Original Research Article

Groundwater Treatment by Electromagnetic Polarization

Abstract

Due to the increased demand for water, it is essential to search for water sources to satisfy the water demand for drinking purposes. In Iraq, there is a continuous decrease in Tigris river water for many reasons. Thus it is necessary to search for other sources. On the other hand, there are rural areas where fresh water is unavailable, so it has become necessary to treat groundwater in such areas. Groundwater can be considered for this purpose. However, most groundwater sources are not suitable before reducing hardness. In the present work, a trial to minimize hardness from the groundwater by electromagnetic polarization is made. Actual samples are taken from Samarra, Salah al-Din Governorate. Laboratory apparatus has been designed and constructed to perform the present work. The investigated parameters are; contact time (5 - 60 sec), initial hardness concentration (800 - 1800 mg/L), and magnetic flux intensity (0.5 - 1.25 Tesla). The results indicated that hardness can be reduced by electromagnetic treatment. The obtained hardness removal efficiency range is 3.25 to 35.2%. Moreover, the addition of γ-Fe2O3 and Fe3O4 gives no improvement in hardness removal.

Keywords: Groundwater, Electromagnetic polarization, Hardness, Magnetic nanoparticles, hardness removal

Introduction

Groundwater sources can fulfill the increasing water demand. However, most of the groundwater is brackish. Therefore, it must be treated to be able for consumption (Mahdi 2008). Magnetic field innovation is a modern and advanced system for water treatment (Goldsworthy et al. 1990). According to Baker and Judd's (1996) review paper, the Anti-scale Magnetic treatment (ATM) of hard water is used to prevent deposits in heat exchangers and domestic devices.

Qahtani (1996) worked on the desalination of seawater with a total dissolved solids (TDS) concentration of 4300 mg/L through the permanent magnetic tube at a high strength of 0.7 T. The salt concentrations of treated solutions were observed to be smaller than those of untreated solutions.

Busch and Busch (1997) prepared hard water and treated it magnetically. They measured a scale before and after treatment. The results showed that a 22% reduction in scale formation was observed due to magnetic treatment.

Barrett and Parsons (1998) discovered that treating hard water with a magnetic treatment reduced the scale accumulated on the walls.

Alimi et al. (2006) studied the impact of a magnetic field on the calcium carbonate scale precipitation process in hard water. Calcium carbonate precipitation was induced after this treatment by degassing dissolved carbonic gas. They found that the nucleation time depends on pH, flow rate, and contact time. Furthermore, the magnetic treatment alters the homogeneous/heterogeneous nucleation ratio. The increase in pH, flow rate, and residence time will promote homogeneous nucleation.

Banejad and Abdosalehi (2009) investigated magnetic flux intensities of 0 - 0.1 T under flow rates of 4 and 30 lit/h to treat hard water. They stated that the magnetic flux intensity, flow rate, and how these elements interact have substantial effects on reducing water hardness. The results revealed that the amount of aragonite in comparison to calcite increased from 70% to 99.99%, and the ratio of calcite/aragonite had the greatest reduction. They got a hardness reduction of 51%.

Tantawy et al. (2015) investigated the effect of magnetic treatment on the ability of groundwater to form scales. Magnetic treatment was performed at 1.4 T and at a flow rate of 10 liters per hour. The amount of temporary hardness-causing ions as well as the weight of scales, were found to be significantly reduced after magnetic treatment by approximately 39.13% and 22.2 %, respectively. The magnetic treatment promotes the formation of crystals of calcite, vaterite, and aragonite.

Abdulrazzaq (2016) studied hard water treatment by Electromagnetic Polarization to enhance the precipitation of Ca^{2+} and $CO3^{2-}$ ions. Results showed that the increase of the electromagnet field would increase CaCO3 precipitation by up to 34 %.

Bali and Gueddari (2018) investigated how a magnetic treatment affected the physicochemical features of hard water. The results show that the magnetically treated water scaling power was inhibited.

Al-Omari (2019) stated that hardness and scale weight dropped by 39.1 and 22.3 % respectively after the magnetic treatment. The operating parameters in this work were; a flow rate of 10 liter/h and a magnetic field strength of 0.5 T. He stated that the magnetic field minimizes the amount of temporary hardness by lowering both the dissolved CO2 and surface tension. Magnetic processes change the shape and size of CaCO3 scale crystals, preventing them from adhering to the substrate and forming hard scales.

Alla (2019) used a magnetic technique for the treatment of water in some selected wells in Kirkuk province for irrigation. Results showed that a large change had happened after subjecting the samples to magnetic flux, especially the total dissolved solids, which was reduced by 30.4-31.25 %.

Aljuboory and Mahdi (2020) studied magnetic field treatment of salinity in groundwater in Kirkuk from April to August 2020 by exposing water to magnetic fields with varying intensities. According to the study's findings, magnetic treatment reduced total soluble solids, electrical conductivity, total hardness, calcium and magnesium hardness, chloride and sodium ion, pH, and potassium ion concentrations, and boosted nutrients ready for soil and plants.

Lu Lin et al. (2020) selected and reviewed 48 studies (published after 2000) about magnetic water treatment for scale control. They stated that magnetic treatment results in the precipitation of crystals. They also stated that 95% of the 48 studies discussed had positive effects and only 5% of the studies observed negligible improvement.

Sergio and Nuria (2021) stated that the effectiveness of magnetic and electromagnetic techniques in preventing scale is not demonstrated since it depends on many parameters such as temperature, pressure, dissolved CO2, pH, magnetic field intensity, water flow, etc. They presented a review of these techniques, together with other techniques, such as chemical softening, the use of inhibitors, ion exchange, electrochemical, and membrane treatments. The latter alters the composition of the water and generates hazardous waste for health and the environment, unlike magnetic and electromagnetic treatments, which are considered non-invasive techniques.

Aldoury et al. (2022) tried to soften groundwater and reduce total dissolved solids employing electromagnetic polarization under different operating parameters (inlet hardness, flow rate, magnetic field strength. The results indicated that hardness can be reduced and no significant total dissolved solids removal.

Jiang et al. (2022) studied the effect of Electromagnetic Fields (EMF) on Reverse Osmosis (RO) membrane scaling control during saline groundwater desalination. The results of the tests showed that EMF was effective for scale control under typical RO operation circumstances.

Qian Lei, et al. (2023) present a new methodology to evaluate the effectiveness of magnetic treatment of feed water for reducing mineral scaling on a reverse osmosis (RO) membrane. They found that this method is insignificant in scale inhibition.

Sirine et al. (2023) evaluated the influence of the magnetic treatment at 0.70 T, upon the scale formation in synthetic solutions exposed to a static magnetic field for different exposure times. The results show that homogeneous $CaCO_3$ precipitation rates in the treated solution were lower than those in the absence of the magnetic field.

A lot of work has been done on the application of magnetic treatment in many fields, including water and wastewater treatment. Many authors conducted research concerning the impact of magnetic fields on solid particle separation in water (Watson et al. 1980; Chin and Fan 2010), the effect of magnetic fields on the physical and spectral properties of water (Maggard 1989), desalination and ion exchange processes in the presence of a magnetic field (Bolto 1996), the use of magnetic particles with magnetic field to remover iron from water (Navartil and Tsair 2003), the use of physical polarization water treatment to inhibit scale (Zeng et al. 2013; Okazaki et al. 2019) and bacterial growth (Zeng et al. 2013), removal of arsenate from water (Tuutijarvi 2013), improvement of irrigation water characteristics (Kareemm 2019), phosphorus removal from water (Zhang et al. 2020), application of magnetic particle technology to treat wastewater by adsorption and coagulation processes (Bolto 1990), removing and recovering soluble Cr (VI) and Zn from wastewater (Chen et al. 1991), the use of a submerged filter system for wastewater treatment utilizing a biofilm system comprised a magnetically anisotropic tubular support medium (Sakai et al. 1994), precipitation of heavy metals from wastewater (Watson et al. 1994; Dunn and Friedman (1997), removing of radioactive elements, actinides, and heavy metals from a solution (Kochen and Navratil, 1997), removal of Cs (I) from radioactive waste (Ambashta et al. 2003), separation of radioactive corrosion products and eventually reduce radiation exposure at nuclear power plants (Song et al. 2004), heavy metals (chromium and lead) removal from synthetic wastewater (Al-Qaissi, 2005), adsorption of water-soluble azo dyes (Wu and Qu 2005), elimination of the majority of hydrophilic compounds as well as a massive portion of hydrophobic compounds from biological treatment secondary effluent (Zhang et al. 2006), removal of Hg(II) from an aqueous solution (Bayramoglu and Arica 2007), adsorption of methylene blue, red basic dye, blue basic dye, nonylphenol, and octylphenol (Kurinobu et al. 2007), separation of wastewater with thin emulsion-bearing cutting oil (Oka et al. 2009), removal of organic matter and nitrogen from the activated sludge using municipal wastewater (Liu et al. 2013), removal of colour, TSS, and COD (Mohammed et al. 2014), removal of heavy metals, fungicides, aromatic compounds, and colourants (Salinas et al. 2018), removal of Congo red (CR) dye (Atta et al. 2019).

Experimental Apparatus, Materials, and Experimental Scheme

Experimental Apparatus

The experiments were carried out using an electromagnetic treatment system (EMT) designed and constructed to conduct the present work. Figure (1) shows the schematic diagram of the experimental apparatus that is designed to give a maximum magnetic flux intensity of 1.5 T.

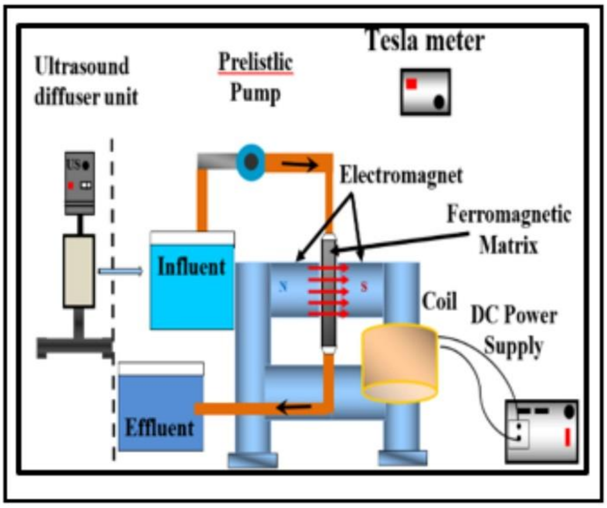

Figure (1) Schematic diagram of the experimental apparatus

Materials and Chemicals

Water Sample

Five samples of groundwater were taken from Samarra groundwater. Table (1) includes some of the physical and chemical properties of these samples. All samples were taken in March 2021.

Table (1) Some of the physical and chemical properties of groundwater samples

Sample No.	TDS, mg/L	Total hardness mg/L	Calcium hardness mg/L	EC Mohs/cm	pH	Temp. $^{\circ}$c	Cation (mg/L)					Anion (mg/L)				
							Ca^{2+}	Na^+	Mg^{2+}	K^+	Fe_3^+	SO_4^{2-}	HCO_3^-	Cl^-	PO_4^{3-}	NO_3^-
1.	2520	1800	1250	3370	7.41	23.4	500	100	120	19.5	0.03	925	420	345	18.08	44.8
2.	2210	1550	1075	3050	7.73	23.7	430	86	105	16	0.025	840	360	295	16	40
3.	1840	1300	900	2540	7.26	24	360	72	88	14	0.021	670	315	260	13	32
4.	1500	1050	613	2315	7.01	22.8	245	61	98	6.24	0.02	450	310	280	7.22	25
5.	1140	800	463	1560	7.20	22.3	185	51	74	3.5	0.015	340	245	190	6	18

Magnetic Iron Oxide

Two types of magnetic nanoparticles are used in the present work, namely iron oxide nanoparticle Maghemite (γ-Fe_2O_3) and Magnetite Fe_3O_4. In addition, a lot of chemicals are used to perform the required tests. All tests were conducted according to (Baird and Eaton 2017).

Experimental Scheme

The studied parameters that affect the electromagnetic polarization technique are; inlet hardness, contact time, and magnetic flux intensity. Table (2) includes the values of the investigated operating parameters. The experimental work is performed through two schemes that enable covering the operating parameters mentioned above.

Table (2) Values of the investigated operating parameters

Inlet hardness (mg/L)	800, 1050, 1300, 1550, 1800
Contact time (second)	5, 10, 20, 40, 60
Magnetic flux intensity (Tesla)	0.5, 0.75, 1, 1.25

First Scheme

A full factorial scheme is followed to perform the experimental work of the first scheme which requires 200 experiments, 100 for plastic tube and 100 for copper tube.

Second Scheme

Depending on the results of the first scheme, the conditions that give the best hardness removal are used to perform other sets of experiments with the use of two magnetic nanoparticles (maghemite and magnetite) at various doses.

Results and Discussion

Results of the First Scheme

Effect of Contact Time on Hardness Removal Efficiency

Figures (2 and 3) represent a sample of the results which indicate the effect of contact time on the removal efficiency under various operating parameters. These Figures indicated that the removal efficiency is increased with the increase in contact time. Yadollahpour (2014) and Moya & Botella, (2021) found that total hardness decreases with the increase of contact time and with the increase of the magnetic flux intensity. This is because increasing contact time will give more chance for crystallization and precipitation. The increase in contact time will give more chance for the magnetic force to do its action on hardness to be removed. The maximum removal efficiency for the plastic tube was 23.75% obtained at a contact time of 60 sec., magnetic flux intensity of 1.25T, and inlet hardness of 800 mg/L. The corresponding removal for the copper tube was 35.2% obtained at a contact time of 60 seconds, inlet hardness of 1050 mg/L, and magnetic field strength of 1.25T. These results agree with those of Cho and Lee (2005), Alla (2019), Kareemm (2019), Aljuboory (2020), and Jiang et al. (2022).

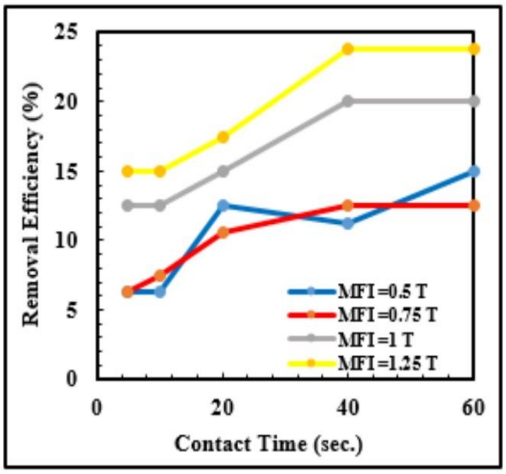

Figure (2) Effect of contact time on the removal efficiency, inlet hardness 800mg/L, Plastic tube

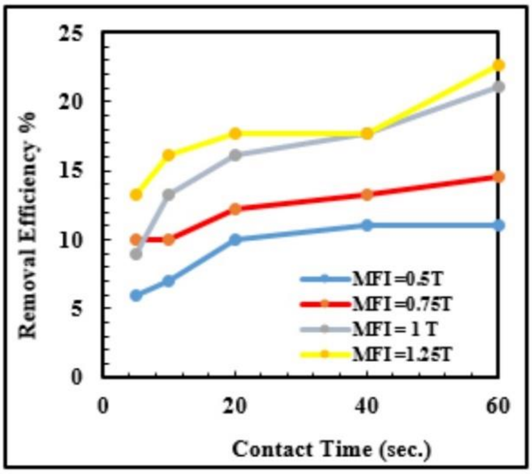

Figure (3) Effect of contact time on hardness removal efficiency, inlet hardness 1800mg/L, Copper tube

Effect of Magnetic Flux Intensity on Hardness Removal Efficiency

A sample of the results is given in Figures (4 and 5). These Figures represent the effect of the magnetic flux intensity on hardness removal efficiency. These Figures show that the removal efficiency is increased with the increase of the magnetic flux intensity. The presence of the magnetic force leads to a change in the crystalline shape of the water, which puts the solution in a state of supersaturation, and this is the basic condition for the salts to begin to crystallize. As soon as crystallization begins, the crystallized particles that were small in size begin to gather to form larger crystals that are easy to be deposited on the walls of the tube or the steel wool matrix (Cai et al, 2009; Al-Mawsili et al. (2010).

Increasing the magnetic flux intensity caused the $CaCO_3$ particles to adhere to each other and form larger groups causing an increase in the precipitation of $CaCO_3$ (Al-Ibady 2015; Abdulrazzaq 2016; Al Helal et al, 2018). Yadollahpour (2014) and Moya & Botella, (2021) found that total hardness decreases with the increase in the contact time and with the increase in the intensity of the magnetic flux. Baker and Judd (1996) showed that the increase of magnetic flux intensity leads to an increase in salt removal due to the following: water molecules are electrically charged, having a small dipole and thus a small dielectric constant. Exogenous electric and magnetic fields may affect this dipole. The change in the electric dipole of water can result in a change in the physical properties of water.

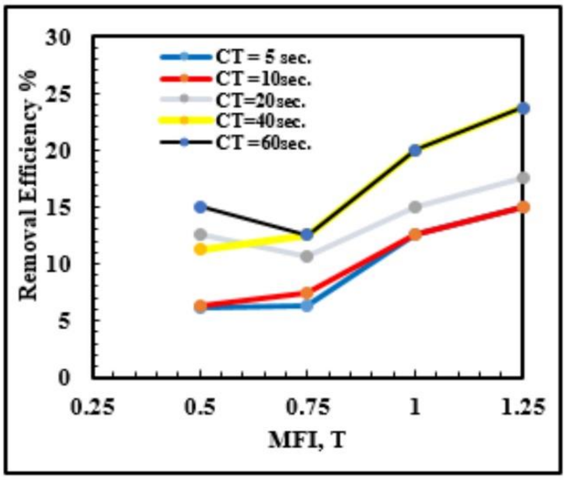

Figure (4) Effect of magnetic flux intensity on the removal efficiency, inlet hardness 800mg/L, Plastic tube

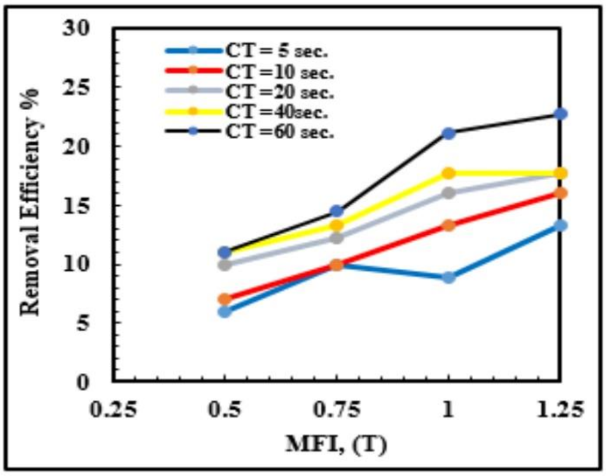

Figure (5) Effect of magnetic flux intensity on hardness removal efficiency, inlet hardness 1800mg/L, Copper tube

. The maximum removal efficiency for the plastic tube was 23.75% obtained at a magnetic field strength of 1.25 T, Contact time of 60 seconds, and Inlet hardness of 800mg/L while the corresponding removal for the copper tube was 35.2% under a magnetic field strength of 1.25 T, Contact time of 60 seconds, and Inlet hardness of 1050mg/L. These results agree with the results obtained by Alimi et al. (2006); Banejad & Abdosalehi (2009); and Al-joobury and Mahdi, (2020).

Effect of Inlet Hardness Concentration on Hardness Removal Efficiency

Figures (6 and 7) represent samples of the results that show the effect of inlet hardness concentration on hardness removal efficiency. These Figures indicated that the general trend is the decrease of removal efficiency with the increase of inlet hardness concentration with some disturbance. These results agree with that of (Shahryari & Pakshir, 2007; Al-Omari, 2019). However, it disobey that of Alla, (2019) since they used different contact times and Neodymium permanent magnets. Fathi et al. (2006) stated that an examination of the available literature on magnetic treatment often introduces contradictory results depending on the operating parameters. Banejad & Abdosalehi (2009) stated that water composition affects hardness removal. This composition depends on the hardness and the applied magnetic field. Magnetic technology had a certain maximum limit, beyond which it could do no more. Y. Zarga et al (2013) stated that supersaturation represents the driving force of crystallization. Sedimentation can take place as long as the crystallization process exists due to the presence of supersaturation conditions. Therefore, no sedimentation can take place when the solution is in saturation or under saturation conditions. Total hardness is the salts of carbonates, bicarbonates, chlorides, sulfates, and nitrate ions. The predominant is the hardness of calcium and magnesium ions. Sawaftah (2017) found that $CaSO_4$ needs at least a magnetic flux intensity of 2 T to be removed. Below this value, magnetic flux affects only bicarbonate removal. Several studies demonstrated that magnetic water treatment influences molecular and physicochemical properties of water that alter the quality of water (Alimi et al, 2006). Fathi et al (2006) stated that a magnetic field changes the process of sedimentation of calcium carbonate. This will explain why the maximum hardness removal is 23.75%.

The highest removal efficiency for the plastic tube is 23.75% when the inlet hardness is 800 mg/L, the contact time of 60 seconds, and the magnetic flux intensity is 1.25T. The corresponding value for the copper tube is 35.2% when the inlet hardness is 1050 mg/L, the contact time of 60 seconds, and the magnetic flux intensity is 1.25T.

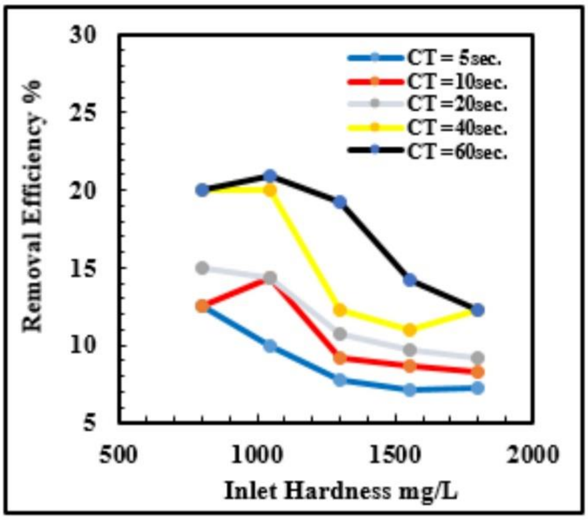

Figure (6) Effect of inlet hardness on hardness removal efficiency at 1T, Plastic tube

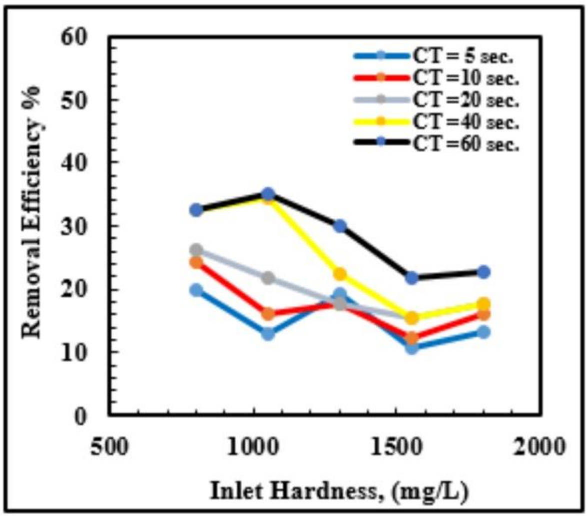

Figure (7) Effect of inlet hardness on hardness removal efficiency, at 1.25T, Copper tube

Careful inspection of Table (3) indicated that $Ca(HCO_3)$/total hardness ranged from 30.39-40.66% and the maximum removal efficiency range is 15.5-23.75% for plastic tubes and 21.9-35.2% for copper tubes. This is because calcium bicarbonate is the most affected by the magnetic force. This explains why the removal efficiency does not exceed 35%

Table (3) Calcium bicarbonate hardness and maximum removal efficiency

No.	**Total hardness, mg/L**	**Anticipated $Ca(HCO_3)_2$, mg/L**	**$Ca(HCO_3)_2$/ total hardness,%**	**Maximum hardness removal efficiency,%**	
				Plastic tube	**Copper tube**
1.	1800	547.132	30.39	22.7	22.7
2.	1550	478	30.84	15.5	21.9
3.	1300	418.27	32.17	19.23	30
4.	1050	411.63	39.2	21.9	35.2
5.	800	325.32	40.66	23.75	32.5

A comparison between the results of the copper tube and the corresponding results of the plastic tube indicated that the removal efficiency for a copper tube is always higher than the corresponding removal efficiency obtained when using a plastic tube. Relative magnetic permeability is the ratio between the permeability of a medium or substance to the permeability of space. The magnetic permeability of copper is (1.256629 $*10^{-6}$) H/m and its relative magnetic permeability is (0.9999936) (Dean & Voss, 1999). For plastic, the magnetic permeability is (1.25 $*10^{-6}$) H/m, and the relative magnetic permeability is (0.9947180) (Thabet and Repetto, 2012). Because copper has higher relative permeability than plastic, the magnetic flux lines that pass through copper are more than that for plastic. This means that the solution passing the copper tube is subjected to a greater magnetic force giving higher removal efficiency. The results agree with that of Baker and Judd (1996); and Ambashta et al. (2011).

Results of the Second Scheme

In this scheme, two types of magnetic nanoparticles (γ-Fe_2O_3 and Fe_3O_4) are added to the groundwater at various concentrations (25, 100, and 200 mg/L) to investigate the performance of magnetic treatment under the following operating parameters (inlet hardness of 800 mg/L, magnetic field strength of 1.25 T, and contact time of 5-60 sec.). The results are shown in Figures (8-11).

These Figures indicated that the hardness removal efficiency range is 18.86 - 30.12% when γ-Fe_2O_3 is used while it is 16.75-33% when Fe_3O_4 is used. The corresponding range for magnetic treatment alone is 20-32.5%. These data indicated that the addition of both types of magnetic nanoparticles can not improve the hardness removal efficiency. This may be due to the fact that there is no interaction between the soluble hardness compounds and the magnetic nanoparticles. The main effect here is the magnetic force which changes the saturation conditions of water and leads to the crystallization and precipitation of part of the hardness compounds. Figures (8 and 9) indicate that the removal efficiency is increased with the increase of contact time until 20 seconds beyond which no appreciable improvement takes place. Increasing contact time gives more chance for the hardness compounds to be crystallized and separated. Figures (10-11) indicate that there are fluctuations in removal efficiency with the increase of dose. Adding magnetic nanoparticles will add hardness since Fe will react with the anions present in groundwater. This is the reason for the reduction of removal efficiency with the increase of dose and explains why the removal efficiency without the addition of magnetic nanoparticles is lower than that without its addition.

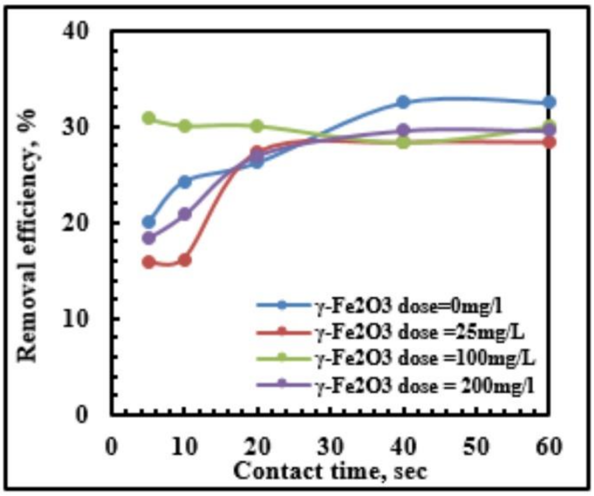

Figure (8) Effect of contact time on removal efficiency, γ-Fe_2O_3

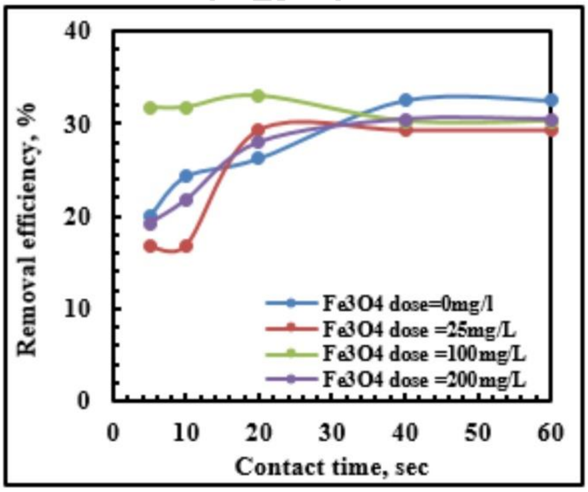

Figure (9) Effect of contact time on removal efficiency, Fe_3O_4

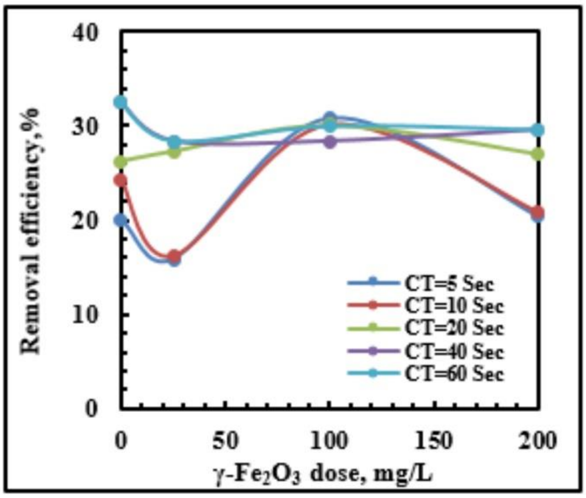

Figure (10) Effect of γ-Fe_2O_3 dose on removal efficiency

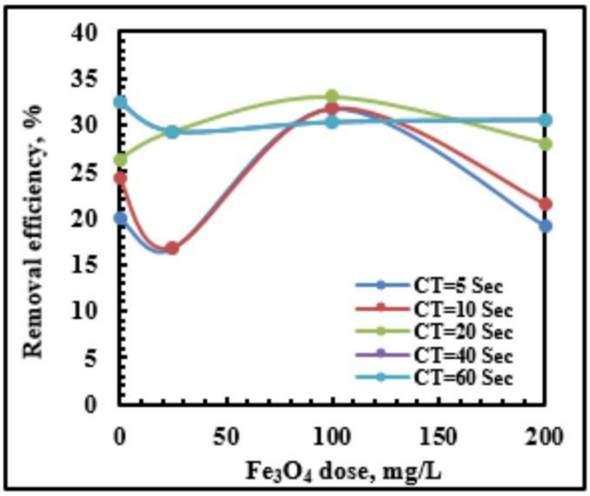

Figure (11) Effect of Fe_3O_4 dose on removal efficiency

Conclusions

The results of the present work proved that the hardness of groundwater can be reduced. However, this reduction (about 32%) is not able to use the treated water for many uses such as drinking or industrial. It may be able to be used for irrigation purposes. Thus, this method can be used as a pre-treatment method. It is found that the contact time, magnetic field intensity, and inlet hardness affect the hardness removal efficiency. Moreover, adding magnetic nanoparticles (γ-Fe_2O_3 and Fe_3O_4) reduces slightly hardness removal.

List of abbriviation

ATM	Anti-scale Magnetic treatment
COD	Chemical oxygen demand
CR	Congo red dye
CT	Contact time
EMF	Electromagnetic Fields
EMT	Electromagnetic treatment system
MFI	Magnetic field intensity
RO	Reverse Osmosis
T	Tesla
TDS	Total dissolved solids
TSS	Total suspended solids, and

Availability of data and materials

The datasets generated and/or analysed during the current study are available in the [GROUNDWATER TREATMENT BY ELECTROMAGNETIC POLARIZATION], **[https://data.mendeley.com/datasets/7gf9v32wfw/1]**

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