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Effect of Square-Wave Electromagnetic Frequency and Exposure Time on pH and Electrical Conductivity of Saline Water

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ABSTRACT

A laboratory-scale electromagnetic device was developed for saline water treatment, comprising a control unit (function generator) and a treatment unit: a polyvinyl chloride (PVC) pipe wrapped with a 20 AWG copper coil. This study investigates the effects of electromagnetic field (EMF) exposure on the chemical properties of saline drainage water by monitoring changes in pH and electrical conductivity (EC) (initial values: pH = 7.76 ± 0.01; EC = 5522 ± 9 μS/cm). The examined operating parameters included square-wave frequency (1–4 kHz) and treatment duration (0–30 min) under controlled flow conditions (flow velocity = 1.4 m/s), with a maximum time-varying magnetic field intensity of 13.95 G. The results revealed a nonlinear response of both parameters to electromagnetic field exposure. The pH increased with treatment time and stabilized after about 15 minutes, reaching a maximum value of 8.1 at 3 kHz. In contrast, EC decreased with increasing treatment duration and similarly stabilized after about 15 min, with a minimum value of 5369 μS/cm observed at 3 kHz. These findings suggest that among the tested conditions, electromagnetic field treatment at 3 kHz yields the most pronounced effect on the measured water quality parameters.

1. INTRODUCTION

In chemistry, salt water is often referred to as an aqueous solution or an electrolyte. An aqueous solution is a homogeneous mixture in which water acts as the solvent and dissolves one or more solutes. However, an electrolyte is a substance that dissociates into ions when dissolved in a polar solvent such as water. When ionic compounds dissolve in water, they dissociate into charged ions that enable electrical conduction. Because water is a highly polar molecule, it effectively surrounds dissolved ions, forming hydration shells that stabilize them in solution. For example, sodium chloride dissociates into Na^+ and Cl^- ions, each surrounded by water molecules oriented according to the ions' charges. This hydration process prevents ion recombination and maintains the dissolved state, as illustrated in Figure 1 [1].

Numerous studies have investigated the effects of permanent magnetic fields, under static or flowing water conditions, and electromagnetic fields generated by solenoids on the physical and chemical properties of water and aqueous solutions. These applications include anti-fouling technology, saline water treatment, and agricultural uses [2-11]. Permanent magnetic systems typically consist of magnets arranged in specific configurations to achieve the desired magnetic exposure [12]. In contrast, electromagnetic systems are formed from conductive wire coils (solenoids) that generate magnetic fields when an electric current passes through them. Their operating characteristics include field intensity, frequency, and waveform. Commercial electromagnetic treatment systems generally consist of a signal generator and a treatment module with a coil wrapped around a pipe [13].

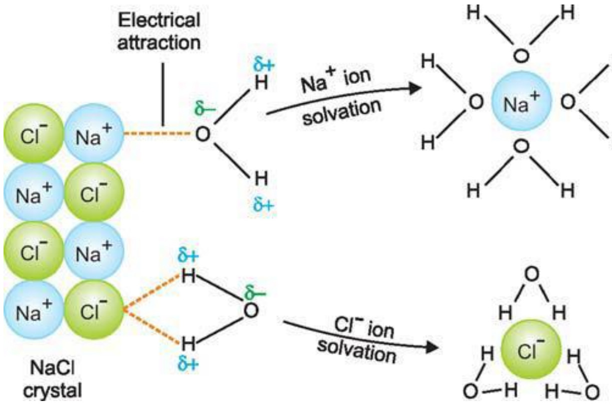

Figure 1. Na^+ and Cl^- ions hydration [1]

The influence of electromagnetic fields on saline water is commonly attributed to changes in ion mobility and redistribution, dipole reorientation of water molecules, and modifications of hydrogen-bond networks, due to the Lorentz force. These processes may alter measurable chemical properties, including potential of hydrogen (pH) and electrical conductivity (EC), without necessarily inducing direct chemical reactions.

Although many studies have examined magnetic and electromagnetic treatment of water, reported findings remain inconsistent [14, 15]. Some researchers have reported significant changes in pH and EC, whereas others observed negligible effects. Therefore, further experimental investigation is required. The present study aims to evaluate the influence of an electromagnetic field on saline water by examining pH and EC responses under controlled operating conditions.

2. METHODS AND MATERIALS

2.1 Salt water test

Saline water samples were collected from the Hajji Ali drainage canal in Babylon Governorate, Iraq (32°27′20.2″ N, 44°21′42″ E). This water source contains a mixture of dissolved ions typical of agricultural drainage water. In the present study, pH and EC, which reflect the activity of dissolved ionic species, were measured, as summarized in Table 1. Measurements were carried out using a multifunctional analytical instrument (Model EZ-9909SP; see Figure 2) capable of simultaneously determining pH, EC (µS/cm), and temperature (°C). Prior to analysis, the instrument was calibrated with standard reference solutions at 25 °C (pH 4.10, 6.86, and 9.18). Double-distilled water was used as the reference with zero conductivity. The measurement resolution was ±0.01–0.02 for pH and ±8.5–9 µS/cm for EC.

Table 1. Chemical properties of the salt water

Samples / Property	Salt Water
pH	7.76 ± 0.01
Electrical conductivity (EC) (µS/cm)	5522 ± 9
Temperature (°C)	25 ± 0.5

Calibration of pH

pH Solution: Dissolve each buffer solution into 3 cups which is filled with 250ml distilled water.

First convert to pH mode then operate as the following.

1. Put electrode into 6.86 solution; Wait until the testing is stabilized;Press "CAL" for 5 seconds, release button; Wait for 6.86 flashes 3 times; Finshed 6.86 calibration; Clean electrode with distilled water.

2. Put electrode into 4.00 solution; Wait until the testing is stabilized; Press "CAL" for 5 seconds, release button; Wait for 4.00 flashes 3 times ; Finshed 4.00 calibration; Clean electrode with distilled water.

3. Put electrode into 9.18 solution; Wait until the testing is stabilized; Press "CAL" for 5 seconds, release button; Wait for 9.18 flashes 3 times; Finshed 9.18 calibration; Clean electrode with distilled water.

7.00/4.00/10.01 are the same calibration steps.

Figure 2. Multifunctional analytical device model number EZ-9909SP

2.2 Electromagnetic treatment system and experimental setup

The electromagnetic treatment system is shown in Figure 3. It consisted of a submersible pump with a discharge capacity of 1 m³/h, producing an average flow velocity of approximately 1.4 m/s, connected to the electromagnetic treatment device. Both components were installed inside a glass tank. This arrangement enabled continuous recirculation of saline water through the treatment unit, allowing repeated exposure during each experiment. Water circulation was maintained for 30 min in each test. Chemical measurements of pH and EC were recorded every 5 min. Each measurement was repeated five times, and the mean value was used to improve the stability and reliability of the recorded data.

The home-built electromagnetic treatment device consisted of two main units: a control unit and a treatment unit. The control unit was responsible for generating the required electrical signal. A Victor 2015H function generator (Victor, China) was used, as shown in Figure 4. This instrument provided adjustable alternating signals with controlled waveform type and frequency, allowing accurate optimization of treatment conditions. Compared with permanent magnet systems, the proposed design offers greater operational flexibility and lower cost.

The treatment unit consisted of a polyvinyl chloride (PVC) pipe with an inner diameter of 0.5 inches, wrapped with a copper coil that generated an electromagnetic field interacting with the flowing saline water. A 20-gauge AWG copper wire (0.81 mm diameter) was used to form a 10 cm long coil, as shown in Figure 5. The generated time-varying magnetic field inside the pipe reached a maximum intensity of 13.95 G. According to Faraday's law, the varying magnetic field also induced an electric field within the treatment zone. The effective exposure length was 10 cm.

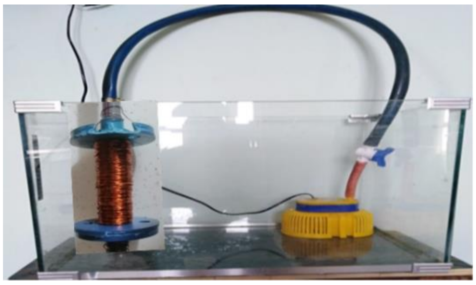

Figure 3. Water magnetic system

Figure 4. Alternating current (AC) power supply or function generator

Figure 5. Treatment unit

The electromagnetic treatment process may influence both dissolved ions and polar water molecules. Charged ions can experience Lorentz forces that affect their motion and redistribution in solution, as illustrated in Figure 6 [16]. Water molecules, which behave as electric dipoles, may also experience torque when moving across magnetic field lines, as shown in Figure 7 [17]. In addition, the polar nature of water allows partial alignment under an applied electromagnetic field, which may modify hydrogen-bond arrangements and hydration-shell structure around dissolved ions, thereby influencing water cluster organization, as illustrated in Figure 8 [18].

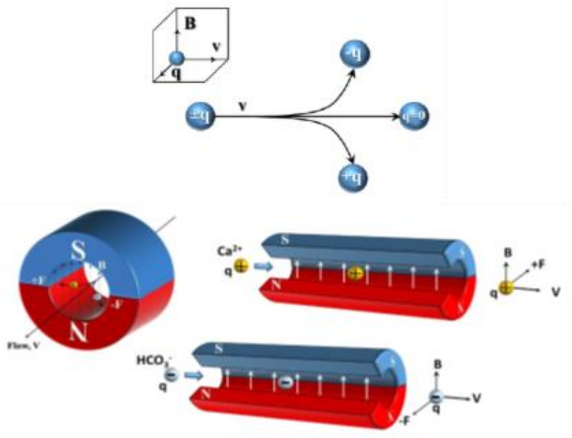

Figure 6. Lorentz force and the right-hand rule movement of charged molecules [16]

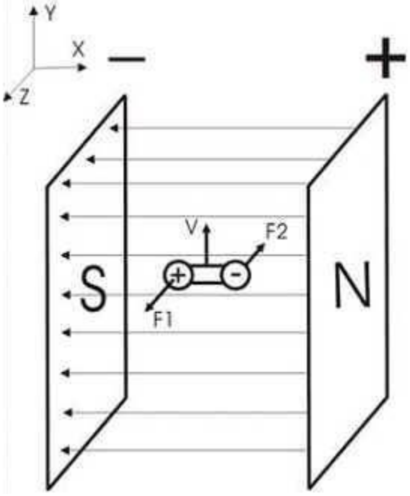

Figure 7. Physical behaviour of the dipole in the magnetic field [17]

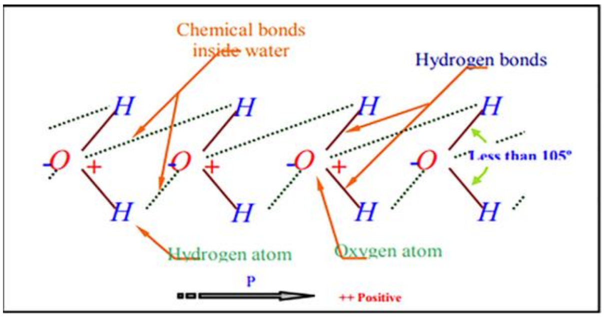

Figure 8. Directional arrangement of water molecule under the electromagnetic field [18]

Using the electromagnetic device produces two effects: one on the charged particles (ions) and the other on the polar water molecules. The Lorentz force exerted upon a charge particle causes them to migrate in opposite directions, as shown in Figure 6 [16]. A water molecule is treated as a charged dipole. When these dipoles move perpendicular to magnetic field lines along the y-axis, Lorentz forces create a torque that tries to rotate the molecule horizontally, as shown in Figure 7 [17]. As depicted in Figure 8, water molecules align with an applied electromagnetic field due to their polar nature. This alignment can change the internal bond angle (from approximately 105° to 103°), redistribute hydrogen bonds, and alter the arrangement of water molecules in the hydration shells surrounding cations and anions, thereby modifying the structure of water clusters [18].

3. RESULTS AND DISCUSSION

3.1 Potential hydrogen

3.1.1 Effect of treatment time

Figure 9 illustrates the variation in pH with treatment time. All measurements were repeated five times, and the data are presented as mean ± standard deviation. Error bars in all figures represent standard deviation.

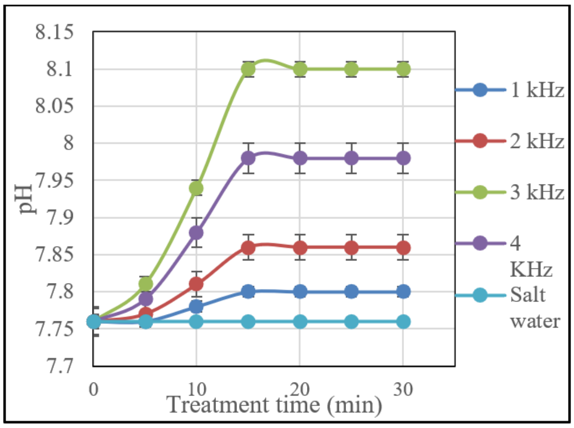

Figure 9. pH vs. treatment time for salt water

The results show that pH increased with increasing electromagnetic treatment time, indicating a reduction in H^+ ion activity. Among the tested frequencies, 3 kHz produced the greatest increase in pH compared with 1, 2, and 4 kHz. After approximately 15 min of treatment, pH values became nearly constant, suggesting that the system had reached a stable equilibrium condition and that the treatment effect had approached saturation.

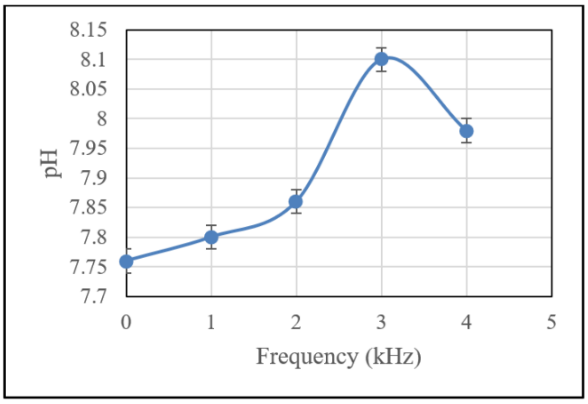

Figure 10. pH vs. frequency of the square wave for salt water

3.1.2 Effect of electromagnetic frequency

Figure 10 shows a nonlinear relationship between pH and electromagnetic frequency. The pH increased with frequency increased from 1 to 3 kHz, then decreased gradually at higher frequencies. A similar trend has been reported previously [19].

The increase in pH after electromagnetic treatment may be associated with field-induced effects on polar water molecules and dissolved ions. These interactions can promote the reorganization of hydrogen-bond networks and modify the proton distribution in solution, thereby influencing the measured pH.

3.2 Electrical conductivity

3.2.1 Effect of treatment time

The variation in EC with treatment time is presented in Figure 11. EC decreased progressively with increasing treatment time. After approximately 15 min, no further significant change was observed, indicating that the treatment process had reached a steady response.

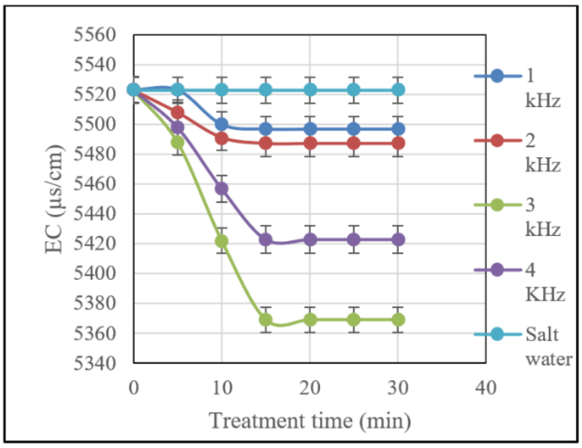

Figure 11. Electric conductivity vs. treatment time for salt water

The minimum EC value was observed at 3 kHz, indicating that this frequency provided the highest treatment efficiency under the investigated conditions. A comparable trend has also been reported in previous studies [8].

3.2.2 Effect of electromagnetic frequency

Figure 12 reveals a nonlinear response of EC to increasing electromagnetic frequency. EC decreased with increasing frequency up to 3 kHz, after which it reversed and increased at higher frequencies.

The reduction in EC following electromagnetic treatment may be attributed to changes in ion mobility, ionic redistribution, and hydration-shell structure under electromagnetic exposure, rather than a change in total ion concentration. As a result, the solution's effective EC decreases.

The observed decrease in EC and increase in pH are consistent with recent experimental findings, which linked these changes to modifications in ion transport behaviour and water structure rather than to direct chemical transformation [20].

A statistical analysis was performed using one-way ANOVA (α = 0.05) in SPSS software. The results showed statistically significant differences in pH and EC among the tested frequencies ($p < 0.05$), confirming that frequency significantly affected the measured parameters. In addition, Tukey's post hoc analysis indicated that 3 kHz produced significantly greater changes in pH and EC than the other tested frequencies ($p < 0.05$).

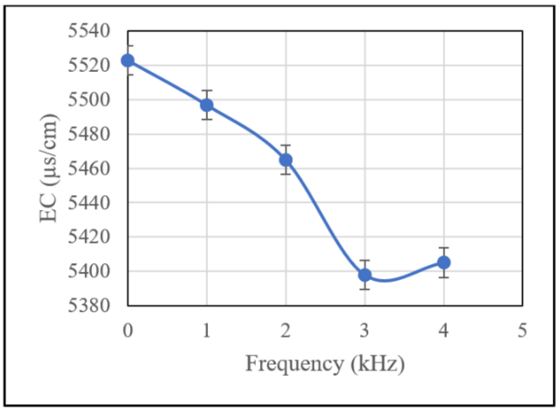

Figure 12. Electric conductivity vs. frequency of square wave for salt water

To explain why 3 kHz provided the optimum treatment condition, the electromagnetic coil geometry was considered. The coil used in this study was custom-wound using 20-gauge AWG copper wire (0.81 mm diameter) arranged in five layers around a PVC pipe with an inner diameter of 1.27 cm, an outer diameter of 2.19 cm, and a length of 10 cm. Each layer contained 123 turns, for a total of 615. The effective coil radius was calculated as follows:

Coil radius: R_{coil} = r (radius of pipe) = 2.19/2 = 1.095 cm = 0.01095 m

Cross-sectional area: $A_{coil} = \pi r^2 = \pi(0.01095)^2 = 0.0003767\ m^2$

Resistance of wire: R = 55.4 Ω

Self-inductance of coil

$$L = \mu_0 \frac{N^2 A_{coil}}{l} = 4\pi * 10^{-7} \frac{615^2 * 0.0003767}{0.1} = 0.00179\ \text{H} = 1.79\ \text{mH} \tag{1}$$

Time constant

$$\tau = \frac{L}{R} = \frac{0.00179}{55.4} = 32.31 * 10^{-6}\ \text{s} = 32.31\ \mu\text{s} \tag{2}$$

$$I_{max} = \frac{V}{R} = \frac{10}{55.4} = 0.1805\ \text{A} \tag{3}$$

To maximize electric-field induction, a square-wave pulse is used [8]. The current and frequency of the square-wave signal used in the present study were 0.1805 A and 3.1 kHz, respectively. The optimal frequency was 3.1 kHz to minimize self-induction in the solenoid coil and maximize the solenoid current.

For practical purposes, for square wave use [21]:

$$\frac{T}{2} \geq 5\tau \quad \text{to get} \quad i(t) = I_{max}\left(1 - e^{-\frac{t}{\tau}}\right) = 99.3\%\, I_{max} \cong I_{max}$$

$$f = \frac{1}{T} = \frac{1}{10\tau} = 3095\ Hz \cong 3.1\ kHz$$

At the instant of voltage reversal (i.e., at the edge of the square wave excitation):

$$-V = L\frac{dI}{dt} + RI$$

$$\frac{dI}{dt} = \frac{-V - RI}{L} = -\frac{2V}{L}$$

Maximum magnetic field (use $r_0 = 0$):

$$B_0 = \frac{\mu_0 ni(t)}{2}\frac{l_0}{\sqrt{\left(\frac{l_0^2}{4} + r_0^2\right)}} = \mu_0 ni(t) = 1.395 \times 10^{-3}\ \mathrm{T} \\ = 13.95\ \mathrm{G} \tag{4}$$

$$\frac{dB_0}{dt} = \mu_0 n\frac{dI}{dt} = 4\pi \times 10^{-7} \times \frac{615}{0.1} \times \frac{2x10}{0.00179} = 86.35\ \mathrm{T/s}$$

$$E_{induction} = \frac{r}{2}\frac{dB}{dt}\frac{0.00635}{2} \times\ 86.35 = 0.274\ \mathrm{V/m}$$

This induced electric field, which exerts a Lorentz force on dipole water molecules and ions, is truly responsible for the treatment of salt water.

4. CONCLUSION

A low-frequency electromagnetic treatment device operating at 1–4 kHz was successfully developed and evaluated for saline agricultural drainage water. The generated electromagnetic field interacted with dissolved ions and polar water molecules, potentially redistributing ions and altering the organization of water molecules. These effects were reflected in measurable changes in pH and EC.

The experimental results demonstrated that both pH and EC were significantly influenced by electromagnetic treatment, confirming a clear response of the aqueous ionic system to the applied field. Among the tested frequencies, 3 kHz produced the strongest effect, resulting in the highest pH and the lowest EC. In addition, most changes occurred during the first 15 min of treatment, after which the measured parameters stabilized.

To assess data reliability, each measurement was repeated five times, and the results were expressed as mean ± standard deviation. The relatively small standard deviation values (±0.01–0.02 for pH and ±8.5–9 µS/cm for EC) indicate good repeatability and experimental stability under the selected operating conditions.

The present findings are valid for the specific experimental conditions employed in this study, including the initial water properties (pH = 7.76 ± 0.01 and EC = 5522 ± 9 µS/cm), ambient temperature (25 ± 0.5 ℃), flow velocity (1.4 m/s), maximum magnetic field intensity (13.95 G), and the geometry of the treatment device. Therefore, direct extrapolation of the results to other systems should be made with caution.

Untreated saline water (the initial condition) was used as the reference state. However, a separate control experiment under identical hydraulic conditions without electromagnetic exposure was not conducted. This limits the ability to distinguish purely hydraulic effects from those induced by the field and represents a limitation of the present work.

Further studies are recommended to investigate wider frequency ranges, different saline water compositions, flow conditions, and device geometries. Additional work combining experimental observations with theoretical modelling would also help clarify the mechanisms governing electromagnetic interactions in aqueous systems.

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