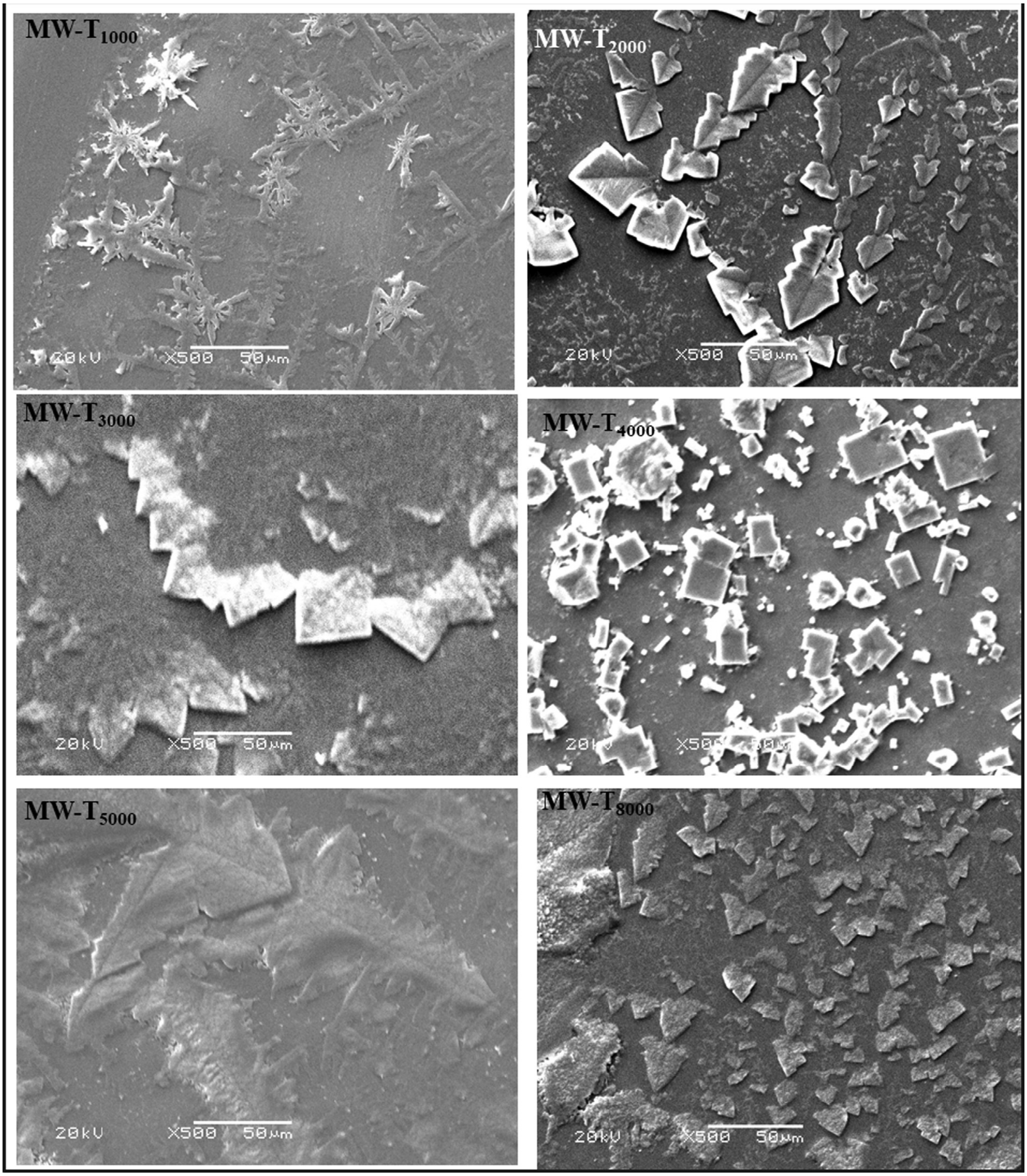


Fig. 5c. SEM of well water after magnetic treatment.

Table 4
Combined analysis of variance for vegetative characters and yield and its components of cucumber (over two years of 2021 and 2022).

S.O.V.	D.F.	Days to first female flower (days)	Days to first male flower (days)	Days to first harvest (days)	Plant length (cm.)	No. of nodes/plant	No. of female flower/node	Total yield /Plant (kg)	No. of fruit/plant	Average fruit weight (gm)
Blocks	2	1.3	0.200	2.043	58.825	1.201	0.108	0.002	8.397	141.997**
Conc.	4	14.148**	21.906**	4.805*	3738.47**	76.159**	3.901**	6.788**	597.589**	514.949**
Treat	1	6.302**	25.025**	1.008	1340.001**	27.075**	0.427	1.860**	173.136**	139.363*
c × t	4	5.598**	4.411	2.680*	57.648	1.124	0.0327	0.147	2.926	247.767**
Error	10	0.583	1.815	0.533	19.183	0.403	0.089	0.091	8.619	23.883

*, ** Significant and highly significant at the 0.05 and 0.01 levels of probability, respectively.

1000 mg/L when using magnetic water treatment. Conversely, the lowest values were observed at a salinity level of 2500 mg/L without magnetic water treatment, underscoring the role of magnetic treatment in boosting plant growth.

The data of number of nods per plant indicated that the best treatments were using magnetic water treatment at water salinity 500 mg /L and 1000 mg/L, while the lowest values were recorded at water salinity 2500 mg /L without using magnetic water treatment, as well as no significant differences between the water salinity at 1000 mg/L without magnetic water treatment and 1500 mg/L with magnetic water treatment and also with water salinity at 500 mg/L.

As for the trait number of female flowers per node on the plant, the highest value was recorded by the water salinity at 500 mg /L with magnetic water treatment with no significant differences with each of the water salinity at 500 mg /L without magnetic water treatment, 1000 mg/L without magnetic water treatment, 1000 mg/L with using of magnetic water treatment and 1500 mg /L with using magnetic water treatment, while the water salinity at 2,500 mg /L without magnetic water treatment recorded the lowest values with no significant differences for the same concentration using magnetic water treatment.

The obtained results in Table 4 indicated that, the total yield per plant (kg), the highest values were recorded at a water salinity 500 mg /L with using of magnetic water treatment, with no significant differences between it and the water salinity at 500 mg /L without using magnetic water treatment, and water salinity at 1000 mg /L with using of magnetic water treatment, on the hand the water salinity at 1500 mg/L with the presence of magnetic treatment recorded 2.77 (kg) with no significant differences between it and the water salinity at 1500 mg/L without using magnetic water treatment and 1000 mg/L with using magnetic water treatment, while the water salinity at 2000 mg /L with magnetic treatment recorded 2.06 (kg) with no differences between it and the water salinity at 2000 mg/L without using magnetic water treatment, on the other side the lowest values obtained at the water salinity were 2,500 mg/L without using of magnetic water treatment. It was also found that, there were no significant differences between the water salinity at 2000 mg /L without using magnetic water treatment and the water salinity at 2500 mg /L using magnetic water treatment.

For number of fruits per plant trait, the obtained results in Table 2 showed that, the salinity of irrigation water at 500 mg /L with the using of magnetic water treatment recorded the highest values with no significant differences between it and the salinity of irrigation water at 500 mg/L without using magnetic water treatment and water salinity at 1000 mg/L with the use of magnetic water treatment and water salinity at 1500 mg /L with the using of magnetic water treatment, while the lowest values were recorded by the concentration in terms of irrigation water at 2500 mg /L without using water magnetic. For the trait, average fruit weight (gm), the highest values were recorded at the irrigation water salinity at 1000 mg/L with the use of magnetic water treatment and without significant differences with the water salinity at 500 mg/L with and without the use of magnetic water treatment, while the lowest values obtained by the salinity of irrigation water at 2500 mg/L without using magnetic water treatment. Magnetic irrigation water treatment saved water, boosted output, accelerated crop maturity, improved crop quality, decreased plant diseases, increased fertilizer efficiency, and lowered farm management costs (Hozayn & Qados, 2010; Selim, 2008; Amiri and Dadkhah, 2006). Magnetic treatment of water modifies the structure of water, increasing mineral dissolvability, lowering surface tension, and providing necessary nutrients for plant development (Altalib et al., 2022; Babu, 2010; El Sayed, 2014; Suchitra & Babu, 2011).

4. Conclusion

Based on this research, magnetic water treatment affects the properties of water molecules. The pH increased from 2 to 2.25, from 4 to 4.5, from 6 to 6.45, from 7.3 to 7.8, and from 8 to 8.7, except at pH10 decreased from 10 to 9.7. In addition, the change of EC decreased from (9 to 6.11) ms, and the circulation of recirculated water via the magnetic water conditioner reduced the TDS and hardness marginally. And the surface tension declined as the treatment with MF increased activation energy while reducing intramolecular energy. As a result, the water cluster size increased, and more hydrogen bonds were formed. Finally, change a morphological feature of a water molecule by using the electronic microscope (TEM and SEM). In summary, magnetic treatment can enhance the efficiency and consumption of water,

CRediT authorship contribution statement

M.A. Abu-Saied: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Eman A. El Desouky:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Mohamed Hafez:** Writing – original draft, Writing – review & editing. **Mohamed Rashad:** Software, Investigation, Data curation, Supervision.

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.

Acknowledgments

We thank the industry "Delta Water" for the devices dedicated to testing. We wish to express our sincere thanks to Mr. Ahmed Ibrahim and Mr. Sherif Ibrahim for granting the devices to perform the experimental test.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2023.102890.

References

Abdel Tawab, R.S., Younes, M.A., Ibrahim, A.M., AbdleAziz, M.M., 2011. Testing commercial water magnetizers: a study of TDS and pH. In: Paper presented at the Fifteenth International Water Technology Conference, IWTC-15.

Abu-Saied, M., Taha, N.A., 2020. Purification of waste water from cationic dye using SPGMA polymer: isotherm and Kinetic study. Global NEST J. 22 (2), 179–184.

Abu-Saied, M.A., Wycisk, R., Abbassy, M.M., El-Naim, G.A., El-Demerdash, F., Youssef, M.E., Bassuony, H., Pintauro, P.N., 2017. Sulfated chitosan/PVA absorbent membrane for removal of copper and nickel ions from aqueous solutions—fabrication and sorption studies. Carbohydr. Polym. 165, 149–158.

Abdelraouf R.E., Abdou S.M.M., Abbas, M.M. Mahmoud, Hafez, M., Popov, Alexander I., Hamed L.M.M., 2020. Influence of N-Fertigation Stress and Agro-Organic Wastes (Biochar) io Improve Yield and Water Productivity of Sweet Pepper Under Sandy Soils Conditions, Plant Archievs, 20(Jan), pp. 3165–3172. http://www.plantarchives.org/SPECIAL%20ISSUE%2020-1/214__3208-3217_.pdf.

Adeniran, K.A., Kareem, K.Y., Yusuf, K.O., Afolayan, S.O., 2020. Effects of electromagnetic treatment of irrigation water on growth and yield of Lagos Spinach (Celosia argentae). Agric. Eng. Int. CIGR J. 22 (2), 32–40.

Ali, Y., Samaneh, R., Zohre, R., Mostafa, J., 2014. Magnetic water treatment in environmental management: a review of the recent advances and future perspectives. Curr. World Environ. 9 (3), 1008–1016.

Alkhazan, M.M.K., Saddiq, A.A.N., 2010. The effect of magnetic field on the physical, chemical and microbiological properties of the lake water in Saudi Arabia. J. Evolution. Biol. Res. 2 (1), 7–14.

Altalib, A.A., Ali, W.M., Al-Ogaidi, A.A., Al-Zubaidy, S.A.S., 2022. Effects of magnetic field treatment of broad bean seeds and irrigation water on the growth and yield of plants. Irrigat. Drainage.

Amiri, M., Dadkhah, A.A., 2006. On reduction in the surface tension of water due to magnetic treatment. Colloids Surf. A Physicochem. Eng. Asp 278 (1–3), 252–255.

Babu, C., 2010. Use of magnetic water and polymer in agriculture. Tropical Res. 8, 806.

Cai, R., Yang, H., He, J., Zhu, W., 2009. The effects of magnetic fields on water molecular hydrogen bonds. J. Mol. Struct. 938 (1–3), 15–19.

Cho, Y.I., Lee, S.-H., 2005. Reduction in the surface tension of water due to physical water treatment for fouling control in heat exchangers. Int. Commun. Heat Mass Transfer 32 (1–2), 1–9.

Deng, B., Pang, X., 2007. Variations of optic properties of water under action of static magnetic field. Chin. Sci. Bull. 52 (23), 3179–3182.

Dontsova, K., 1998. Soil structure and infiltration as affected by exchangeable Ca and Mg, and soil amendment. MS thesis. West Lafayette, Ind.: Purdue University, Department of Agronomy.

Dunstan, D.E., 1994. Electrophoretic mobility and dielectric response measurements of colloidal hematite. J. Colloid Interface Sci. 163 (1), 255–258.

El Sayed, H.E.S.A., 2014. Impact of magnetic water irrigation for improve the growth, chemical composition and yield production of broad bean (Vicia faba L.) plant. Am. J. Experimental Agric. 4 (4), 476.

Ghauri, S., Ansari, M., 2006. Increase of water viscosity under the influence of magnetic field: American Institute of Physics.

Gleick, P.H., 2014. Water, drought, climate change, and conflict in Syria. Weather Clim. Soc. 6 (3), 331–340.

Hachicha, M., Kahlaoui, B., Khamassi, N., Misle, E., Jouzdan, O., 2018. Effect of electromagnetic treatment of saline water on soil and crops. J. Saudi Soc. Agric. Sci. 17 (2), 154–162.

Hafez, M., Popov, A.I., Rashad, M., 2019. Influence of Agro-industrial wastes and Azosirillum on Nutrient Status and Grain Yield under Corn plant Growth in Arid Regions. Bioscience Research 16 (2), 2119–2130 https://www.isisn.org.

Hafez, M., Popov, A.I., Rashad, M., 2020a. 'A Novel Environmental Additives to Decrease Nitrate Level in Agriculture Wastewater and Enhancement Nutrient Status under greenhouse plant growth in calcareous soil', Plant Archievs, 20 (Jan), pp. 3165–3172. Available at: https://www.plantarchives.org/SPECIAL%20ISSUE%2020-1/209__3165-3172_.pdf.

Hasaani, A.S., Hadi, Z.L., Rasheed, K.A., 2015. Experimental study of the interaction of magnetic fields with flowing water. Int. J. Basic Appl. Sci. 3 (3), 1–8.

Herzog, R.E., Shi, Q., Patil, J.N., Katz, J.L., 1989. Magnetic water treatment: the effect of iron on calcium carbonate nucleation and growth. Langmuir 5 (3), 861–867.

Horneck, D.A., Hart, J.M., Topper, K., Koepsell, B., 1989. Methods of soil analysis used in the soil testing laboratory at Oregon State University.

Hozayn, M., Qados, A.A., 2010. Irrigation with magnetized water enhances growth, chemical constituent and yield of chickpea (Cicer arietinum L.). Agric. Biol. J. N. Am. 1 (4), 671–676.

Iwasaka, M., Ueno, S., 1999. Effects of 14 Tesla Magnetic Field on Hydration and Structure of Water Molecules. In: Electricity and Magnetism in Biology and Medicine, Springer, pp. 271-274.

Joshi, K., 1996. Effects of magnetic field on water investigated with fluorescent probes. J. Indian Chem. Soc. 43 (9), 620–622.

Khatab, S., Gomaa, E., Khalf-Allah, M., El-Aziz, A., Abido, I.M., El-Gamal, A., Al-Abed, M.S., 2016. Inheritance of powdery mildew resistance and some economic traits in Cucumber (Cucumis sativas L.). Alexandria Sci. Exchange J. 37 (April-June), 116–126.

Kronenberg, K., 1985. IEEE Trans. Magn. MAG-21 (5), 2059.

Lewis, J., Sjöstrom, J., 2010. Optimizing the experimental design of soil columns in saturated and unsaturated transport experiments. J. Contam. Hydrol. 115 (1–4), 1–13.

Liu, X., Zhu, H., Meng, S., Bi, S., Zhang, Y., Wang, H., Ma, F., 2019. The effects of magnetic treatment of irrigation water on seedling growth, photosynthetic capacity and nutrient contents of Populus× euramericana 'Neva'under NaCl stress. Acta Physiol. Plant. 41 (1), 1–13.

Maheshwari, B.L., Grewal, H.S., 2009. Magnetic treatment of irrigation water: its effects on vegetable crop yield and water productivity. Agric Water Manage. 96 (8), 1229–1236.

Mohamed, A.I., Ebead, B.M., 2013. Effect of magnetic treated irrigation water on salt removal from a sandy soil and on the availability of certain nutrients. Int. J. Eng. 2 (2), 2305–8269.

Moustafa, M., Abu-Saied, M.A., Taha, T.H., Elnouby, M., El Desouky, E.A., Alamri, S., Shati, A., Alrumman, S., Alghamdii, H., Al-Khatani, M., Al-Qthanin, R., Al-Emam, A., 2021. Preparation and characterization of super-absorbing gel formulated from κ-Carrageenan–Potato peel starch blended polymers. Polymers 13 (24), 4308.

Moustafa, M., Abu-Saied, M., Taha, T.H., Elnouby, M., El Desouky, E., Alamri, S., Alghamdii, H., 2022. New blends of acrylamide/chitosan and potato peel waste as improved water absorbing polymers for diaper applications. Polym. Polym. Compos. 30, 09673911221077559.

Pang, X.-F., Deng, B., 2008. The changes of macroscopic features and microscopic structures of water under influence of magnetic field. Phys. B Condens. Matter 403 (19–20), 3571–3577.

Pang, X.-F., Deng, B., Tang, B., 2012. Influences of magnetic field on macroscopic properties of water. Mod. Phys. Lett. B 26 (11), 1250069.

Pang, X.-F., Jalbout, A., 2004. Conductivity properties of the proton transfer exposed in externally applied fields in hydrogen-bonded systems. Phys. Lett. A 330 (3–4), 245–253.

Pang, X.-F., Shen, G.-F., 2013. The changes of physical properties of water arising from the magnetic field and its mechanism. Mod. Phys. Lett. B 27 (31), 1350228.

Pohlmeier, A., Vergeldt, F., Gerkema, E., Van As, H., Van Dusschoten, D., Vereecken, H., 2010. MRI in soils: Determination of water content changes due to root water uptake by means of a multi-slice-multi-echo sequence (MSME). Open Magn. Resonance J. 3 (1), 69–74.

Qu, F., Santos, D., Morais, P., 2004. The effects of external magnetic field upon the stability of ionic magnetic fluids. J. Magn. Magn. Mater. 272, 943–945.

Rashad, M., Kenawy, E.-R., Hosny, A., Hafez, M., Elbana, M., 2021. An environmental friendly superabsorbent composite based on rice husk as soil amendment to improve plant growth and water productivity under deficit irrigation conditions. Journal of Plant Nutrition, vol. 44, NO. 7, 1010–1022, 2021. https://doi.org/10.1080/01904167.2020.1849293.

M. Rashad, M. Hafez, Popov, A.I., 2022. Humic substances composition, properties as an environmentally sustainable system: A review and way forward to soil conservation. Journal of Plant Nutrition, 2022, Vol. 45, NO. 7, 1072–1122.

Selim, A.-F.-H., El-Nady, M.F., 2011. Physio-anatomical responses of drought stressed tomato plants to magnetic field. Acta Astronaut. 69 (7–8), 387–396.

Selim, M., 2008. Application of magnetic technologies in correcting under ground brackish water for irrigation in the arid and semi-arid ecosystem. In: Paper presented at the The 3rd International Conference on Water Resources and Arid Environments.

Shahin, M., Mashhour, A., Abd-Elhady, E., 2016. Effect of magnetized irrigation water and seeds on some water properties, growth parameter and yield productivity of cucumber plants. Curr. Sci. Int 5 (2), 152–164.

Suchitra, K., Babu, E., 2011. A pilot study on silt magnetized and non-magnetized water in the on-farm water use efficiency management. In: Centre for Water Resources, Anna University, Chennai, India.

Szcześ, A., Chibowski, E., Hołysz, L., Rafalski, P., 2011. Effects of static magnetic field on water at kinetic condition. Chem. Eng. Process. 50 (1), 124–127.

Taha, T.H., Abu-Saied, M., Elnouby, M.S., Hashem, M., Alamri, S., Mostafa, Y., 2019. Designing of pressure-free filtration system integrating polyvinyl alcohol/chitosan-silver nanoparticle membrane for purification of microbe-containing water. Water Supply 19 (8), 2443–2452.

Taha, T.H., Elnouby, M.S., Abu-Saied, M., Alamri, S., 2020. Tested functionalization of alginate-immobilized ureolytic bacteria for improvement of soil biocementation and maximizing water retention. RSC Adv. 10 (36), 21350–21359.

Taha, T.H., Abu-Saied, M., Elnouby, M., Hashem, M., Alamri, S., El Desouky, E., Morsy, K., 2022. Profitable exploitation of biodegradable polymer including chitosan blended potato peels' starch waste as an alternative source of petroleum plastics. Biomass Convers. Biorefin., 1–9

Wan, S., Kang, Y., Wang, D., Liu, S.-P., 2010. Effect of saline water on cucumber (Cucumis sativus L.) yield and water use under drip irrigation in North China. Agric Water Manage. 98 (1), 105–113.

Wu, T., Brant, J.A., 2020. Magnetic field effects on pH and electrical conductivity: implications for water and wastewater treatment. Environ. Eng. Sci. 37 (11), 717–727.

Zhao, G., Mu, Y., Wang, Y., Wang, L., 2021. Response of winter-wheat grain yield and water-use efficiency to irrigation with activated water on Guanzhong Plain in China. Irrig. Sci. 39 (2), 263–276.

Further reading

ALtamimi, D.A.M., 2014. Effect of magnetic water and depth of drip irrigation water and yield of cucumber in green houses. Diyala Agric. Sci. J. 6 (1), 179–186.