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Electrochemical-magnetic method for the recovery of concentrated effluent from water membrane processes

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ABSTRACT

In this study, the electrochemical-magnetic production of chlorine from concentrated effluent (brine) was investigated. The efficiency and effectiveness of this process was evaluated using different experimental settings in an electrochemical-magnetic plant. The magnetic fields were created by a neodymium magnet with a magnetic flux density of 0.8 T. Box–Behnken design and response surface method were used to optimize the process and determine the optimal values of parameters for maximum chlorine production. The results showed that the optimal condition of the chlorine generation was 19.8 mg/L (as free chlorine residual) that was obtained at the NaCl concentration of 16.8 g/L, the electric potential of 6 V, the electrolysis time of 7.5 min and the current density of 20 mA/cm^2. The results showed that the magnetic electrochemical approach leads to higher chlorine production (186 mg/L) than the electrochemical method (137 mg/L). Moreover, the produced active chlorine was optimized based on energy consumption, which was 77 mg/L for the energy consumption of 0.2 kWh/l. The application of magnetic fields in conjunction with electrolysis process presented a promising approach for chlorine production from the concentrated brine effluent of water membrane processes. This can be attributed to the Lorentz force, which acts on charged particles in the presence of a magnetic field, causing them to move in a certain direction. This alternative method has the potential to reduce the cost and environmental impacts associated with chlorine production, making it a suitable option for industrial applications.

Keywords: Electrochemical-magnetic method; Concentrated effluent; Membrane processes; Box–Behnken design; Chlorine production; Lorentz force

1. Introduction

The recovery of brine concentrated effluent from water membrane processes refers to the process of reducing the volume and increasing the concentration of the brine effluent that is produced during water membrane processes. Water membrane processes, such as reverse osmosis (RO) and nanofiltration (NF), are commonly used to remove pollutants and impurities from water [1,2]. These processes work by applying pressure to force water molecules into a semipermeable membrane, leaving dissolved solids and other substances behind. However, a major drawback of these processes is the production of brine effluent. Brine effluent is a highly concentrated solution of salts (especially

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NaCl) and other dissolved solids that comes out of water [3,4]. In many cases, this concentrated stream must be discharged into water resources that in turn can have environmental implications. To address this issue, efforts are ongoing to develop and optimize techniques for recycling and managing brine water. Chlorine production from the concentrated brine effluent involves the use of electrolysis process. Electrolysis process is commonly used to produce chlorine from brine water [5,6]. Electrolysis is a process in which an electric current is passed through a solution or molten salt to cause chemical reactions. In the case of brine water electrolysis, the concentrated reject water is first purified and filtered to remove solid particles or impurities [2,7,8]. Then it enters an electrolytic cell that consists of electrodes immersed in a brine water solution. The electrolytic cell is divided into two parts by an ion permeable membrane. The positive electrode, called the anode, is made of a material such as titanium that is coated with a metal oxide catalyst [9]. The negative electrode, called the cathode, is usually made of graphite. When an electric current passes through the brine water, chlorine gas is produced at the anode and hydrogen gas is produced at the cathode. This brine water is usually rich in chlorine ions (Cl^-) and can be used to produce chlorine [10,11]. Sodium hydroxide (NaOH) is also formed as a byproduct at the cathode. The production of chlorine is very important in various industries including water treatment, chemical synthesis and bleaching processes [12]. Traditional methods of chlorine production, such as the chlor-alkali process, have been around for decades. However, these processes often require large amounts of energy and have significant environmental impacts. To address these issues, many studies focused on developing alternative and more sustainable methods for chlorine production [13]. One of these methods is the electrochemical-magnetic method, which combines the use of magnetic fields with electrochemical processes. The purpose of this innovative approach is to improve the efficiency and sustainability of chlorine production [14,15]. The magnetic fields increase the movement and transfer of ions and create a more efficient electrolysis. This application of the magnetic fields can be achieved through several methods such as the use of permanent magnets or electromagnets [6,16]. The application of magnetic fields in conjunction with electrolysis helps facilitate ion movement and can improve the overall efficiency of chlorine production. Increased ion transport speeds up the chemical reactions involved and leads to the production of chlorine gas. In addition, it can help reduce the overall costs of chlorine production by reducing reliance on traditional raw materials and reducing waste management costs [17]. In general, the use of magnetic fields can potentially reduce energy consumption and environmental impacts associated with chlorine production. Chlorine production from concentrated brine effluent using electrochemical-magnetic method is an emerging research field. This hybrid approach combines the use of magnetic fields with the electrolysis process to increase chlorine production efficiency and reduce energy consumption [18,19]. Several studies and researches have been conducted to investigate the feasibility and potential of electrochemical-magnetic method in chlorine production [17]. In one study, Liu et al. [20] carried out a comprehensive study on the scalability and economic viability of electrochemical-magnetic approach for chlorine production. They investigated the technical feasibility, energy consumption and cost analysis of implementing electrochemical-magnetic method technology in a large-scale chlorine production plant. Additionally, De Luca et al. [21] evaluated that Lorentz force on sodium and chlorine ions in a saltwater solution flow under a transverse magnetic field. Moreover, in another study, Li and Chen [22] studied the effect of magnetic field on the dynamics of gas bubbles in water electrolysis. The traditional methods of ion recovery from saltwater have high energy consumption and limited ion recovery capability. The magnetic electrochemical method is an alternative approach that can overcome these limitations. This method shows several advantages over existing salt recycling methods. Compared to reverse osmosis and distillation, it achieves higher desalination efficiency with less energy consumption. In addition, compared to electrodialysis and ion exchange methods, it shows superior ion recovery capability. The selectivity of the magnetic electrochemical method allows the production of high purity desalinated water and makes it ideal for various industrial and domestic applications. Moreover, the scalability of the method makes it a suitable option for large-scale water treatment plants. The use of magnetic fields in conjunction with the electrolysis process can increase the efficiency of chlorine production, reduce energy consumption and improve the economic feasibility of the process. Further studies are needed to optimize various parameters and confirm the scalability of electrochemical-magnetic technology for industrial applications. The aim of this study was to investigate an alternative method for the production of chlorine from brine concentrated effluent produced by membrane processes using an electrochemical-magnetic approach.

2. Methods and materials

The study aimed to investigate the effects of magnetic fields on the electrolysis process for chlorine production using the synthetically brine solutions. The Box–Behnken design (BBD) and response surface methodology (RSM) were employed to optimize the process.

2.1. Samples preparation

The synthetic saline effluent was prepared with distilled water using sodium chloride (NaCl, Fisher Scientific, ACS Reagent, Waltham, Massachusetts, U.S.) added at the concentration of 15, 25 and 35 g/L. The initial pH of the saline solutions was respectively set at 0.9 and 1.3 using HCl (0.02 to 0.14 M.). Initial pH values varying from 0.9 to 1.3 were chosen in order to avoid exceeding the limit value of pH (pH = 2.0) from which chlorine gas can be decomposed into hypochlorite ion (ClO^-) and hypochlorous acid (HClO) [23].

2.2. Experimental set-up

The electrochemical-magnetic plant has been demonstrated in Fig. 1. The electrolytic reactor unit used had 400 mL of capacity, and was made in polyvinyl chloride material with a dimension of 135 mm (L)×35 mm (l)×140 mm (h).

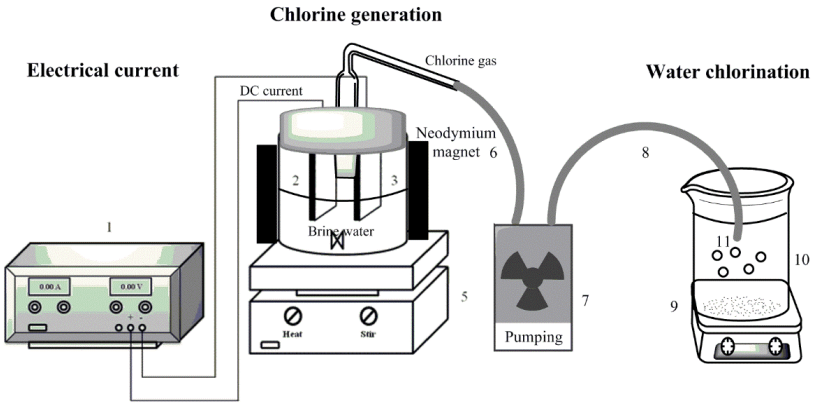

Fig. 1. Schematic diagram of the experimental unit for chlorine gas production: (1) power supply; (2) anode electrode (graphite); (3) cathode electrode (graphite); (4) electrolytic cell; (5) magnetic stirrer; (6) neodymium magnets; (7) vacuum pump; (8) injection tube; (9) magnetic stirrer; (10) chlorination tank; (11) air diffuser.

The electrolytic cell was comprised of one cathode and one anode electrode. Type of electrodes was graphite with a height of 4 cm, diameter of 0.5 cm. The distance between the electrodes was also 1.5 cm. At the inlet of the pump, a cellulosic filter was used to capture carbon particles separated from the graphite anode. Furthermore, the magnetic fields were created by a neodymium magnet with a magnetic flux density of 0.8 T.

2.3. Electrochemical production of chlorine gas

In each experiment, electrolytic cell was filled with the 100 mL intended solution, and then electrolysis process was performed in the cell. Sodium chloride solutions were with different initial concentrations of 15, 25 and 35 g/L. The positive (red) pole of the power supply is connected to a carbon electrode (cathode) and its negative pole connected to the other carbon electrode (anode). The electrical voltages (6, 9 and 12 V) were applied by the DC power supply. DC power supply was with an adjustable electrical voltage of 0 to 30 V, and a current intensity of 0 to 5 A (DaZheng Co., China). During the process, the chloride ions present in the electrolyte solutions in the vicinity of the anode are reduced to chlorine gas. The collected chlorine gas in the headspace of the electrolytic cell was removed by a vacuum pump with a flow rate of 0.85 L/min and then injected into the chlorine injection cell contained with 30 mL of deionized water. Sodium hypochlorite was also formed inside the electrolytic cell. Due to the corrosion of the anode the carbon particles may have been drained by the pump and injected into chlorination cell. To prevent this, a cellulosic filter was placed on the output. After the end of the electrolysis process, 10 mL of the chlorinated water (with and without dilution) was taken by pipette to measure of active chlorine by spectrophotometer. All experiments were carried out under standard conditions and ambient temperature (25°C).

2.4. Analytical details

Active chlorine was measured by colorimetric method. The diluted chlorinated samples (10 mL) were transmitted into the cuvette of DR5000 spectrophotometer (American Hach Company). Then a N,N-diethyl-1,4-phenylenediamine sulfate (DPD) powdered reagent was poured into the cuvette to measure the free chlorine produced. The pink color formed was a reason for the free chlorine. After selecting the free chlorine measurement program, the free chlorine content of the samples was read as mg/L at the wavelength of 530 nm. The concentration of the free chlorine produced in the electrolytic cell for a number of tests was also measured.

2.5. Experimental design and statistical analysis

BBD and RSM were used to optimize the process and determine the optimal values of parameters for maximum chlorine production. According to the preliminary range of extraction variables determined by single-factor experiment, a three-level-three-factor BBD was applied to determine the best combination of extraction variables for the production of active chlorine. The BBD is a type of RSM used in experimental design and optimization. It is named after George Bucks and Donald Behnken, who introduced the design in the 1960s. BBD is a three-level factorial design that is particularly useful when the relationship between a response variable and several independent variables is not linear. This design consists of a series of experimental runs at three different levels of each independent variable, which are selected based on a fractional factorial design with a cube of the response surface [24]. A key advantage of BBD is that it requires less experimental implementation compared to other RSM schemes, such as central composite design (CCD). However, BBD does not provide as accurate an estimate of the response surface as CCD, especially in regions outside the design space. BBD is a cost-effective design that allows for efficient exploration of the design space and optimization of the response variable. However, it has certain limitations, such as limited coverage of the response surface curvature. Hence, it is important to carefully consider the design constraints and interpretation of the results when using BBD [25]. RSM is a statistical technique used in design of experiments (DOE) to optimize the response or output of a system or process. It is a compilation of statistical and mathematical techniques that are established on the fit of polynomial equation to the experimental data. It involves

modeling the relationship between multiple input variables and the output response in order to identify the optimal combination of input variables that leads to the desired output. RSM usually involves fitting a mathematical equation or surface to experimental data obtained from various combinations of input variables. This equation or surface can then be used to predict the response for any given set of input variables [24]. By analyzing the shape and contour of the response surface, it is possible to identify the direction and degree of influence of each input variable on the response. The objective of RSM is to find a combination of input variables that maximizes or minimizes the response depending on the objective. This can be achieved by using optimization techniques, such as gradient ascent or descent, in the response surface equation. RSM is used in various fields including manufacturing, engineering and process optimization. It allows practitioners to understand and optimize complex systems by providing insights into the relationship between input variables and output responses. Using RSM, engineers and scientists can effectively improve processes, reduce costs, and increase product quality [24].

NaCl concentration (X_1), electric potential (X_2) and electrolysis time (X_3) were the independent variables selected to be in this experimental design, the active chlorine production was selected as the response for the combination of the independent variables (Table 1). In this design, 15 experiments were performed, which were designed in one block (Table 2). Considering the minimum and maximum values of the initial concentrations of sodium chloride (15 and 35 g/L), the electrical voltages (6 and 12 V) and the electrolysis times (5 and 10 min), along with the central axial points, in total 15 tests were obtained. The geometric view of a three-factor BBD has been demonstrated in Fig. 2. For create reproducibility and the determination of confidence interval and lack of fit (LOF), the number of central points for three variables was considered 3 points [24,26]. In order to minimize the effect of unexplained variability, all the experiments were carried out in random order. The generalized second-order polynomial model used in the response surface analysis was explained by Eq. (1) [27].

$$Y = b_0 + \sum_{i=1}^{k} b_i \cdot X_i + \sum_{i=1}^{k} b_{ii} \cdot X_i^2 + \sum_{j} \sum_{i=2}^{k} b_{ij} \cdot X_i X_j \quad (1)$$

Table 1
Experimental range and levels of independent factors

Factor	Range and levels		
	–1	0	1
NaCl concentration, g/L	15	25	35
Electric potential, V	6	9	12
Electrolysis time, min	5	7.5	10

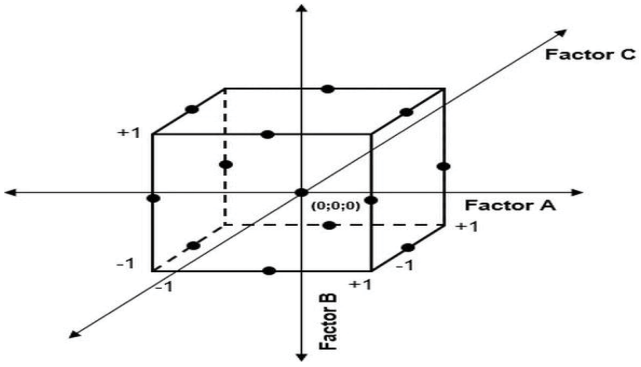

Fig. 2. Geometric view of a three-factor Box–Behnken design.

Table 2
Box–Behnken design matrix and experimental results

Experiment no.	Experiment plan			Observed free chlorine (mg/L)	Predicted free chlorine (mg/L)	Error (ε)
	NaCl concentration (g/L)	Electric potential (V)	Electrolysis time (min)			
1	25	9	7.5	50	29.99	20.01
2	25	6	5	0.04	0.16	–0.12
3	35	12	7.5	137	117.85	19.14
4	25	12	5	37.5	51.09	–13.59
5	25	9	7.5	12.5	29.99	–17.49
6	15	9	10	1.5	3.14	–1.64
7	15	12	7.5	8	–6.94	14.94
8	25	12	10	39.5	59.81	–20.31
9	35	9	5	49.5	56.83	–7.33
10	25	6	10	12.5	8.88	3.61
11	25	9	7	26.5	29.99	–3.49
12	35	9	10	69	65.56	3.43
13	15	6	7.5	0.75	4.50	–3.75
14	35	6	7.5	5	4.55	0.45
15	15	9	5	0.56	–5.58	6.14

where Y is experimental response, b_0 is average of the experimental response, b_i is estimation of the principal effect of the factor j for the response Y, b_{ii} is estimation of the second effect of the factor i for the response Y, b_{ij} is estimation of the interaction effect between factors i and j for the response Y. The coefficients of this model are calculated in the experimental region by the least square method [3,26]:

$$B = \left(X^T X\right)^{-1} X^T Y \tag{2}$$

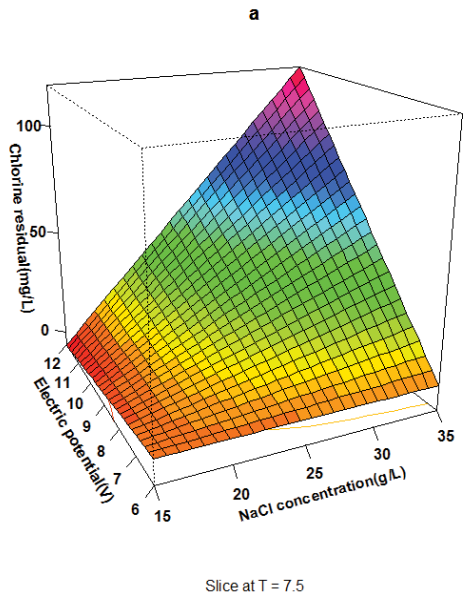

Fig. 3. Response surface for the amount of free chlorine produced as a function of electric potential and NaCl concentration.

where B – vector of estimates of the coefficients; X – model matrix; Y – vector of the experiment results. A three-factorial and a two-level CCD, with six replicates at the center point led to a total number of twenty experiments employed for response surface modeling. The independent process variables used in this study were: the NaCl (electrolyte) concentration (X_1), the applied electrical potential (X_2), and electrolysis time (X_3). Gas chlorine production (Y_1) and energy cost (Y_2) was considered as dependents factors (response). The values of process variables and their variation limits were selected based on the preliminary experiments. The models were used to evaluate the effect of each independent variable to the responses. According to analysis of variances (ANOVA which was applied to assess effects of studied variables, interactions and statistical significance of models) the fitness of the polynomial model equations were expressed by the coefficient of determination R^2 and LOF. The optimal extraction conditions were estimated through regression analysis and 3-D response surface plots. The analysis of experimental design and calculation of predicted data were performed using R 3.6.2 software.

3. Results

The results of this study are presented in Tables 2–4, as well as Figs. 3–7. In Table 2, the order and number of experiments, the observed and predicted free chlorine concentration, also the error (difference between observed and predicted values) based on the minimum, maximum and central points of the NaCl concentration, electric potential and electrolysis time has been shown. In Table 3, the values of regression coefficients, standard error, t-test value and p-value variables are shown. In this table, the interaction of variables is also observed. Table 4 shows the analysis of variance of the proposed model, in which the values of

Table 3
Regression coefficients of the proposed model

	Regression coefficient	Standard error	T-value	P-value
Intercept	29.9900	3.6873	8.1334	0.00001018
NaCl concentration (X_1)	31.2112	5.0490	6.1817	0.0001039
Electric potential (X_2)	25.4638	5.0490	5.0433	0.0005041
Electrolysis time (X_3)	4.3625	5.0490	0.8640	0.4078154
X_1:X_2	31.1875	7.1403	4.3678	0.0014039

Multiple R-squared: 0.90, Adjusted R-squared: 0.86.

Table 4
ANOVA results for the proposed model response surface

Source	df[a]	Sum of square	Mean square	F-value	Pr. > F
FO (X_1, X_2, X_3)	3	13,132.6	4,377.5	21.4651	0.0001119
TWI (X_1, X_2)	1	3,890.6	3,890.6	19.0776	0.0014039
Residual	10	2,039.4	203.9		
Lack of fit	8	1,321.2	165.2	0.4599	0.8238439
Pure error	2	718.2	359.1		

[a]Degree of freedom.

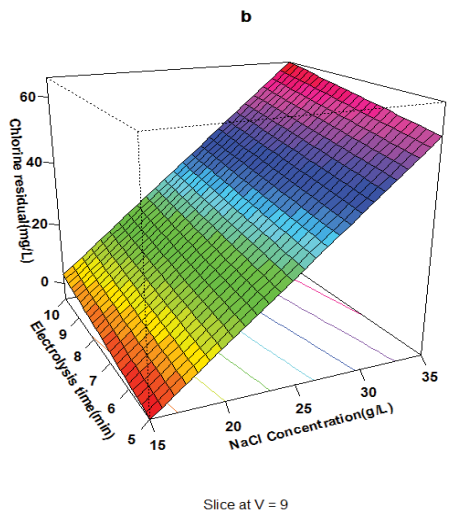

Fig. 4. Response surface for the amount of free chlorine produced as a function of electrolysis time and NaCl concentration.

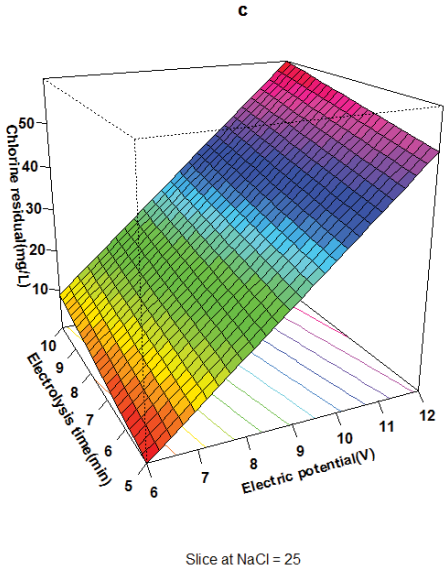

Fig. 5. Response surface for the amount of free chlorine produced as a function of electrolysis time and electric potential.

F-test, *p*-value and LOF of the model are indicated. In addition, in this table, the square of the Pearson correlation coefficient (R^2) is also given. In Fig. 3, the response surface for the amount of free chlorine produced as a function of electric potential and NaCl concentration. In Fig. 4, the response surface is given as a function of the electrolysis time and NaCl concentration. Moreover, in Fig. 5 the response surface of the amount of free chlorine is shown vs. electrolysis time and electric potential. Contour plots of the response surfaces for the amount of free chlorine produced have been also depicted in Fig. 6. The residuals plots related to the results of the response surface first order model for chlorine production have been demonstrated in Fig. 7.

4. Discussion

4.1. Chlorine gas production

The experimental results showed that chlorine production was affected by all three independent variables as well as their interaction. BBD and RSM analysis allowed determination of optimal settings for maximum chlorine production in the presence of the magnetic fields. The maximum free chlorine formation in the chlorination cell was 137 mg/L that is obtained at NaCl concentration of 35 g/L, electric potential of 12 V and electrolysis time of 7.5 min (Table 2). The results also showed that the optimal condition of the chlorine generation (19.8 mg/L as free chlorine residual) was occurred at NaCl concentration of 16.8 g/L, electric potential of 6 V and electrolysis time of 7.5 min. The formation of chlorine gas in the electrolyte cell was due to the oxidation of chloride ions around the anode. Injection of this gas into deionized water cell resulted in the formation of residual free chlorine [19]. Besides, in the electrolytic cell, free chlorine reacted in the form of hypochlorite ion with sodium ions produced by electrolysis of sodium chloride and sodium hypochlorite was formed [8,16]. Key et al. [28] reported maximum free chlorine concentration in electrolytic cell was 5,600 mg/L, which occurred at a concentration of sodium chloride 25 g/L and electrolysis time of 10 min.

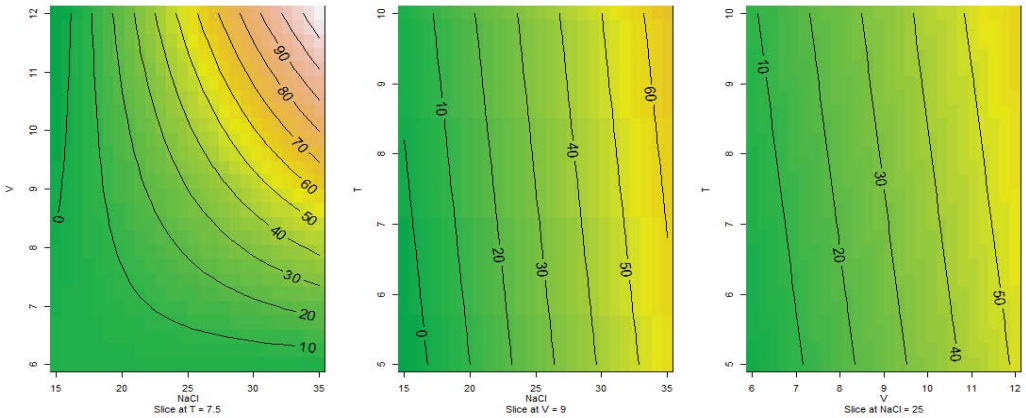

Fig. 6. Contour plots of the response surfaces for the amount of free chlorine produced.

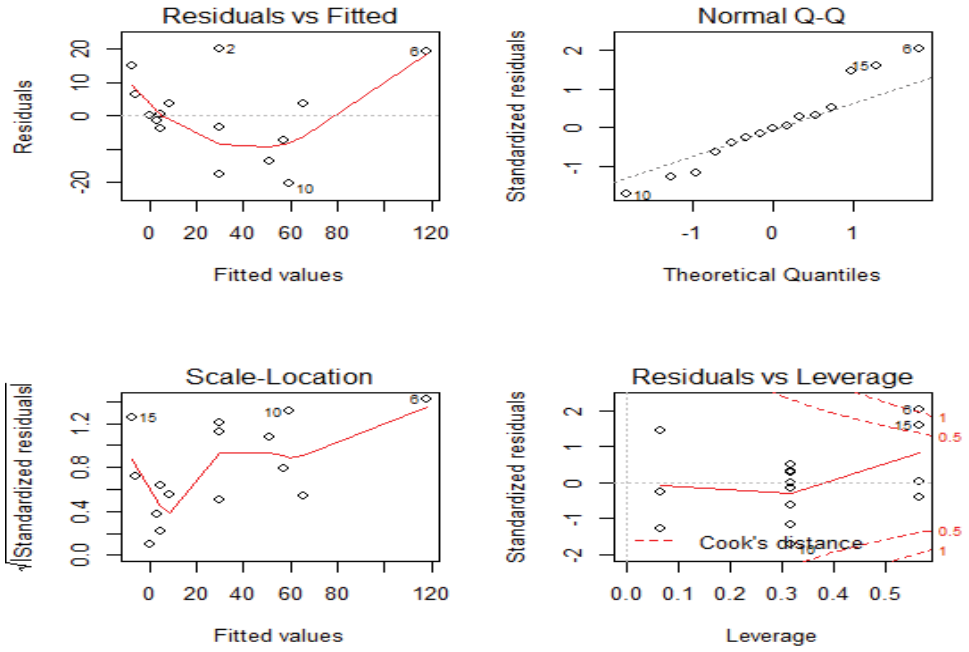

Fig. 7. Residuals plots related to the results of the response surface first-order model for chlorine production.

They concluded that the maximum free chlorine concentration was formed in the range of 5 to 15 min. Lacasa et al. [29] reported an amount of free chlorine released from electrolysis in synthetic saline water (200 mg/L), which was achieved at the time of 45 min. In this study, the inert graphite electrode is selected because of its lack of reaction with chlorine, its high potential for chlorine production, low cost and easy access to it. Saha and Gupta [30] designed new electro-chlorinator using graphite electrodes for water disinfection. In their study, the optimal amount of free chlorine was reported to be 2.5 mg/L, which was obtained at the electrolysis time of 30 min. Table 3 shows that all three variables affected the amount of free chlorine formation. According to this table, with the increase of each of the independent variables, the amount of free chlorine formation increased. The results of this study showed that the most effective variables in chlorine production were NaCl concentration (P = 0.0001) and electric potential (P = 0.0005). In addition, the interaction between NaCl concentration and electric potential was statistically significant (P = 0.0014). By increasing the applied electrical voltage, the amount of energy given to each coulomb increases the charge, so that each electron exchanged between the electrodes will have more energy [3]. Then, chlorine molecules are formed at a higher rate. Besides, when more ions of chloride are present in the solution, it increases the conductivity of the solution and, as a result, more electrons flow. In addition, the presence of more chloride ions forms more chlorine molecules [4]. Naderi and Nasseri [3] optimized the free chlorine, electric and current efficiency in an electrochemical reactor for water disinfection purposes. In their study, CCD was applied to determine the optimal experimental factors for chlorine production. The results of their study showed that the optimum value of electrical efficiency (42 mg·Cl_2/kJ) was obtained at the electric potential of 15.73 V during 15.63 min in the presence of 63.42 g/L of sodium chloride [3]. Domga et al. [10] surveyed the most important parameters during brine electrolysis. They optimized chlorine production using graphite electrodes. In their study the optimum condition for brine electrolysis (24% active chlorine) was obtained at the NaCl concentration of 320 g/L (pH = 2). In Fig. 3, the response surface for the amount of free chlorine produced as a function of electric potential and NaCl concentration. The results showed that with the increase of both electric potential and NaCl concentration, the free chlorine formation was enhanced. In Fig. 4, the response surface is given as a function of the electrolysis time and NaCl concentration. According to this figure, increasing the NaCl concentration increased the production of residual active chlorine, but increasing the electrolysis time had a very small effect on chlorine production and this effect was not statistically significant. Electrolysis time is another parameter that can be increased the oxidation of chloride ions and can be formed chlorine gas. But in the study, the effect of electrolysis time variable on chlorine production was not statistically significant (P = 0.4078). In Fig. 5 the response surface of the amount of free chlorine is shown vs. electrolysis time and electric potential. This figure has been shown that chlorine production increased with increasing voltage. It has been also indicated that the increase in electrolysis time variable did not have a significant effect on chlorine production. Moreover, contour plots of the response surfaces for the amount of free chlorine produced have been also depicted in Fig. 6. Zaviska et al. [23] optimized the electrochemical production of active chlorine from synthetic saline effluent by CCD experimental design. The optimal amount of active chlorine in their study was 31 mg/L, which was reported at sodium chloride concentration of 47 g/L, electrolysis time of 27 min and a current intensity of 1.06 A. They concluded that the variables of the current intensity and electrolysis

time were two parameter effective factors in the production of active chlorine. Data analysis and interactions between dependent and non-dependent variables were performed through multi-way analysis of variance (ANOVA). The *p*-value in Table 3 show that the effect of independent variables and the intercepts on chlorine production was statistically significant at 95% confidence interval ($p < 0.05$). Furthermore, the free chlorine production was function of the first-order polynomial equation. The quality of the proposed model was evaluated by the coefficient R^2 and LOF. R^2 equal to 0.90 provides a very good correlation between predicted and observed values (Table 3). R^2 should be at least 0.80 for a good fit of a model [23]. The lack of fit that describes the fitting of the model to the data is presented in the table of the analysis of variance of the model (Table 4). The value of this parameter was 0.4599 that statistically is not significant. The LOF in a very good model should be greater than 0.05. The adequacy of the model was also evaluated by the residual values against the predicted values (Fig. 7). The random dispersion of the residuals around the straight line shows that there are no increasing or decreasing trends, and the dominance of the positive or negative residuals. This suggests that the proposed model was relatively good. The issue of concentrate disposal is becoming an increasing challenge with the increasing use of desalination production processes. Isa et al. [31] in a study evaluated the suitability of *in-situ* production of free available chlorine. Their results showed that the produced free available chlorine was 76 mg/L at NaCl concentration 3 g/L, current density 6 mA/cm^2 and electrolysis time 60 min. In their study the data fitted well with a quadratic model and R^2 was 0.8693 [31]. Additionally, the produced active chlorine was optimized based on energy consumption, which was 77 mg/L for the energy consumption of 0.2 kWh/L. The system consumed much less energy than other chlorine production methods. The optimization of chlorine production by electrochemical-magnetic method as a function of energy consumption has been demonstrated in Fig. 8.

4.2. Magnetic fields effects

According to the results obtained from this study, it was found that the presence of magnetic field and electric potential simultaneously in the experimental range led to higher chlorine production. It has been observed that applying a magnetic field during electrolysis can have a significant effect on the process. The magnetic field can affect ion migration and diffusion rates, leading to changes in electrode reactions and overall electrolysis efficiency. These effects are attributed to the Lorentz force, which acts on the charged particles in the electrolyte and changes their direction and distribution [32]. An important observation is that applying a magnetic field can reduce the overpotential required for electrode reactions, effectively reducing the input energy required for electrolysis. This can be particularly important for processes such as water splitting, where the hydrogen evolution reaction typically requires a high potential. By reducing this excess potential, the overall energy consumption of the electrolysis process can be reduced, making it more efficient and cost-effective [33]. In addition, magnetic fields can also affect the formation and stability of electrode products. For example, in the electrolysis of metal ions, a magnetic field can affect the nucleation and growth of metal deposits, leading to different morphologies and properties. This can be useful for certain applications that require special characteristics of electrode products [34]. Ibanez et al. [14] designed a novel combined electrochemical-magnetic method for water treatment. According to their results, the spectroscopic analysis of electrical conductivity (EC) samples confirmed that Fe(III) was the predominant form of oxidized iron even when produced in an inert atmosphere. A magnetic field has a beneficial effect on the deposition performance of EC agents derived from iron anodes. The deposition samples that were affected by the magnet reached a lower turbidity level faster than the samples without magnet. The effectiveness of the presence of a magnetic field in the precipitation of coagulants from a suspension was confirmed by monitoring the turbidity change vs. time with and without exposure to a magnetic field, up to a 30% improvement. The results obtained from their study confirmed the results of the present study [14]. A higher concentration of salt water has a positive effect on chlorine production. The integration of magnetic fields in the electrolysis process caused changes in the system dynamics and electrolyte behavior. It was observed that the presence of magnetic fields changes the electrical conductivity and mass transfer characteristics of the system [35]. This led to an increase in chlorine production due to the better transfer of ions to the electrodes. The presence of a magnetic field can have several effects on the electrolysis process. A magnetic field can affect the movement of charged particles (ions) in an electrolyte solution. This can lead to a change in the migration rate of ions towards the electrodes, which affects the overall efficiency of the process [36]. Moreover, electrolysis usually involves splitting water into hydrogen and oxygen gas. Applying a magnetic field can affect the direction and rate of gas evolution, potentially affecting gas bubble formation and overall reaction kinetics. In addition, the magnetic field can lead to the polarization of the electrodes and the asymmetric growth of metal deposits on the electrode surfaces [37]. This can affect the uniformity and quality of the electrodeposition process. In addition, the presence of a magnetic field can modify the redox reactions that occur at the

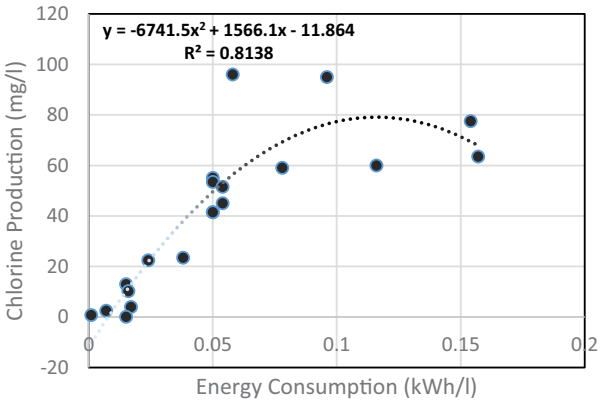

Fig. 8. Optimization of chlorine production by electrochemical-magnetic method as a function of energy consumption.

electrolyte-electrode interface. This can change the electrochemical potential and thus affect the overall reaction kinetics. Magnetic fields can induce convective currents in the electrolyte solution, leading to increased mass transfer [38]. This can increase the rate of release of ions and species involved in the reaction, potentially improving the overall efficiency of the electrolysis process. It is important to note that the exact effects of the magnetic field on electrolysis depend on various factors such as the strength and direction of the field, the specific electrolyte and electrodes used, and the applied current density [33]. The Lorentz force, which is created when an electric current passes through a magnetic field, was also investigated in this study. Based on Lorentz theory, whenever a charged particle is placed in magnetic and electric fields that are perpendicular to each other, the particle exerts a force perpendicular to the lines of both types of field [16]. The Lorentz force affected the movement of charged species in the electrolyte and led to changes in the electrolysis process. Analysis showed that the Lorentz force had a significant effect on chlorine production, with higher force values being associated with increased chlorine production. Finally, the results revealed that the addition of magnetic fields significantly improved chlorine production. Furthermore, the Lorentz force generated by the magnetic fields played an important role in enhancing the overall electrolysis process. Monzon and Coey [39] studied the magnetic fields in electrochemistry and focused on the electromagnetic forces acting on electric currents. They showed that Lorentz force was the predominant mechanism in magneto-electric interaction. In another study, Li and Chen [22] carried out a study on the effect of the configuration of the magnetic field on the movement of gas bubbles that evolve from platinum electrodes. The results in this study determined the optimal arrangement of an electrode and a magnetic field to increase the conductivity and effectiveness of water electrolysis. Oxygen and hydrogen bubbles evolve from the surface of the anode and cathode, respectively, and show different behavior in the presence of a magnetic field due to their paramagnetic and diamagnetic properties [22]. A magnetic field perpendicular to the surface of the horizontal electrode causes the bubbles to rotate. The oxygen and hydrogen bubbles rotate in opposite directions to create a swirling current and spread the bubbles between the electrodes, which increases the conductivity and effectiveness of the electrolysis. For vertical electrodes under the influence of a parallel magnetic field, the horizontal Lorentz force effectively separates bubbles and increases the conductivity and effectiveness of electrolysis. However, if the arrangement of the electrodes and the magnetic field result in upward or downward Lorentz forces that counteract the buoyancy force, a sluggish flow in the channel prevents the bubbles from moving, reducing the conductivity and charging performance [2]. The effects of magnetic fields in the electrolysis process have been studied extensively, and while there is still much research to be conducted. Despite many advantages of the approach, there are still many challenges and uncertainties regarding the effect of magnetic fields on the electrolysis process. The optimal conditions and parameters for magnetic field application are not yet fully understood, and there is a lack of standardization in experimental setups and methodologies. Moving forward, more research is needed to better understand the mechanisms underlying the effects of magnetic fields on electrolysis. This includes studying the interactions between the magnetic field and different electrolyte compositions, evaluating the effect of magnetic field strength and orientation, and investigating the scalability and practical feasibility of magnetic field-assisted electrolysis in real-world applications. Furthermore, exploring new materials and designs for electrodes that can better take advantage of the potential benefits of magnetic fields could be a future research direction. This could include the development of innovative electrode materials with enhanced catalytic properties under the influence of a magnetic field or the exploration of new reactor configurations to optimize the use of magnetic field effects.

5. Conclusion

Brine water management is one of the most important problems of water desalination. Disposal of brine water into the sea has serious negative effects on the environment and marine life. The results of the study showed that the electrolysis process has shown promising results when used in combination with magnetic fields to produce chlorine from brine water. The results also indicated that the electrolysis process in connection with magnetic fields can significantly reduce the energy consumption for chlorine production compared to traditional methods. Moreover, the results revealed valuable insights for the design and optimization of electrolysis-based chlorine production processes using magnetic fields from brine water. This study identified potential areas for future research to further advance the application of these processes. One of the main practical concepts of this study is the high efficiency of electrochemical-magnetic processes in water desalination and ion recycling. The results showed that these processes can achieve rapid salt removal and significant ion recovery efficiency and become promising alternatives to traditional desalination methods. These results suggest that electrochemical-magnetic processes have the potential to play an important role in addressing the growing challenges of water scarcity worldwide. Another practical concept is the energy efficiency of these processes. This study indicated that this method requires relatively little energy compared to other desalination technologies. This feature not only reduces operating costs, but also minimizes the environmental impact associated with energy consumption in water desalination. Therefore, the results strongly support the practical adoption of this method as sustainable and economical solutions for water desalination and ion recycling. In terms of potential areas for future research, several ways can be explored to advance the application of electrochemical-magnetic processes in water desalination and ion recovery. One of the key fields is optimization of process parameters and system design. Investigating the effects of various factors such as electrode materials, membrane properties, and magnetic field strength can lead to improved performance and cost-effectiveness of processes. Moreover, further research could focus on scaling up electrochemical-magnetic systems for practical applications. This study mainly examines processes in laboratory-scale settings, and transition to larger-scale

implementation requires addressing various engineering challenges. Furthermore, investigating the integration of the process with renewable energy sources such as solar or wind energy can be an important field for future research.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Consent for publication

The authors declare that they have no competing interests.

Ethics approval and consent to participate

Not applicable.

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Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

All authors contributed to the study conception and design. MN carried out the conceptualization, VP conducted the methodology, AHM carried out the supervision, GRE and MP carried out editing. All authors read and approved the final manuscript.

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