Treatment efficacy of Groundwater 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. There is a continuous decrease in Tigris River water supply in Iraq 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-Fe_2O_3 and Fe_3O_4 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). It is proven that magnetic treatment can reduce scale formation (Busch and Busch 1997, Barrett and Parsons 1998, Alimi et al. 2006, Tantawy et al.2006, Bali and Gueddari 2018, Al-Omari 2019). Al-Omari (2019) for example, investigated the effect of magnetic treatment on the ability of groundwater to form scales. Magnetic treatment was performed at 1.4 T and a flow rate of 10 liters per hour. The temporary hardness-causing ions and the weight of scales were reduced after magnetic treatment by approximately 39.13% and 22.2 %, respectively. Lu Lin et al. (2020) 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 mentioned that 95% of the 48 studies discussed had positive effects and only 5% 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 CO_2, pH, magnetic field intensity, water flow, etc. 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. The results revealed an increase in the amount of aragonite 70% to 99.99%. They got a hardness reduction of 51%. Abdulrazzaq (2016) studied hard water treatment by Electromagnetic Polarization to enhance the precipitation of Ca^{2+} and CO_3^{2-} ions. They stated that the increase of the electromagnet field would increase $CaCO_3$ precipitation by up to 34 %. Alla (2019) treated magnetically groundwater taken from many wells in Kirkuk by and got 30.4-31.25% reduction in dissolved solids. 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. Aldoury et al. (2022) tried to soften groundwater and reduce total dissolved solids by employing electromagnetic polarization under different operating parameters (inlet hardness, flow rate, magnetic field strength). They got an appreciable reduction of hardness while no improvement of dissolved solids is achieved. Jiang et al. (2022) studied the effect of Electromagnetic Fields (EMF) on Reverse Osmosis (RO) membrane scaling control during saline groundwater desalination. The results 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 were slowed by the magnetic field.

Many 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 remove 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).

It is worth to mention that electromagnetic treatment of water has many applications in agriculture, industry, and other fields. Karkush et al (2019) studied the magnetic field influence on the chemical and electrical properties of water treated by reverse osmosis. They circulated water for 24 hour in magnetic fields of intensities 500, 1000, 1500, and 2000G. they found that magnetization increases Mg, K, Na, Cl, and SiO_2 and decreases Ca and SO_3. They stated that the main application of magnetic water is the improvement of the geotechnical properties of soft and swelling soil due to calcite precipitation in pores which increases the bond between soil particles and the strength of the soil. AL-Ani et al (2021) studied the influence of magnetized water on the geotechnical properties of expansive soil. They stated that The expensive soils suffer from volume expansion due to the presence of clay minerals. The magnetized water technology is applied in many fields such as agriculture, industry, and other applications. They studied the effect of potable water treated by reverse osmosis passing from a magnetic field of 500, 1000, 1500, and 2000G on the chemical and swelling properties of soil. They stated that applying magetism will improve the soil properties. It reduces liquid limit from 113 to 72% and plastic limit from 55 to 22%, free swelling from 333.7 to 25.4%, and the uplift movement from 21.66 to 14.25mm. Moreover, they found that the unconfined compressive strength was increased from 23.36 to 49.49kPa at a water content of 32%. Jawad et al (2023) studied the effect of a magnetic field on the physicochemical properties of tap water employing magnetic strength of 2000-8000G while circulating tap water for 6 hours. They found that the concentration of certain negative ions such as Na and Cl were increased while the concentration of Mg, K, Ca, and SO_4 ions was reduced when tap water was subjected to the magnetic field. Moreover, they found that 8000G is enough to increase neucleation of alkaline content preventing the formation of calcium and sulfate crystals in water. Saba et al (2023) studied the effect of magnetized water for a circulation time of 7 and 14 days on the shear strength. They found that the shear strength increases by 17-45% when the magnetic strength increases from 2000 to 8000G for 7 days of circulation. The corresponding range for 14-day circulation is 49.92 to 120%. Moreover, they obtained a considerable decrease in organic matter, gypsum, sulfate, and total soluble solids content. On the other hand they get an increase in pH.

It is important to assess the groundwater state before the treatment decision takes place Moreover, monitoring its quality is very important. Electrical resistivity and induced polarization techniques have been developed for these purposes. Rehman et al (2016) used a combined electrical resistivity and induced polarization techniques in addition to chemical analysis to determine groundwater pollution at Al Misk Lake, Eastern Jeddah, Saudi Arabia. They found that the groundwater found on either side of the dam in the survey area is unfit for human or agricultural use. Brahmi et al (2021) assessed groundwater and soil pollution by leachate using electrical resistivity and induced polarization survey for Tebessa municipal landfill, NE Algeria. They found that the landfill center represents the main source of the aquifer and soil pollution. Their chemical analysis shows high levels of Pb 3.5 μg/g, Cd 7.1 μg/g, Cu 0.09 μg/g, and Zn 05 μg/g. They stated that these high levels of heavy metal in the vadose zone are due to the leakage of the leachate and Cd, Pb, Cu, Zn, Fe, and Mg presence in the sediments caused degradation of water quality. Edite (2023) stated that soil and groundwater pollution is one of the most serious problems. The pollutant sources include landfills and industrial waste disposal, saline intrusion, accidental spills of chemical products or hydrocarbon, and pollutants of agricultural origin. Electrical resistivity and induced polarization (IP) methods have been used in the diagnosis and monitoring of polluted areas since the electrical properties of contaminated formations are distinct from the surrounding medium. Meng et al.(2024) mentioned that soil and groundwater pollution impacts industry, agriculture, and health. Thus, for the purpose of successful treatment strategies, it is important to include electrical resistivity (ERT) and induced polarization (IP) in the detection and monitoring of pollutants. They have applied ERT and IP techniques to 30 contaminated sites and proved their effectiveness.

Electrical resistivity (ERT) and induced polarization (IP) had been applied in other fields such as exploration for groundwater (Ahzegbobor et al 2016, Aziman et al 2018, Tariku et al 2025), Oil Spill Investigation (William et al 2023), Detection of Ore Bodies (Zhaoyang et al 2024), Determination of groundwater flow path (Revil et al(2024).

The present work aims to reduce the hardness content of groundwater taken from many wells in Samarra by magnetic treatment. The operating parameters are groundwater hardness (800-1800 mg/l), magnetic field (0.5-1.25T), and contact time of (0-60) seconds.

Methodology

Since magnetic technology has been used in many scientific areas such as scale removal, agriculture and industry, the present work is performed to investigate the possibility of using magnetic treatment to reduce hardness of groundwater. Many samples taken from many wells in Samarra, Salah Aldin governate, Iraq were used to conduct the present work. The hardness of these samples is 800, 1050, 1300, 1550, and 1800 mg/L. A laboratory apparatus (Figure 1) is designed and constructed to perform the experiments of the present work. Details of this apparatus are given in Mohammed (2022). Flow rates can be provided to the tube subjected to a magnetic field from the supply tank by a pumping device. Different flow rates can give a contact time of 0-60 seconds. The magnetic field strength can be varied from 0 to 1.25T. This work aims to reduce groundwater hardness by different magnetic field strengths under various contact times. Moreover, to investigate the effect of using different doses (25,100, and 200 mg/l) of two types of magnetic nanoparticles (Maghemite (γ-Fe_2O_3) and Magnetite Fe_3O_4.) on the hardness removal. The experiments is divided into two groups, the first group includes 200 experiments to investigate the effect of contact time, magnetic field strength, and inlet hardness on hardness removal efficiency. Based on the first group results, the operating parameters that gives the best result is used to perform 30 experiments of the second group were performed to investigate the effect of dose (25,100, and 200 mg/l) of Maghemite (γ-Fe_2O_3) and Magnetite Fe_3O_4 on hardness removal efficiency.

Experimental Apparatus, Materials, and Experimental Scheme

Experimental Apparatus

An electromagnetic treatment system (EMT) was designed and constructed to conduct the present work. Figure (1) shows the schematic diagram of the experimental apparatus which can give a maximum magnetic flux intensity of 1.5 T. Details of this apparatus is given in Mohammed (2018).

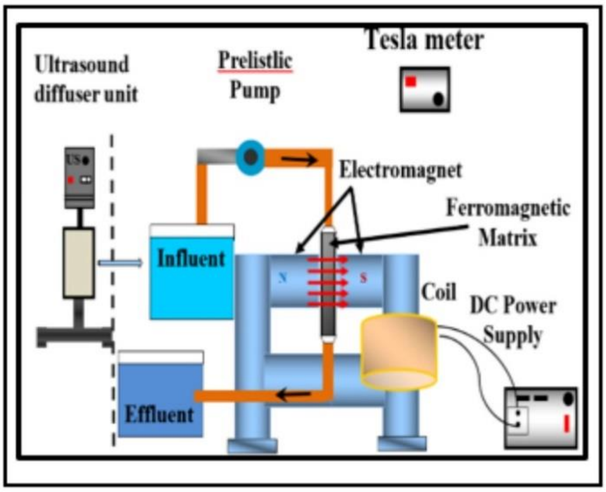

Figure (1) Schematic diagram of the experimental apparatus

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 while Table (2) includes the apparatus and standard procedures employed in the present work. 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. °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

Table (2) Analytical techniques and apparatus used in this study

No.	**Analysis**	**According to**	**Apparatus**
1.	Total hardness	2340-C1 (SMWW)	Burettes, laboratory glasses
2.	Calcium hard	2340-Ca^{2+}	Arithmetic method
3.	pH	4500-Ph-B (SMWW)	pHmeter Trans (BP3001)
4.	EC	2510-B-2	YL-TDS2-A
5.	TDS	2540	YL-TDS2-A
6.	Temperature	2250-B	Mercury thermometer
7.	D.O.	4500-DO-G	DO-meter HANNA HI 93732N
8.	SO_4^{2-}	4500- SO_4^{2-}—E	HANNA C-99
9.	Cl^-	4500-Cl^- -B	Burettes, laboratory glasses
10.	HCO_3^-	2320- HCO_3^-—B	Burettes, laboratory glasses
11.	PO_4^{3-}	4500- PO_4^{3-}	Spectrophotometer JENWAY
12.	NO_3^-	4500- NO_3^- -B	Spectrophotometer JENWAY
13.	Ca^{2+}	3500-Ca^{2+} -B	Burettes, laboratory glasses
14.	Na^+	3500-Na^+-B	Flame photometric JENWAY
15.	Mg^{2+}	3500-Mg^{2+}-B	Arithmetic method
16.	K^+	3500-K^+-B	Flame photometric JENWAY
17.	Fe_3^{2+}	4500-Fe_3^{2+} (SMWW)	Spectrophotometer JENWAY

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 Work

The studied parameters that affect the electromagnetic polarization technique are; inlet hardness, contact time, and magnetic flux intensity. Table (3) includes the values of the investigated operating parameters. The experimental work is performed through two groups that enable covering the operating parameters mentioned above.

Table (3) 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 Group

The operating parameters investigated in this group are Inlet hardness (800-1800mg/L), magnetic flux intensity (0.5-1.25T), and contact time of (5-60 seconds). Two hundred experiments were performed to cover these parameters according to full factorial mode. 100 experiments for plastic tube and 100 for copper tube.

Second Group

Depending on the results of the first group, the conditions that give the best hardness removal are used to perform other 30 experiments with the use of two magnetic nanoparticles Maghemite (γ-Fe_2O_3) and Magnetite Fe_3O_4 at various doses (25, 100, 200 mg/L).

Results and Discussion

Results of the First Group

Effect of Contact Time on Hardness Removal Efficiency

Figures (2 and 3) represent a sample of the results indicating the effect of contact time on the removal efficiency under various operating parameters. These Figures show that the removal efficiency 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 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 allows 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).

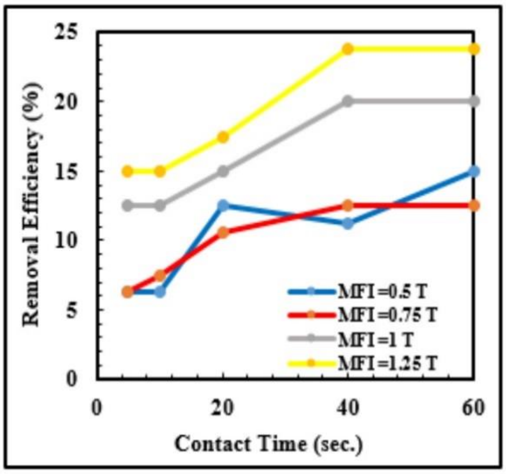

Figure (2) Effect of contact time on the removal efficiency, inlet hardness 800mg/L, Plastic tube

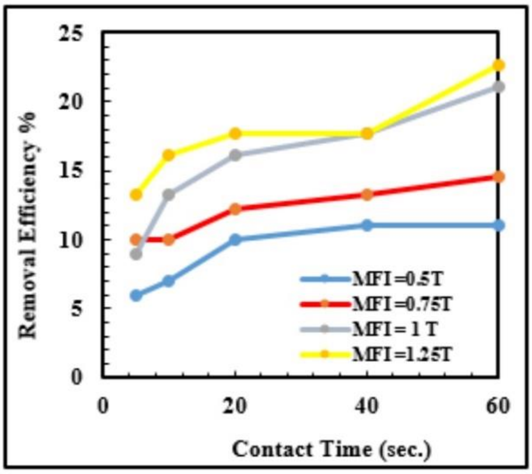

Figure (3) Effect of contact time on hardness removal efficiency, inlet hardness 1800mg/L, Copper tube

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.

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).

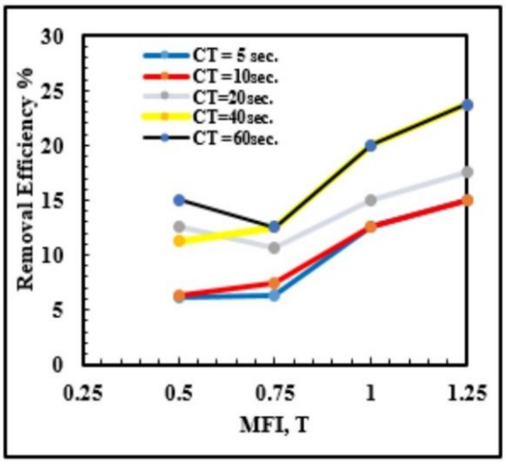

Figure (4) Effect of magnetic flux intensity on the removal efficiency, inlet hardness 800mg/L, Plastic tube

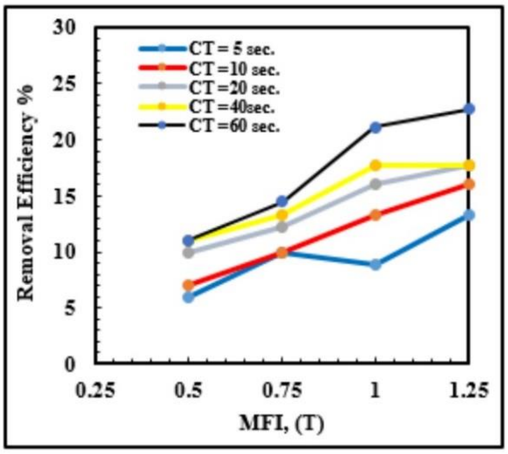

Figure (5) Effect of magnetic flux intensity on hardness removal efficiency, inlet hardness 1800mg/L, Copper tube

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.

Careful inspection of Table (4) 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%

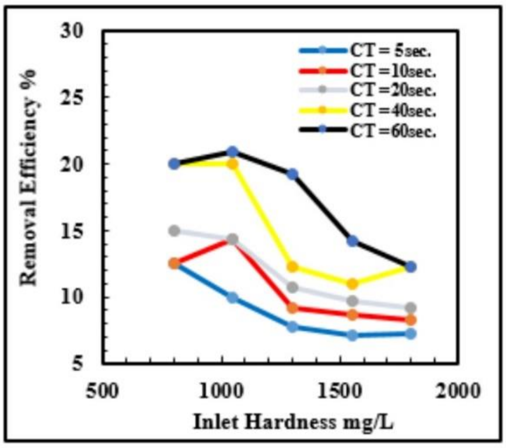

Figure (6) Effect of inlet hardness on hardness removal efficiency at 1T, Plastic tube

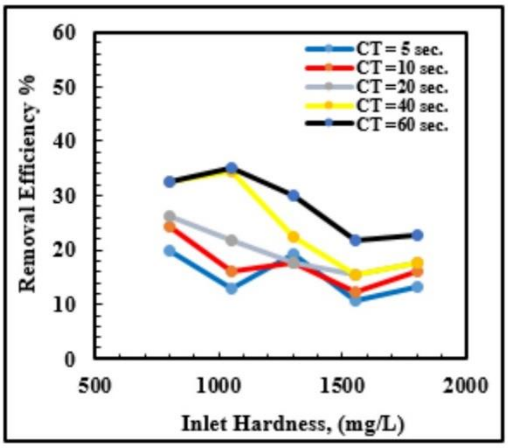

Figure (7) Effect of inlet hardness on hardness removal efficiency, at 1.25T, Copper tube

Table (4) 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 Group

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 with the addition of magnetic nanoparticles is lower than that without its addition.

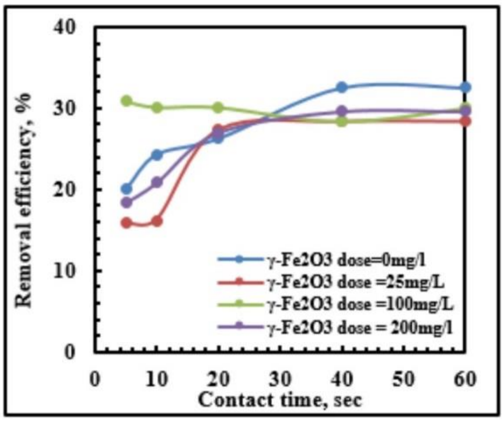

Figure (8) Effect of contact time on removal efficiency, γ-Fe_2O_3

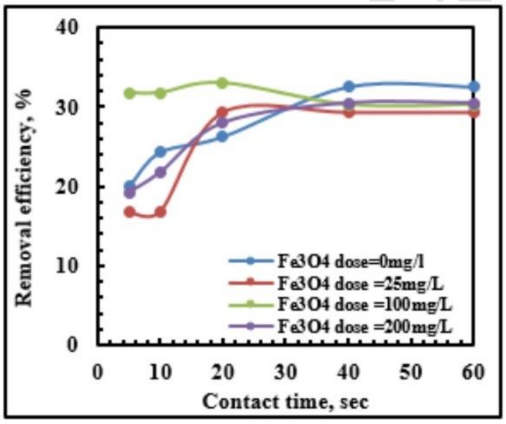

Figure (9) Effect of contact time on removal efficiency, Fe_3O_4

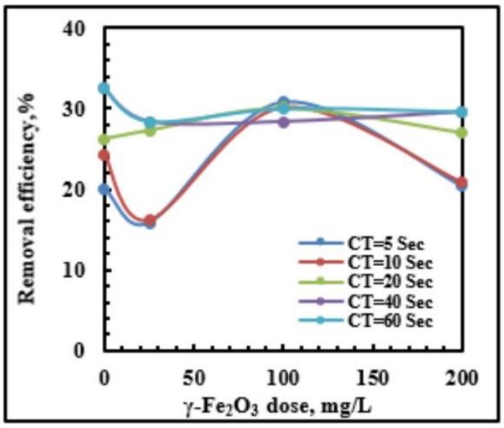

Figure (10) Effect of γ-Fe_2O_3 dose on removal efficiency

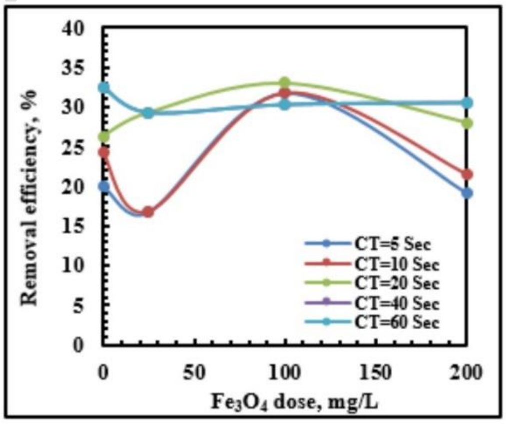

Figure (11) Effect of Fe_3O_4 dose on removal efficiency

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. The followingadditional conclusion can be made

- It is found that the increase in contact time will increase hardness removal
- It is found that the increase in magnetic field intensity will increase hardness removal
- It is found that the increase in inlet hardness will reduce hardness removal
- It is found that copper tube gives higher hardness removal as compared with plastic tube.
- It is found that adding different doses of magnetic nanoparticles (γ-Fe_2O_3 and Fe_3O_4) reduces slightly hardness removal.

List of abbreviations

COD	Chemical oxygen demand
CR	Congo red dye
CT	Contact time
ERT	Electrical resistivity
IP	induced polarization
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]**

Disclaimer (Artificial intelligence)

Option 1:

> Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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