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Solar Powered Electrocoagulation System for Groundwater Remediation at Al-Raaed Station for Irrigation Purposes: Batch Mode

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ABSTRACT

Although groundwater is a vital component of the world's freshwater supplies, it is frequently endangered due to the overconsumption of natural resources and the massive amounts of waste generated by modern society. The primary objective of this study is to analyze the effects of electrocoagulation on pH, electrical conductivity (EC), and the concentrations of contaminants (Ca, Mg, Cl, SO_4, HCO_3, CO_3, K, Na, NO_3) in groundwater at a laboratory scale. Various types of electrodes, such as iron (Fe) and aluminum (Al), can be used in electrocoagulation. Iron electrodes (Fe) were used in this study. Compared to aluminum electrodes, iron electrodes require less energy, produce less floc, and have lower operational costs. A higher current was required for aluminum (Al) electrodes compared to iron (Fe) electrodes. This study examined the efficiency of pollutant removal under various conditions, including frame number (18, 9, 5), detention time (10–120 minutes), voltage (5–30 V), and pH (5, 8.2, 12). At a potential difference of 30 V and an electrode distance of 0.5 cm, the removal efficiencies for Ca, Mg, HCO_3, K, Na, SO_4, Cl, NO_3, and TDS were 61%, 80%, 62%, 85%, 51%, 85%, 76%, 72%, and 76%, respectively. The optimal conditions for pollutant removal include a voltage of 30 V, a detention time of 60 minutes, 18 frames, and a pH of 5.

1. INTRODUCTION

To meet global water demands, groundwater is a crucial resource [1]. The expansion of urban, industrial, and agricultural sectors, coupled with poor management practices, has led to the infiltration of various contaminants into groundwater reservoirs. As a result, hydrological environments are constantly being exposed to rising levels of water-soluble chemicals in groundwater, which has irreversible environmental effects and reduces the resource's quality [2]. Most people do not realize the importance of groundwater resources or the harmful effects of environmental pollution on them due to their hidden nature [3]. According to what Kaur found, there is a wide range of physical, chemical (organic and inorganic), bacterial, and radioactive factors in groundwater contaminants [4]. Groundwater contamination by organic or inorganic pollutants, either from soil leaching or human activities, is a significant environmental concern. The remediation of this water source is a top priority, as it serves as a primary drinking water source in many countries [5].

Groundwater is essential for both drinking and industrial applications. As a result, pollutants from those sources can pose health risks to humans and significantly raise the maintenance costs of industrial systems if they are not adequately managed. Pretreatment of groundwater has involved a wide range of technologies, including biological, chemical, and physical processes. There are advantages and downsides to each of these processes.

Groundwater treatment is essential for ensuring its safety for consumption, as it contains heavy metals such as iron and manganese.

A growing number of countries, particularly in Latin America, are relying on groundwater as their primary supply of potable water due to rising demand. An estimated half of the world's population gets all the water they need from underground sources [6]. Because of its relatively higher water quality compared to surface water, groundwater is commonly drunk untreated and is the primary source of drinking water for over half of the global population [7]. Although there isn't a lot of microbiological contamination in groundwater, naturally occurring (geogenic) toxins like fluoride and arsenic can nonetheless lower its quality. Even though microbial contamination is typically given top priority because of the massive epidemic of disease and the significant mortality rates among children [7].

In the realm of water quality measures, hardness has long been studied for its significance. There are a lot of issues with hard water in both residential and commercial settings. Anions, which include bivalent and trivalent cations like magnesium and calcium as well as, to a lesser extent, aluminum and iron, are responsible for the hardness of water. To meet the increasing demand for high-quality soft water, efficient and cost-effective technologies must be developed [8].

Recent studies have shown electrocoagulation to be a viable and appealing option. Research on the electrocoagulation process is ongoing to remove ions, organic substances, colloidal and suspended particles, dyes, surfactants, oil, and heavy metals from a range of wastewater and water types. These include wastewater from electroplating [9], laundry [10], textile [11], and restaurant [12]. Electrocoagulation was found by Orescanin et al. [13] to be an effective method for treating groundwater that is unsafe for human consumption due to the presence of heavy metals, suspended particles, color, and turbidity. If groundwater has a complicated mixture of contaminants, electrochemical treatment may be the best option for cleaning it. To remove hardness, COD, and turbidity all at once, Zhao et al. [14] devised a combined electrocoagulation-reverse osmosis (RO) method, in which the efficacy of electrocoagulation as a pretreatment for generated water before RO membranes was studied. Based on their investigation of permeate flux and effluent quality, they proved that the method could be used to treat produced water from a single Canadian oil field [14]. A comparison of the advantages and disadvantages of treatment methods technologies is shown in Table 1.

Currently, electrocoagulation (EC) is gaining significant attention due to its efficiency and minimal environmental impact. Simple equipment, uncomplicated operation, a shortened reactive detention period, no chemical additives, and a lowered volume of sludge that settles swiftly are just a few of the many advantages of the EC process. To eliminate turbidity, COD, BOD, and TSS from MWW, multiple authors utilized batch and continuous mode EC processes. Higher energy consumption leads to lower flow rates and higher current densities, which in turn leads to higher pollutant removal, as reported by study [15]. Common electrode materials for electrochemical chromatography (EC) include iron (Fe) and aluminum (Al); under ideal conditions, Al is shown to have a greater removal efficiency than Fe [15, 16]. Using a direct DC supply from photovoltaic (PV) panels, studies have been conducted to successfully treat wastewater and water for remote Australian communities using solar-powered electrocoagulation (SPEC) [17, 18]. The solar-powered EC process is advantageous from an environmental perspective because it uses solar energy with low environmental impact. According to Srivastava and Srivastava [19], PV panels are great for off-grid water treatment because of their longevity, adaptability, low maintenance requirements, and quiet operation.

Due to inadequate or nonexistent power supply, the operation of such EC facilities may be severely restricted in remote areas. PV or solar energy is the best option for resolving this issue. Typically, aluminum is utilized as the electrode material in the EC process. Here are the primary responses:

$$\text{Anode:} \quad Al(s) \rightarrow Al^{+3} + 3e^- \tag{1}$$

$$\text{Cathode:} \quad 3H_2O + 3e^- \rightarrow 1.5H_2(g) + 3OH^- \tag{2}$$

The complex precipitation kinetics cause the Al^{3+} and OH^- ions produced by electrode reactions (1) and (2) to react and form different monomeric species, which subsequently change into $Al\ (OH)^3(s)$.

$$Al^{+3} + 3H_2O \rightarrow Al^{+3} + 3H^+ \tag{3}$$

New amorphous $Al\ (OH)^3$ (s) "sweep flocs" have a lot of surface area, so they may quickly absorb organic chemicals that are soluble in water and catch particles in suspension. Lastly, the flocs can be easily removed from the water by electro-flotation, a process that involves sedimentation and flotation caused by hydrogen bubbles created at the cathode [20, 21]. Reduction, oxidation, breakdown, deposition, coagulation, absorption, adsorption, precipitation, and flotation are some of the removal mechanisms that can be employed in EC. In previous publications, SPEC cells with less complex electrode geometry have been detailed [22].

Table 1. Comparison of advantages and disadvantages of treatment methods technologies [23]

Method	Advantages	Disadvantages
Chemical precipitation	1. Technologically simple. 2. Adapted to high pollutant loads. 3. Significant reduction in the chemical oxygen demand.	1. Chemical consumption (lime, oxidants, H2S, etc.) 2. Ineffective in the removal of the metal ions at low concentration. 3. High sludge generation, handling, and disposal problems (management, treatment, operational cost).
Chemical oxidation	Integrated physicochemical process Simple, rapid, and efficient process. 2. Efficient treatment for cyanide and sulfide removal 3. Initiates and accelerates azo-bond cleavage (hypochlorite treatment). 4. Increases biodegradability of the product	1. Chemical required. 2. Generations, transports, and management of the oxidants. 3. Efficiency is strongly influenced by the types of oxidants. 4. Some colors must be resistant to treatments and require greater ozone doses.
Adsorption	1. Simple equipment. 2. Wide variety of target contaminants (adsorption). 3. Highly effective process (adsorption) with fast kinetics. 4. Excellent quality of the treated effluent. 5. Excellent ability to separate a wide range of pollutants, in particular, refractory molecules (CAC is the most effective material). 6. CAC: efficient for chemical oxygen demand removal; highly efficient treatment when coupled to coagulation to reduce suspended solids, chemical oxygen demand, and color.	1. Relatively high investment (CAC) Cost of materials (CAC, CAA). 2. Nondestructive processes, non-selective methods. 3. Performance depends on the type of material (CAC). 4. Requirement for several types of adsorbents. 5. Rapid saturation and clogging of the reactors (regeneration costly). 6. Not efficient with certain types of dyestuff and some metals (CAC).

Electrocoagulation	1-Simple equipment and easy to operate. 2. It does not produce secondary pollutants as it does not require chemical additives, which makes it a green technology. 3. Treated wastewater is palatable, clear, colorless, and odorless. 4. The pH neutralization effect is made effective in a much wider range (4-9). 5. An efficient technique for recovering/recycling precious metals: a novel method for recovering gold and silver from rinse baths. 6. Adaptation to different pollutant loads and flow rates. 7. The floated scum by gas bubbles can remove easily by skimming or sedimentation.	1. Passivation phenomena. 2. Recombination phenomena. 3. In some cases, the close distance between two electrodes causes distortion phenomena and thus affects the efficiency of the electric field. 4. Require pre-treatment techniques to enhance the removal of efficiency of pollutants at continuous feeding of wastewater. 5. Require the use of some electrolytic materials to enhance the conductivity of the process.

Abd Al-Hamza and Abd Al-Hamed [24] examined how voltage, electrode number, distance, form, and reaction time affect dairy effluent electrocoagulation. This has aluminum-iron electrodes. Voltage, reaction length, and electrode distance improved COD, BOD, EC, TDS, color, and oil-grease elimination. Choose square, triangular, or perforated cylindrical electrodes. Electrocoagulation eliminates COD and BOD most efficiently (88.03% and 87.97%) for the first electrode in 20 cylindrical holes. The first electrode's highest TDS removal and EC efficiency at 20 cylindrical holes are 99.38% and 99.42% in the third square form.

Ibrahim and Hameed [25] stated that MBBR and Electro-flotation were used to create a hybrid worldwide development treatment system. Iron and aluminum electrodes increase the removal of persistent and non-biodegradable dissolved organic dyes (Methylene blue dye). Without chemical reagents, the treatment system outperformed any single procedure. This study simulated wastewater characteristics from textile dyeing at the General Establishment of Cotton Textile Industry in Baghdad. H_2 gas production at 1:13L is one of the most sustainable and valuable byproducts. Thus, the continuous system's optimal color, COD, and BOD removal efficiencies were 90.08%, 100%, and 100% at 200V, 2cm electrode distance, 5 minutes, pH=7, 8 electrodes, 30gm media weight.

Faisal and Hmood [26] examined tests of zeolite permeable reactive barriers to remove cadmium from a shallow aquifer. Batch tests characterized the zeolite's equilibrium sorption properties in cadmium-containing aqueous solutions. A 1D numerical finite difference model has been constructed to characterize groundwater contaminant transport, taking Langmuir equation-based (PRB) sorption into account. Based on numerical measurements, the PRB saturates after ~120 h due to reduced retardation factor, indicating a decline in zeolite functioning. A reasonable agreement was found between model predictions and experimental results of Cd^{+2} concentration over the soil bed with a zeolite permeable reactive barrier.

Researching the viability of batch mode solar powered EC as a means of remediating groundwater contaminated with contaminants was our primary aim. While EC experiments use a solar-powered DC supply via a battery, the EC reactor takes advantage of groundwater flow. To improve the operating conditions of the SPEC process and achieve maximal removal of contaminants, experiments were carried out to investigate the impacts of groundwater operating parameters, including voltage, detention duration, number of frames, and TDS.

Ammar et al. [27] introduced a new wastewater treatment device, a split-plate airlift electrochemical reactor. Two aluminum plates inside the reactor serve as split plates for internal loop generation of the airlift system (the zone between the plates acts as a riser and the other two zones as a downcomer) and as electrodes for electrocoagulation. This apparatus for zinc removal was tested using simulated wastewater contaminated with zinc ions. The effect of initial zinc concentration (50-800 ppm), electrical current density (2.67-21.4 mA/cm^2), initial pH (3-11), air flowrate (12-50 LPH), and implicitly electrocoagulation time was studied. This split-plate airlift reactor can be used as an electrocoagulation cell to treat wastewater with Zink ions. Zink removal increased with current density and electrolysis time. Initial pH between 7 and 9 yielded the highest removal percentage. Increasing the operating current density from 2.67 to 21.4 mA/cm^2 reduces the minimum electrocoagulation time needed to remove $\geq$ 90% of Zn(II) from 90 to 22 min.

Mohammed and Al-Mureeb [28] stated that lead ions were separated from wastewater in an electrocoagulation cell with aluminum anode and stainless-steel cathode electrodes. The influence of pH, current density, initial lead concentration, electrode surface area, electrode gap, and sodium chloride concentration on electrocoagulation cell performance was evaluated. The results showed that pH 9 had higher removal effectiveness and shorter treatment times with higher current density and lower electrode gaps. Pb(II) concentration decays from 250mg/l to 2.5mg/l at 0.025 l/min after 7min electrolysis, achieving 99% removal efficiency.

Al-Hashimi et al. [29] stated that electrocoagulation purifies water through electrochemical processes. Electrocoagulation and electroflotation are two methods that use electric currents to introduce metal ions directly from sacrificial electrodes to treat polluted water. Water is electrolyzed, and hydrogen gas is produced using specific reactor designs. The method is most effective at a pH range of 7.0–7.5 but becomes less effective at pH levels outside the range of 3.5–9. The electrocoagulation procedure reduces water turbidity based on electrical current and operation duration. The Electrocoagulation technique removes turbidity by 85% for batch and 62% for continuous flow and total suspended material by 96% for batch and 66% for continuous. The ideal temperature of 35℃ was determined for efficient removal of turbidity, total suspended solids, and sulfate ions.

Atiyah et al. [30] stated that carwashes produce lots of dirty wastewater daily. It contains a lot of detergents, oil, grease, heavy metals, suspended particles, hydrocarbons, and biological materials. Foil electrode electrocoagulation was used to remove COD, turbidity, and TDS from carwash wastewater and lower its electrical conductivity. This treatment uses a thin aluminum foil electrode. The effects of voltage and treatment time were examined. The best results were 97.94%, 99.90%, 25.31%, and 15.57% COD, turbidity, TDS, and EC elimination at 30 volts and 90 minutes.

Thus, an adequate quantity and quality of water for human health, livelihood, and productivity is the ultimate aim of groundwater management. Contemporary models of water management center on three interrelated ideas: water resources, ecosystems, and water security. The term "Water Resources Management" (WRM) refers to the steps taken to ensure that all water uses are adequately planned for and managed regarding the amount and quality of water resources. Supporting and guiding water management are the institutions, infrastructure, incentives, and information systems. Pumping wells are used to extract groundwater, which is often located deep within aquifers, porous rocks, and sediments. Aquifers are a type of renewable water resource that can be filled up again and again over hundreds of years—if not thousands—of years—by rainfall infiltration.

Moreover, a distinct strategy is needed for the detection and management of contaminants in groundwater compared to surface water. Surface water pollution is typically easy to spot, can happen fast and aggressively, but is usually reversible if the source of the contamination is removed. Worldwide, contamination is becoming an ever-greater concern to both urban and rural regions, even though most groundwater is naturally of good quality. There is a vast spectrum of naturally occurring contaminants, from elements like iron that are not particularly harmful to more pervasive and potentially fatal ones like arsenic and fluoride. No amount of groundwater planning or investment, backed by solid institutions and the right legal framework, can ensure sustainability in the long run. Until the monetary and human consequences become insurmountable, groundwater quality management is nearly always disregarded.

This paper aims to evaluate the efficiency of electrocoagulation in removing cations, anions, and TDS from groundwater at the Al-Raaed station for safe irrigation use.

2. MATERIALS AND METHODS

2.1 Groundwater

The Al-Raaed station in Baghdad, Iraq, is the site of the groundwater well used in this investigation. Located 20 km west of Baghdad at longitude 12 44" 40' east and latitude 33 20" 10' east, the experimental field station was the site of the study. The terrain here is very flat, or almost so, and is at an elevation of 34.1 meters above sea level. Table 2 displays the GW characterization.

Table 2. Initial characterization of groundwater

Pollutants	GW of Al-Raeed Research Station
EC (μs/cm)	7500
pH	8.2
Pollutants (ppm)	
TDS	5390
Ca	130
Mg	200
SO_4	1321
Cl	990
HCO_3	750
CO_3	0
K	15.5
Na	1200
NO_3	10.1

2.2 Experimental setup

Electrocoagulation was performed in a glass EC cell that had a net capacity volume of 70 L and measured 30 cm in width, 50 cm in length, and 60 cm in height. There were eighteen electrode mesh frames made of metal that made up the device. Frames with an inter-electrode distance of half a centimeter serve as anodes and cathodes, respectively. Because the electrode plates are detachable, they may be cleaned more easily. Through the battery, the electrodes are linked in parallel with the charge controller. Dekra Solar's IP60 solar photovoltaic module is seen in Figure 1.

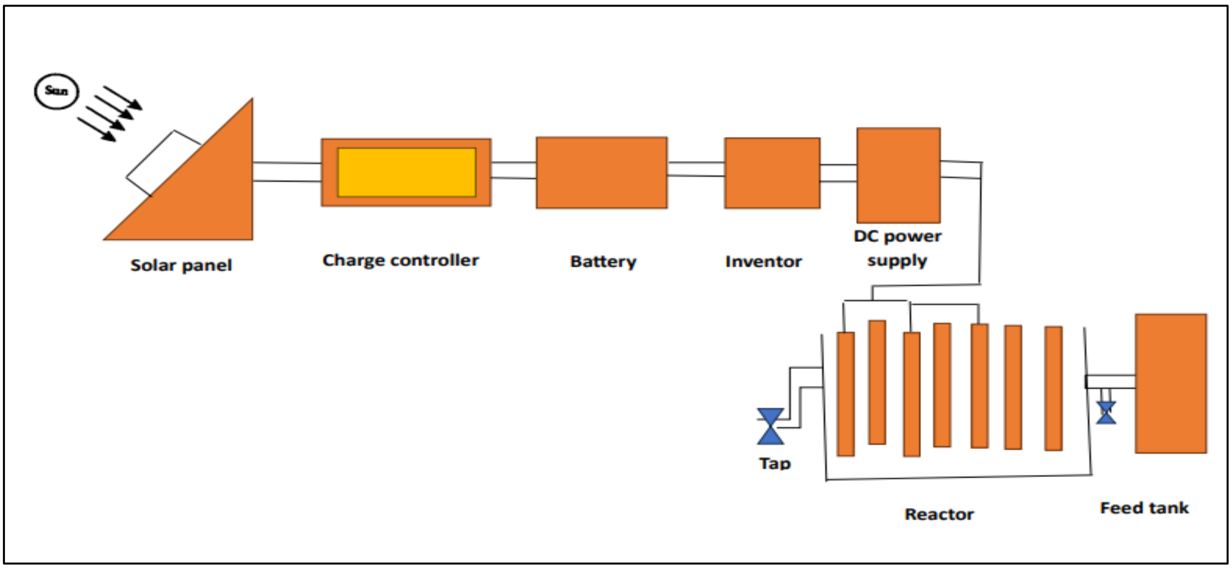

Figure 1. Typical experimental setup

The Current density is equal to 6-40 mA/m² at different voltage-applied experiments. The sunlight intensity is 5-6 kWh/m². d in March and (7-8) kWh/m². d in July. The operation time is 2 hr per day. Moreover, the solar panel efficiency is about 20-30%.

2.3 The equipment

The needed equipment used in the research was tabulated in Table 3.

Table 3. Equipment and tools used in the experimental work

No.	Equipment and Tools	Description
1	Solar panel	Dekra solar, IP60P
2	MPPT	12/24v, current 10A, China
3	Electrolyzer	applied voltage 30V, Aluminum, and Iron electrodes with dimensions (8 mm in diameter, 6.5 cm in height)
4	DC power supply	(WANPTEK, Chain, type: NPS605W; 0-50V/5A) ranging (10-50) V
5	Feed Tank	(plastic tank V=250 L)
6	pH meter probe	(Eco tester pH meter, EUTECH Instruments, Singapore), ORION 3 STAR, Thermo, USA.
	battery	100 A, Korea

The removal efficiency was calculated as

$$\text{Removal efficiency (\%)} = [(C_o - C_e)/C_o] \times 100 \qquad (4)$$

where, the starting and ending pollutant concentrations are represented by C_o and C_e, respectively. The elimination efficiency for treatment is compared with the FAO standard (Table 4).

Table 4. FAO standard for irrigation purposes

Pollutants	FAO Standard for Irrigation Water
pH	6-8.5
EC	3000
Pollutants (ppm)	
TDS	2000
Ca	400
Mg	60
SO_4	960
Cl	1065
HCO_3	610
CO_3	3
K	2
Na	920
NO_3	10

3. RESULTS AND DISCUSSION

3.1 Effects of voltage and detention time

The capacity of the EC process to remove heavy metal ions is dependent on the quantity of voltage and current, according to multiple studies [31, 32]. This study investigates how voltage affects cations, anions, and total dissolved solids. The voltage range that the study covers is 5 to 30 V. When first starting the EC process, ions degrade for 120 minutes. The optimal removal occurred at minute 60, with a pH of 8.2 and a spacing of 0.5 cm between the electrodes. With an increase in voltage, the anode is more likely to dissolve. This causes large amounts of metal hydroxide flocs to develop, which can enhance the solution's ion removal effectiveness, as shown in Figures 2, 3, and 4.

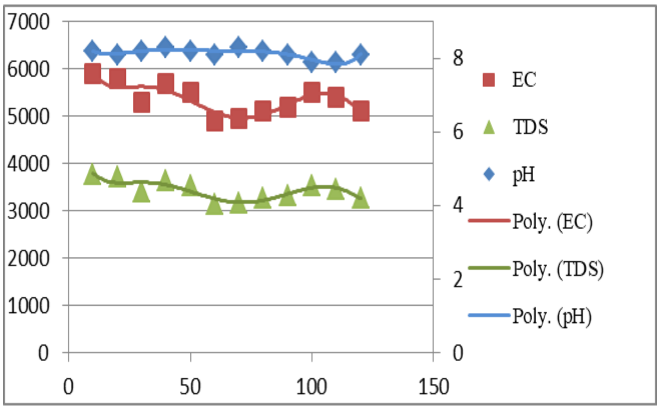

Figure 2. pH, EC, TDS with 5 voltages (No. of frames 18, pH=8.2, time= 120min)

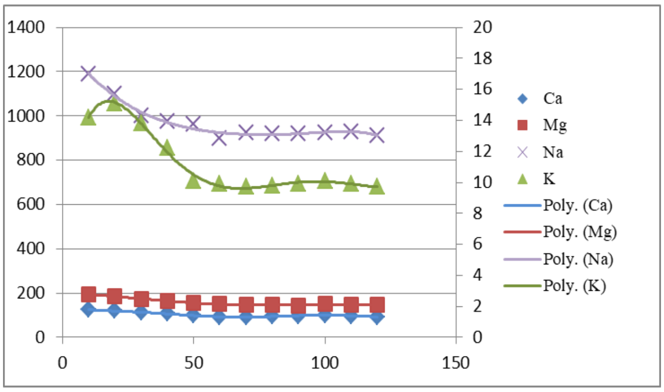

Figure 3. Ca, Mg, K, Na with 5 voltages (No. of frames 18, pH=8.2, time= 120min)

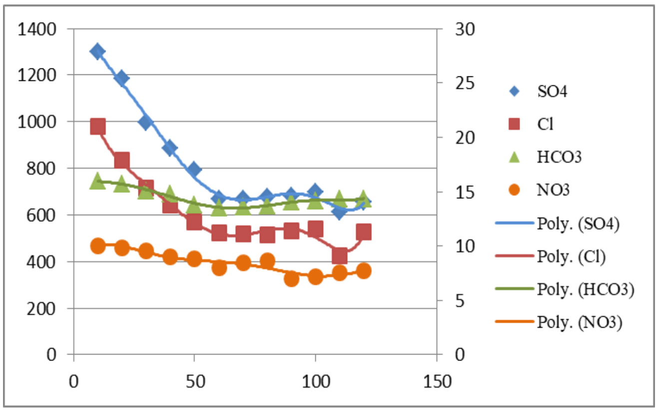

Figure 4. SO_4, Cl, HCO_3, NO_3 with 5 voltages (No. of frames 18, pH=8.2, time= 120min)

The chemical bonds of the pollutants can be weakened by an increase in the number of free electrons caused by a higher current density [33]. Because of this, it's not hard for metal ions to form oxide complexes. Complexes of oxides flocculated and precipitated after destabilization. Previous studies have come to the same conclusion. According to Chen et al. [34], voltage and current density are two of the most important factors that could affect the efficiency of the EC process. Compared to high voltage, the removal efficiencies at 10 V are negligible; for Ca, Mg, K, and SO_4, respectively, they are 32%, 37%, 38%, and 32% (Figures 5, 6, 7).

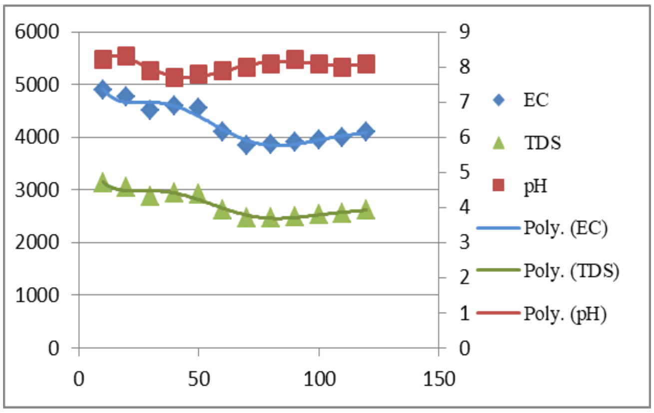

Figure 5. pH, EC, TDS with 10 voltages (No. of frames 18, pH=8.2, time= 120min)

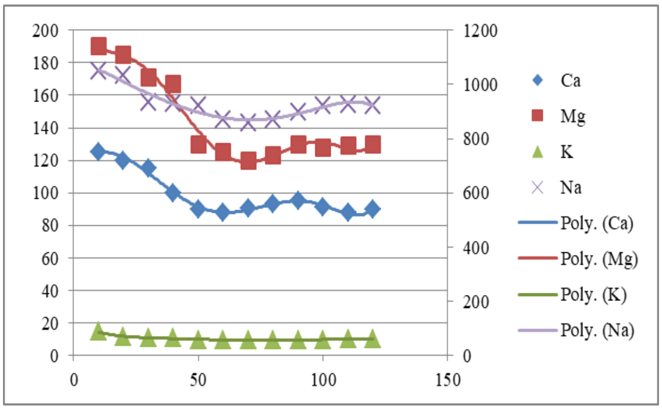

Figure 6. Ca, Mg, K, Na with 10 voltages (No. of frames 18, pH=8.2, time= 120min)

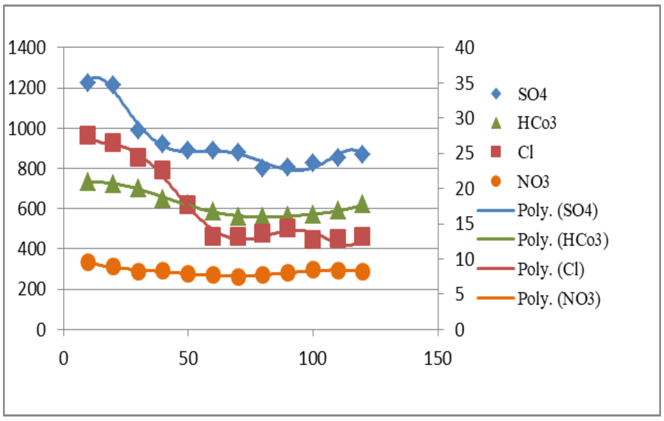

Figure 7. SO_4, HCO_3, CO_3, Cl, and NO_3 with 10 voltages (No. of frames 18, pH=8.2, time= 120min)

To eliminate heavy metal ions, the voltage needs to be increased, and the precise amounts of Al^{+3} and OH produced by the EC process need to be defined more precisely. As the time of electrolyzation grows, the sacrificial anode generates more metal ions, and hydrolysis forms a large number of metal hydroxyl complexes [35]. The removal efficiencies for Ca, Mg, HCO_3, and Cl were 36%, 55%, 23%, and 57%, respectively, when the voltage was raised (Figures 8, 9, and 10).

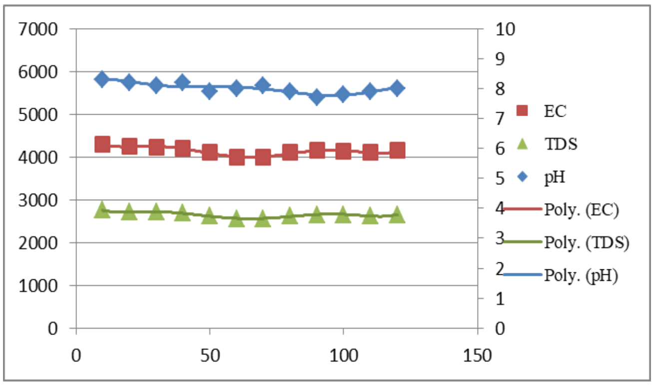

Figure 8. pH, EC, TDS with 15 voltages (No. of frames 18, pH=8.2, time= 120min)

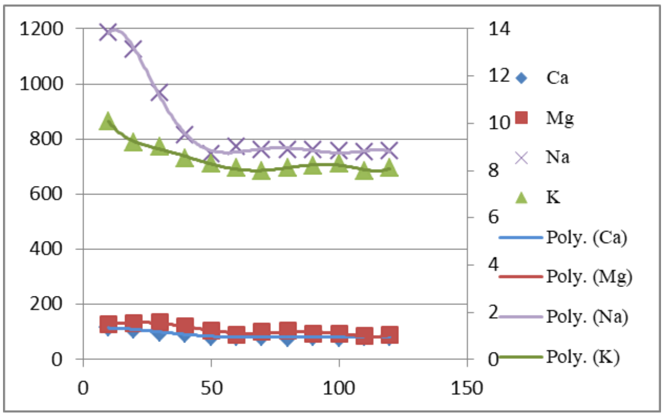

Figure 9. Ca, Mg, K, Na with 15 voltages (No. of frames 18, pH=8.2, time=120min)

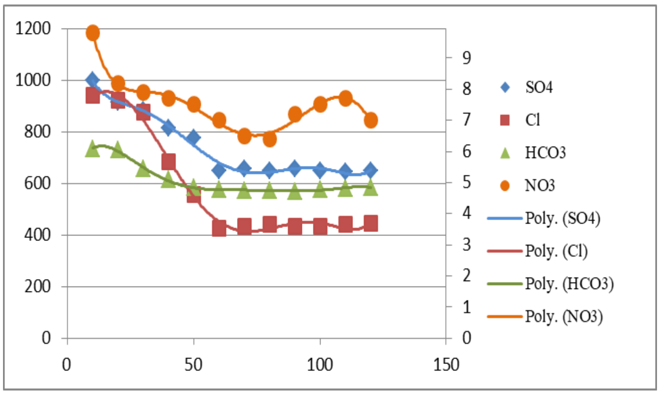

Figure 10. SO_4, HCO_3, CO_3, Cl, and NO_3 with 15 voltages (No. of frames 18, pH=8.2, time= 120min)

The intended impact is achieved as the voltage increases through the production of additional coagulants, specifically Al^{+3} ions [36]. The applied voltage is the most important parameter in electro-flotation operations for controlling the reaction rate [37]. According to Bazrafshan and Mahvi [38], this variable is known to control the amount of coagulant released, which in turn affects the growth of flocs by altering bubble creation. As a result of the voltage rise, the removal efficiency is great. Figures 11, 12, and 13 demonstrate that the removal efficiencies for Mg, SO_4, K, and NO_3 were 60%, 55%, 70%, and 38%, respectively, with a voltage of 20.

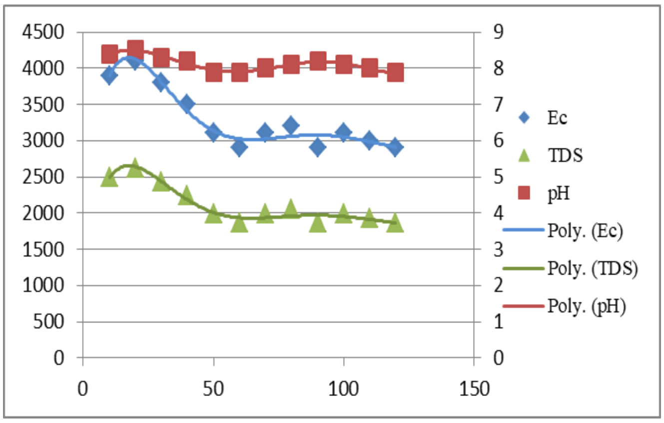

Figure 11. pH, EC, TDS with 20 voltages (No. of frames 18, pH=8.2, time= 120min)

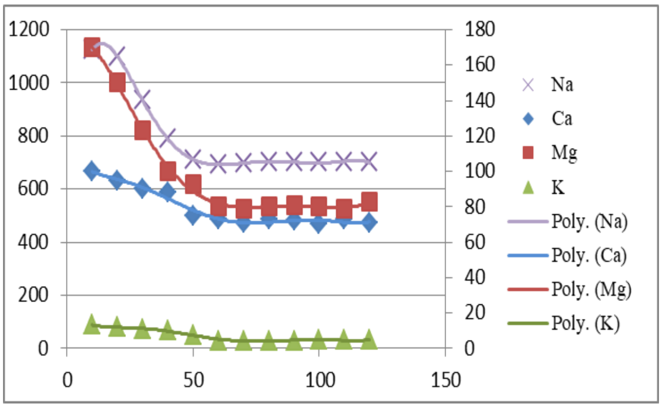

Figure 12. Ca, Mg, K, Na with 20 voltages (No. of frames 18, pH=8.2, time= 120min)

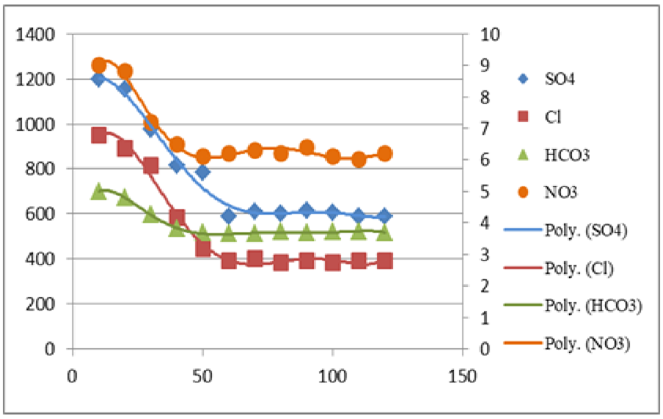

Figure 13. SO_4, HCO_3, CO_3, Cl, NO_3 with 20 voltages (No. of frames 18, pH=8.2, time= 120min)

With an increase in the concentration of total dissolved solids (TDS) in water, there is a direct correlation between the concentration of charged particles in the solution and its electrical conductivity [39]. As a result of the high electrical current passing through the solution at a constant voltage and the formation of a thick layer of scum between the two electrodes, the conductivity value increases [40]. The result is a solution resistance that eventually breaks down [41].

In Figures 14, 15, and 16, the removal efficiencies at a voltage of 25 are displayed. There was an efficiency of 53% for Ca, 70% for Mg, 61% for Cl, and 85% for K removal, respectively.

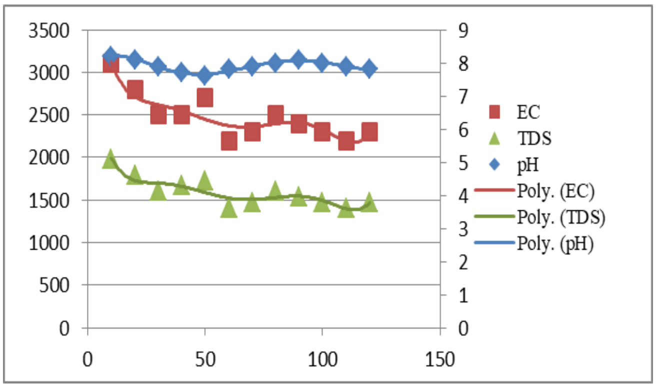

Figure 14. pH, EC, TDS with 25 voltages (No. of frames 18, pH=8.2, time= 120min)

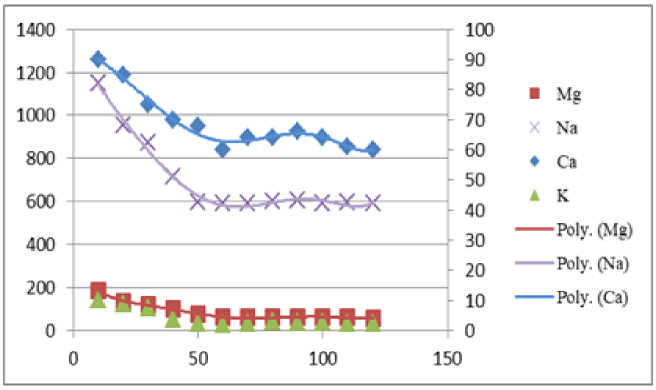

Figure 15. Ca, Mg, K, Na with 25 voltages (No. of frames 18, pH=8.2, time= 120min)

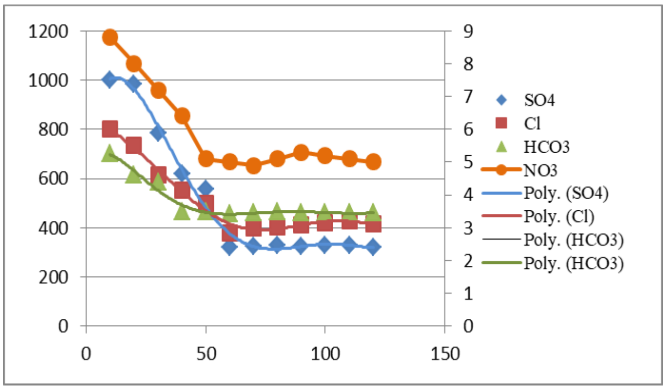

Figure 16. SO_4, HCO_3, CO_3, Cl, and NO_3 with 25 voltages (No. of frames 18, pH=8.2, time= 120min)

Also, the cathode and anode conduct electrical electrons more efficiently due to the presence of metal hydroxyl species, which acts as a bridge [42]. However, according to Mollah et al. [37], a bigger quantity of precipitate is produced when a voltage is applied, which leads to the disappearance of color.

3.2 Effects of the number of frames (distance between electrodes)

Experiments were carried out using fluids that had constant pollution loading and inter-electrode distances of 0.5 cm. The number of frames was 18, and the effect of electrode distance on removal effectiveness was evaluated. Figures 17, 18, and 19 show how the interelectrode spacing affects the efficiency of metal ion removal.

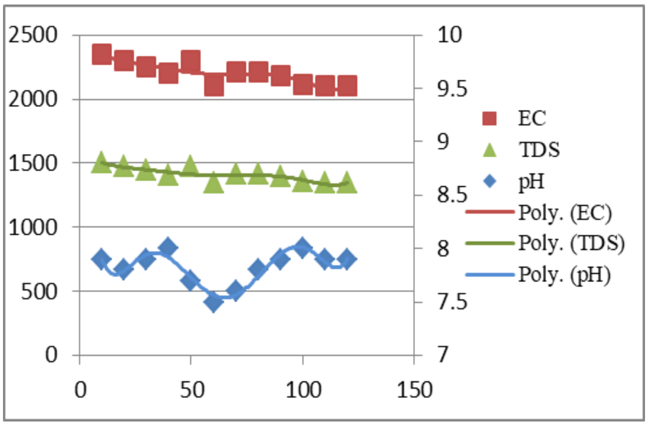

Figure 17. pH, EC, TDS with 30 voltages (No. of frames 18, pH=8.2, time= 120min)

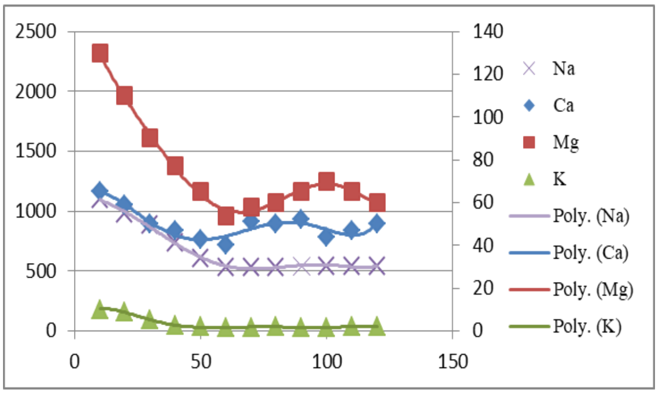

Figure 18. Ca, Mg, K, Na with 30 voltages (No. of frames 18, pH=8.2, time= 120min)

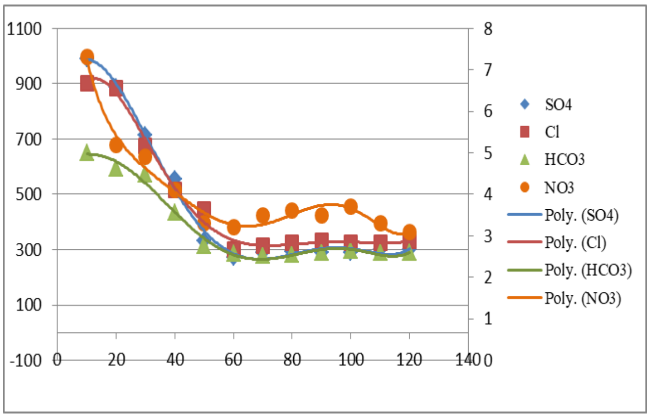

Figure 19. SO_4, Cl, HCO_3, NO_3 with 5 voltages (No. of frames 18, pH=8.2, time= 120min)

Ions will move more quickly with a smaller gap between them since their journey is shorter; this increases the likelihood that they will collide and generate OH radicals [43]. Ohmic resistance also drops when distance drops [44].

The removal efficiency of ions was 73% for Mg, 79.3% for SO_4, 89% for K, and 68.3% for NO_3. Furthermore, the Electric Field Equipotential lines—responsible for ion dissolution, H_2 gas generation, and TDS conversion to scum will become denser and more intense as the inter-electrode distance decreases [45]. Therefore, we concluded that 0.5 cm was the sweet spot for our experiments.

The elimination effectiveness of contaminants with the number of frames 9 is shown in Figures 20, 21, and 22. Reducing the number of frames affects the removal efficiency. As the distance increases, the electric flux lines become less straight, and no amount of voltage can improve the removal efficiency. Thus, the optimal pH range for iron EC is determined to be 5-9. The removal efficiency of ions was 48.46% for Ca, 62.5% for Mg, 68.2% for SO_4, 75% for K, and 46.6% for Na. The effluent must meet specific conductivity standards for use in electrochemical treatment systems [46]. As shown in Figures 23, 24, and 25, the removal effectiveness drops significantly as the distances between the electrodes increase. When the number of frames decreased to 5 frames, the removal efficiency decreased; it became 55% for Mg, 47.38% for SO_4, 57.57% for Cl, 64.51% for K, and 39.58% for NO_3.

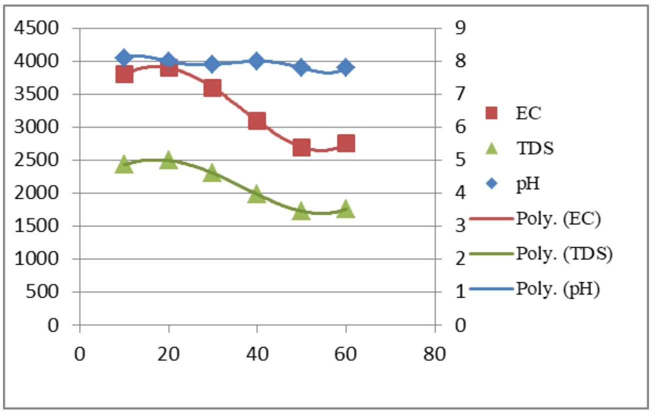

Figure 20. pH, EC, TDS with 30 voltages (No. of frames 9, pH=8.2, time= 60min)

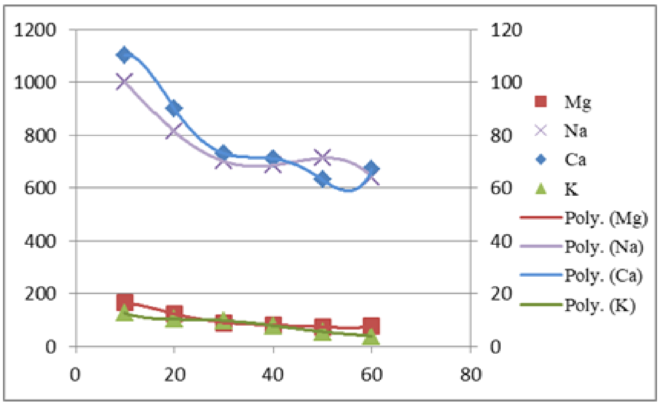

Figure 21. Ca, Mg, K, Na with 30 voltages (No. of frames 9, pH=8.2, time= 60min)

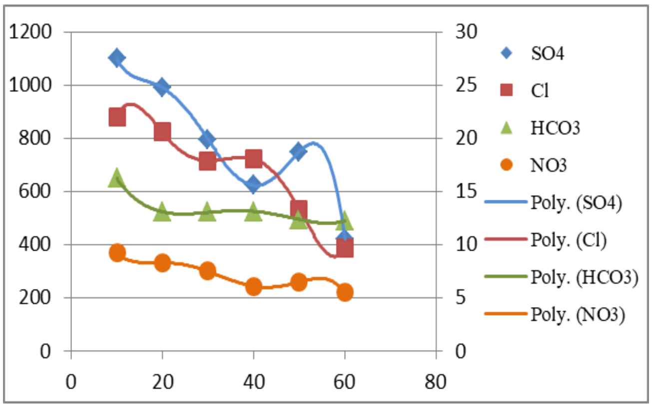

Figure 22. SO_4, HCO_3, CO_3, Cl, NO_3 with 30 voltages (No. of frames 9, pH=8.2, time= 60min

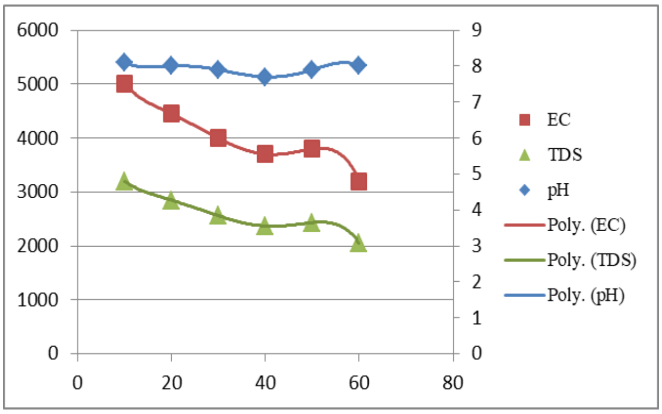

Figure 23. pH, EC, TDS with 30 voltages (No. of frames 5, pH=8.2, time= 60min)

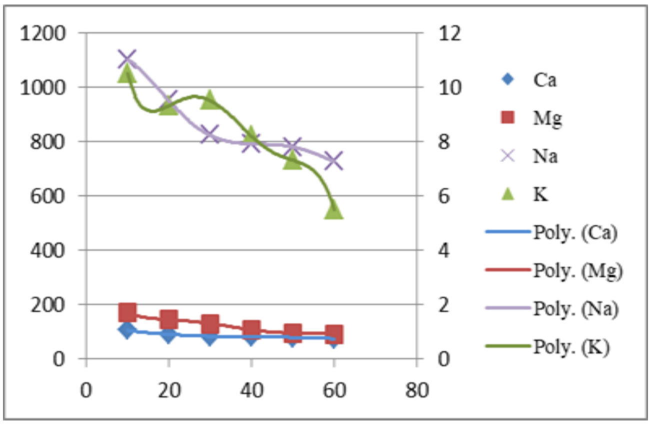

Figure 24. Ca, Mg, K, Na with 30 voltages (No. of frames 5, pH=8.2, time= 60min

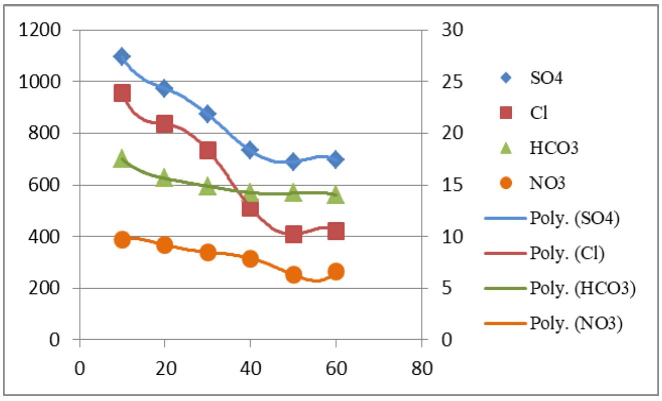

Figure 25. SO_4, HCO_3, CO_3, Cl, NO_3 with 30 voltages (No. of frames 5, pH=8.2, time= 60min

3.3 Effects of pH

Parthasarathy and Narayanan [47] found that metal hydroxide complexes dissolve at high pH 9-12 because of an aphorism. Because these free OH radicals are recombined with H+ radicals, the generation of H_2 gas and its bubbles will diminish. As a result, the rate of ion dissociation will slow down, and the electro-flotation process will not work as well [48]. Effects of starting pH and electrolysis duration on heavy metal removal efficiency. The electrocoagulation process relies heavily on pH as an operational parameter. The first influence of pH was investigated at 30 V with pH values of 5, 8.2, and 12. The removal efficiencies for Ca, Mg, HCO_3, K, Na, SO_4, Cl, and TDS were 61%, 80%, 62%, 85%, 51%, 85%, 76%, 72%, and 76% respectively, as shown in Figures 26, 27, and 28. Because of batch EC, the pH changed. Variables such as pH can affect the coagulant species that form during the coagulation process. The optimal conditions for pollutant removal were a potential difference of 30 V, a detention time of 60 minutes, 18 frames, and a pH of 5. As a result of ionic species adsorption, the heavy metal removal effectiveness is impacted by the starting metal ion concentration charge of the aluminum hydroxide precipitates [36].

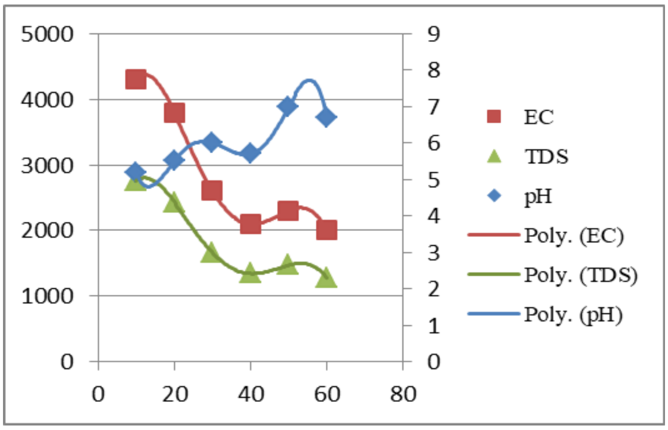

Figure 26. pH, EC, TDS with 30 voltages (No. of frames 18, pH=5, time=60min)

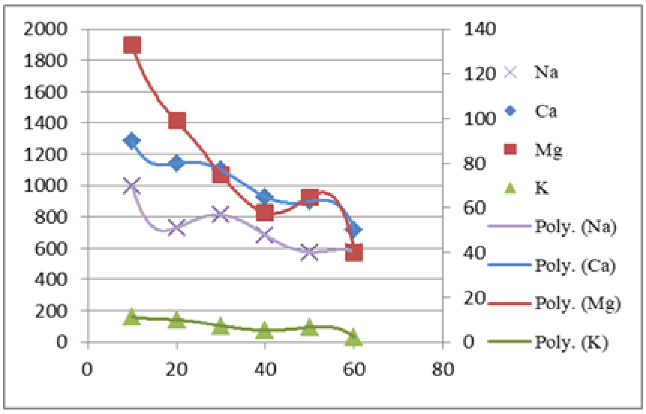

Figure 27. Ca, Mg, K, Na with 30 voltages (No. of frames 18, pH=5, time=60min)

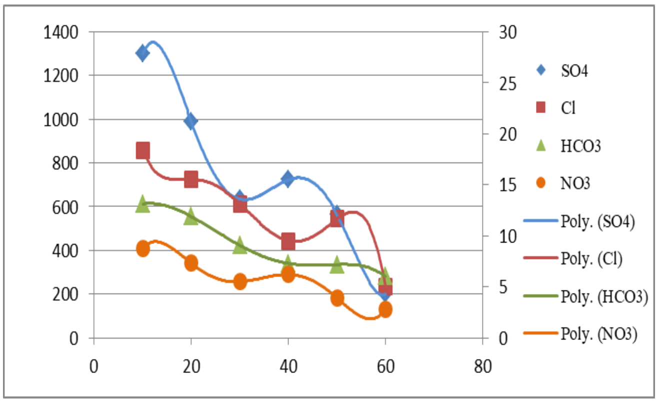

Figure 28. SO_4, HCO_3, CO_3, Cl, NO_3 with 30 voltages (No. of frames 18, pH=5, time=60min)

Figures 29, 30, and 31 show that the removal effectiveness is quite poor when the pH is 12. The removal efficiency was 57%, 70%, 77%, 55.6%, and 65.3% for Ca, Mg, SO_4, HCO_3, and NO_3. Therefore, the alkalinity is decreasing the removal efficiency, and the acidity is increasing it.

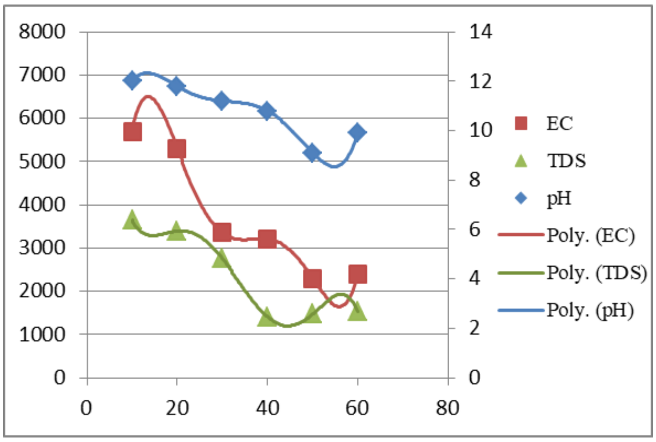

Figure 29. pH, EC, TDS with 30 voltages (No. of frames 18, pH=12, time=60min)

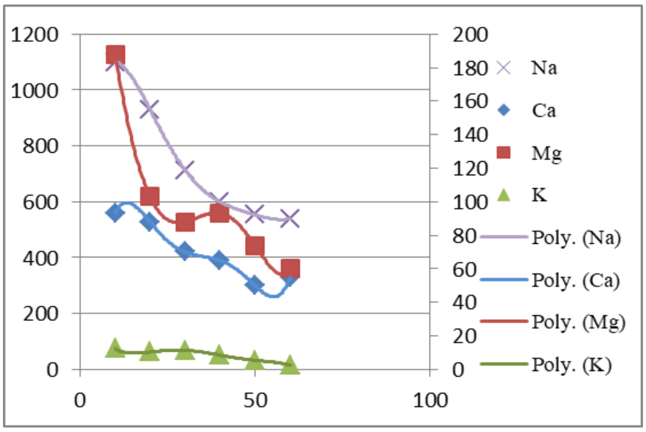

Figure 30. Ca, Mg, K, Na with 30 voltages (No. of frames 18, pH=12, time=60min)

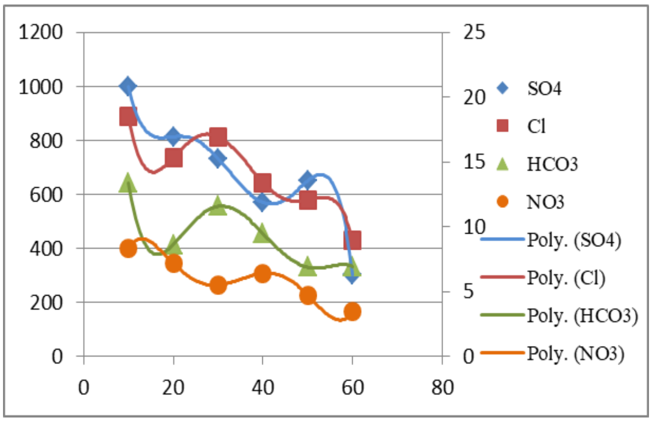

Figure 31. SO_4, HCO_3, CO_3, Cl, NO_3 with 30 voltages (No. of frames 18, pH=12, time=60min)

3.5 Kinetics models

The research suggests that a pseudo second-order model, rather than a pseudo first-order model, is more appropriate for describing a diffusion-controlled process. The values of R^2 for the first pseudo and second pseudo are 0.92 and 0.91, respectively, as shown in Figures 32(A) and 32(B). The pseudo-first-order kinetic model for SO_4 adsorption onto aluminum hydroxide and the K adsorption onto the same material is well supported by both theoretical and experimental evidence.

The data indicate that SO_4 is more effectively removed than K. Similar to previous research that found a first-order kinetic model to be well-correlated with elements, this study found that a second-order model was better suited to K elimination. The pseudo-first-order model for removing K from an aqueous solution has been described in other works [49, 50].

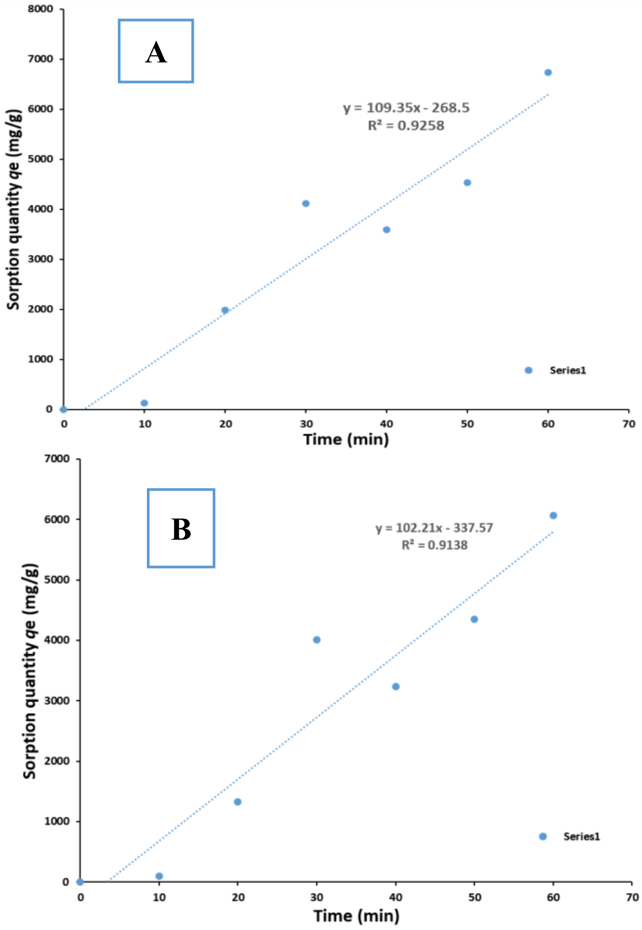

Figure 32. (A) The first pseudo and (B) Second pseudo for SO_4 and K elements

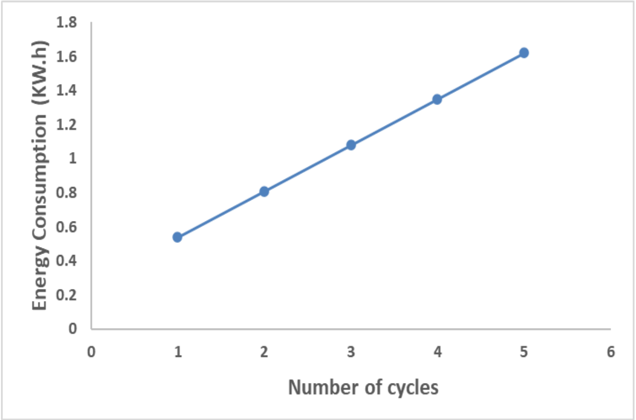

Figure 33. The relation between energy consumption number of cycles

3.4 The energy consumption

It was determined that the energy consumption increases with the cycles, as shown in Figure 33. This could be explained by the increase in the thickness of the passivation layer. The power requirement of the EC process for a 6 L setup starts from 0.4 kW and increases per cycle by approximately 0.45 KW. Using this model, by the end of the fifth cycle, the approximate power requirement of the EC process is 1.67K W, or equivalent to about a 200% increase, in which a solar panel is utilized in the electrocoagulation approach to be considered as an economic method for treating groundwater pollution [51].

Finally, when compared to other types of treatments such as membrane infiltration and chemical precipitation. It is found that electrocoagulation improves the cleanliness of most groundwater streams while reducing operational costs and sludge production.

One such method that is widely used, very dependable, and economical is EC. It produces less sludge than other methods and has a high efficiency in removing pollutants. Many different kinds of water and pollutants have been successfully treated using electrocoagulation: Industrial Wastewater: It is highly effective in removing organic chemicals, oils, and heavy metals from wastewater that originates from businesses including food processing, textile manufacturing, and petroleum refining.

Reliable and cost-effective water treatment technologies have sparked a resurgence of interest in electrocoagulation. The coagulant is broken down anodically on-site, and then iron (or aluminum) hydroxides with a high sorption capacity are made by a cathodic reaction happening at the same time. Pollutants can be removed by depositing them on the cathode electrode or letting them float (hydrogen evolution). In conventional chemical precipitation, on the other hand, settling is the main way that pollutants are removed. This is usually done by adding a basic salt that mixes with dissolved pollutants to make compounds that are not soluble. Electrocoagulation does not increase the concentration of salts or make more anions, which is different from chemical metal precipitation. As a result, electrocoagulation yields more compact metallic sludges than chemical precipitation does. Electrolytic treatment has low operating expenses in large-scale applications because of its inexpensive equipment, short retention period, and straightforward operation.

4. CONCLUSIONS

After implementing a solar-powered electrocoagulation system (SPEC) with iron electrodes to treat groundwater at the Al-Raaed station in Abu-Garib, Baghdad, Iraq, the following findings were achieved:

1- The current study shows that employing a battery for lab-size batch SPEC is a very successful method.

2- At a potential difference of 30 V and an electrode distance of 0.5 cm, the removal efficiencies for Ca, Mg, HCO_3, K, Na, SO_4, Cl, and TDS were 61%, 80%, 62%, 85%, 51%, 85%, 76%, 72%, and 76% respectively. The optimal conditions for pollutant removal were a potential difference of 30 V, a detention time of 60 minutes, 18 frames, and a pH of 5.

3- Preliminary results indicate the feasibility of using SPEC for irrigation water treatment.

Thus, the SPEC method is currently getting a lot of interest in treatment because of its adaptability and lack of negative effects on the environment. Since SPEC is so effective at removing a wide variety of contaminants. Electrical current (DC) is drawn from photovoltaic (PV) panels and stored in batteries. Using solar power makes EC therapy more efficient and lowers the treatment cost. For different contaminants, clearance efficiencies of up to 85–95% have been recorded. SPEC is a practical, cost-effective, and energy-efficient method for treating a range of groundwater pollution in the experiments mentioned above. Interest in SPEC is on the rise as a result of encouraging outcomes.

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