Indian Journal of Advances in Chemical Science

Article

Defluoridation of Drinking Water in Batch and Continuous-flow Electrocoagulation Techniques

C. Krupavathi, S. Srinivasa Gowd*

Department of Geology, Yogi Vemana University, Kadapa, Andhra Pradesh, India

ABSTRACT

The purpose of the research sought to assess the elimination of fluoride through drinking water by electrocoagulation (EC) in batch or continuous-flow reactors with a variety of usage circumstances. The implications of altering applied voltage, initial concentration, and initial pH on fluoride elimination effectiveness have been studied utilizing mild steel electrodes. The findings with distilled water and groundwater have been compared. The best F^- efficiency of elimination through distilled water was 84.9% and 79.4% in batch and continuous mode, accordingly, under the maximum applied voltage of 25 V. The elimination effectiveness through groundwater was 79.6% and 28.7% in batch and continuous modes, correspondingly. Despite minimal F^- content levels of 10 mg/L and initial pH values that varied between 5 and 10, the final pH ranged from 6.35 to 7.96, demonstrating the superiority of EC over traditional coagulation for drinking water treatment. The highest F^- elimination effectiveness of 84.9% was noticed under an initial pH of 6.42. Raising the level of fluoride from 20 mg/L to 50 mg/L caused a pH rise regardless of the voltage used. Thus anticipated, increased starting F^- concentrations contributed to lower F^- effectiveness in elimination. These findings highlight the significance of starting F^- contents in determining both the final pH of treated water and F effectiveness in elimination.

Key words: Electrocoagulation, Fluoride, Distilled water, Mild steel.

1. INTRODUCTION

Energy and water are currently considered to be the most significant global issues during the twenty-fourth century [1-4]. Both the quantity and quality of water have been harmed through rising pollution, especially in India. In contrast to earlier times where surface water is the main source of water, India currently relies more on groundwater to provide irrigation and drinking water [5,6]. Fluoride and nitrate are typical groundwater contaminants that originate mostly from natural and manmade sources. The most severely impacted locations in the country are rural communities with inadequate essential facilities for water delivery and treatment. Various particular procedures to eliminate such contaminants exist, including coagulation, chemical precipitation, electrocoagulation (EC), adsorption, and ion exchange. Creative, low-cost, decentralized, and effective techniques of purifying groundwater for consumption by people are required, particularly in rural regions, and EC is one such treatment strategy.

1.1. EC

EC involves injecting an electric current into an aqueous media to destabilize and/or oxidize suspended or dissolved pollutants [7-10]. The anode, sometimes known as the sacrificial' electrode, dissolves during EC as a result of current flow. Subsequently is typically made of metals such as aluminum or iron. Dissolving the anode leads to the creation of metal cations, as stated in equation 1.

Metal cations create polymeric metal hydroxides (equation 3), comparable to coagulant salts including alum and ferric chloride in traditional chemical coagulation. Cations and similarly charged polymeric metal hydroxide compounds are capable of neutralizing negatively charged substances or substances [11]. Neutralized particles can link collectively and create aggregates or flocs, effectively removing pollutants [12].

$$M_{a\rightarrow} M_a^{n+} + ne^- \quad (1)$$

$$2H_2O \rightarrow 4H^+ O_2 \uparrow +4e^- \quad (2)$$

Cathode: deposition of metal oxide layer

$$M_a^{n+} + \left(OH^-\right)_n \rightarrow M^a\left(OH\right)_n \quad (3)$$

$$2H_2O + 2e^- \rightarrow H_2 \uparrow +2OH^- \quad (4)$$

The EC technique eliminates the need for chemical coagulants and flocculants, leading to less sludge production [13,14]. Throughout electrolysis, gas bubbles may carry contaminants to the solution's surface, allowing for easy concentration, collection, and removal. EC involves little maintenance due to its electrical control and lack of mechanical components. As brief, the EC technique combines coagulation, electroflotation, and electrooxidation in one unit.

***Corresponding author:**
S. Srinivasa Gowd,
E-mail: ssgowd@gmail.com

ISSN NO: 2320-0898 (p); 2320-0928 (e)
DOI: 10.22607/IJACS.2024.1201007

Received: 10th October 2023;
Revised: 28th December 2023;
Accepted: 02th January 2024

1.2. Fluoride in Drinking Water

Fluoride contamination is a major issue in India and globally. Indian regulations prescribe an acceptable fluoride value of 1 mg/L [15,16]. In some areas of India, individuals consume groundwater, vegetables, and other foods that contain greater concentrations of fluoride as recommended. According to Khyalia *et al*. [17], agricultural products from Andhra Pradesh in India may have fluoride levels that vary between 0.2 and 11 mg/kg.

To remove fluoride from drinking water at a low cost, a technologically efficient treatment technology is necessary [18,19]. Multiple research studies have shown that EC is able to defluoridate water. Two of the investigations utilized continuous flow systems and Al electrodes. The scientific literature does not provide a systematic comparison of F^- elimination effectiveness in batch and continuous flow reactors utilizing Fe electrodes [20]. Four of the 12 examined research used real water, and one compared the efficiency of F^- elimination with synthetic and real water samples.

The current study aimed to assess the removal of fluoride through drinking water utilizing EC in batch and continuous-flow reactors under various operating circumstances. The efficiency of eliminating fluoride was investigated using different voltage, content, and pH settings. They evaluated fluoride elimination effectiveness between double-distilled water solutions and groundwater from a deep tubewell. During every experiment, the pH, conductivity, turbidity, sludge production, and electrode dissolution had been observed. The occurrence of F in several phases (supernatant, sludge, and electrode deposition) was investigated.

2. MATERIALS AND METHODS

2.1. Collection of Water Samples

Fluoride compounds have been produced with double-distilled or ground water. Groundwater samples have been obtained through a tubewell at this region. The tubewell has a depth around 250 ft.

2.2. Experimental Configuration and Technique for EC Batch Reactors

Figure 1 shows the EC batch reactor, which was a 1 L glass beaker. Two iron electrodes (14.5 cm × 2.5 cm × 0.1 cm) with a 9 cm immersion depth and 3 cm inter-electrode spacing had been utilized. The electrodes had been attached to a transformer with an ability of 0–30 volts and 0–3 amps that converted AC current to DC. Research took place using voltages of 10V, 15V, 20V, and 25V. Experiments had been recorded for conductivity, pH, and turbidity. The supernatant at the reactor's surface has been gathered as periodically and kept in test tubes. The residual samples had been passed through 47 mm diameter cellulose nitrate sheet using nominal pore size of 0.45 mm (Whatman India).

Figure 1: An EC batch reactor and experimental equipment were used to eliminate fluoride.

2.3. Sampling

This is involved circulating electricity for 180 min and swirling continuously through a magnetic stirrer. Samples are taken through the reactor's top every 15, 30, 45, 60, 80, 100, 120, 150, and 180 min.

The samples had been evaluated for pH, turbidity, conductivity, and fluoride. In trials utilizing groundwater, samples have been taken each 20 min in the 4^{th} h.

2.4. Experimental Setting and Technique for an EC Continuous Flow Reactor

The continuous-flow EC reactor measures 36 cm × 12 cm × 11.5 cm and has a volume of 4 L [Figure 2]. The experiment utilized two mild steel electrodes measuring 14.5 cm × 2.5 cm × 0.1 cm, having a 10 cm immersion level and 3 cm inter-electrode interval. The electrodes had been attached to a transformer with an ability of 0–30 volts and 0–3 amps, which converted AC current to DC. A peristaltic pump (Miclins India, Model No. PP 30) was utilized to manage the flow rate to the reactor. The EC procedure took place about 6 h at a flow rate of 1 L/h. Fluoride solutions were produced utilizing purified water or groundwater containing 10 mg/L of fluoride. During 30 min, samples are taken through the reactor outflow to test pH, conductivity, turbidity, and fluoride levels. The samples had been passed through 47 mm diameter cellulose nitrate sheet having a nominal pore size of 0.45 micrometers (Whatman India).

3. ANALYTICAL METHODS

The investigation employed just high-quality analytical chemicals and prepared solution stocks using double-distilled water. A stock solution of 100 mg/L sodium fluoride has been created in double distilled water and applied with the water used for feeding as needed.

3.1. pH, Turbidity, and Conductivity

The pH of every sample has been determined by a digital desktop pH meter (Labquest, Vernier International, USA) calibrated utilizing a pH 7 buffer solution (Merck India). Conductivity has been determined with a digital conductivity meter (Model: YK-22CT, Lutron). Turbidity has been measured using a digital turbidity meter (Model 331, Electronics India). pH changed with NaOH and HCl solutions.

3.2. Sludge Collection

Sludge had been passed through using 0.45 micrometer filter paper (Filter paper No. 42, Whatman India) and weighed. Weighing the sludge after 24 h of drying at 110°C served to figure out its mass.

3.3. Electrode Consumption

Electrode weight was obtained before and after each experiment. Throughout EC, the anode weight decreased while the cathode weight increased. To conduct the research, the electrodes were turned upside down and sandpapered before every test.

3.4. Fluoride Analysis

Fluoride content has been measured by an ion-selective fluoride electrode (Orion, USA). Fluoride content is unable to detected without filtering due to the excellent sensitivity of the Orion 4 Star electrode (Thermo Electron Corporation, USA), which is capable of measuring up to 15 mg/L.

4. RESULTS AND DISCUSSIONS

4.1. Fluoride Reduction using an EC Batch Reactor

Using EC batch tests, three operating factors have been investigated for the elimination of fluoride effectiveness. Voltage used, initial concentration, and initial pH. Aside from fluoride, pH, and turbidity, conductivity was evaluated throughout each experiment. Assessment of sludge generation and electrode dissolution has been carried out for every test.

4.2. Effect of Applied Potential

The electrochemical cell's voltage primarily determines the pace of coagulant formation and pollutant elimination. To ensure consistency, the current delivered to the electrodes was consistent throughout each trial. Figure 3 illustrates the impact of applied voltage on fluoride elimination rate with a level of 10 mg/L. Increasing the potential being used between 10 V and 25 V resulted in an increase in elimination of fluoride between 57% and 84.9%. Increasing the voltage being applied causes more current to flow via the reactor, leading to faster anode dissolution, as per Faraday's law. Biswas and Sudha [21] found that dissolving the metal anode causes the creation of cationic coagulating ions, such as metal oxides and hydroxides. This raises the quantity of iron hydroxide accessible in the solution to generate complexes and precipitate the ions.

4.3. Conductivity

As depicted in Figure 3, conductivity fluctuated during the trial period. Conductivity in the supernatant ranged from 0.045 mS/m at 25 V to 0.062 mS/m following 180 min at 10 V. The maximum number of coagulant ions is probably generated at 25 V, leading to increased floc production and settlement. Floc settling and removal from the supernatant may reduce ion concentrations. In more voltages, conductivity decreases relative to lower voltages.

4.4. pH and Turbidity

Table 1 summarizes the findings of pH monitoring in the EC reactor at various voltages throughout experiments 1–4. The starting pH ranged from 6.42 to 6.70 across all four voltages, with a final pH range of 6.87–7.26. The turbidity of the reactor supernatant increased over time at all applied voltages, as seen in Figure 4. As coagulant production rises over time, the development of floc also rises. The ultimate turbidity varied with applied potential, from 1.4 NTU at 10 V to 4.2 NTU at 25 V.

4.5. Effect of the Initial Concentration

Experiments were performed at the highest voltage of 25 Volts; with starting levels of fluoride varying between 10 and 50 mg/L. Table 1 summarizes the findings from experiments 4 to 8. At beginning levels of 10 mg/L and 50 mg/L, the highest effectiveness of elimination was 84.9%, while the lowest rate is 63.59%.

4.6. Conductivity

In the run, the conductivity of the reactor supernatant was measured at various intervals. Conductivity fluctuated initially but gradually rose through time. During an EC procedure, the dissolution of the anode causes the current to grow according to conductivity, whereas resistance decreases while the voltage remains steady. During the experiment, conductivity improved as ions were generated in the solution. At 25 V, the final conductivity is 0.045 mS/cm for initial concentrations of 10 mg/L and 0.271 mS/cm considering beginning concentrations of 50 mg/L.

4.7. pH and Turbidity

Table 1 summarizes the results of evaluating pH changes with varying initial levels. The initial pH measured between 6.31 and 6.92 for doses of 10–50 mg/L. The final pH varied more in every case, ranging from 7.26 for 10 mg/L to 9.39 for 50 mg/L. The EC procedure converts water to hydrogen gas and hydroxyl ions, leading to an alkaline solution. EC and typical coagulation vary in that the earlier raises or preserves neutral pH, while the other reduces it. Turbidity rose at increasing starting levels, primarily due to floc formation in solution during EC.

4.8. Effect of Initial pH

Initial pH significantly impacts fluoride elimination effectiveness and final water quality. Experiments have been carried out using double-

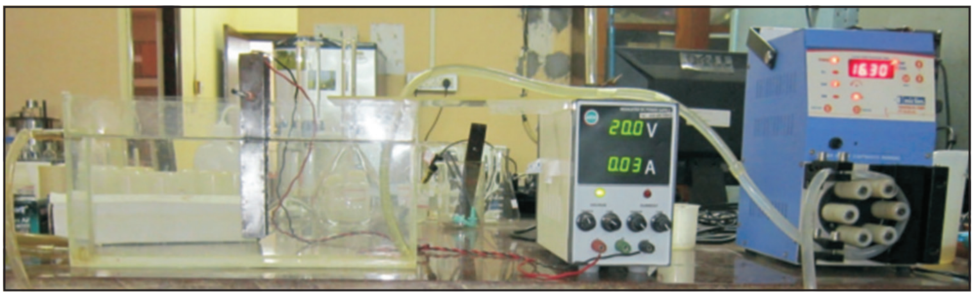

Figure 2: Experimental configuration of continuous flow electrochemical procedure.

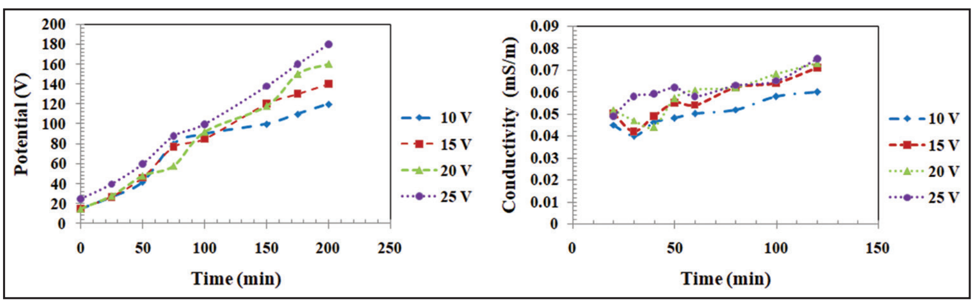

Figure 3: The study investigates the impact of applied voltage on the removal of fluoride in an EC batch reactor, examining the variation in conductivity over time of 10 mg/L.

distilled water, an initial fluoride content of 10 mg/L, a voltage of 25 V, and altering the initial pH between 5 and 10. Table 2 summarizes the data and underlines the benefits of EC over conventional coagulation. In CC, adding coagulant lowers the pH of the solution, requiring neutralization to reach an acceptable level, But 2 distinct events have been noticed in EC.

a. All trials showed an increase in pH, regardless of the baseline pH [Table 1]. Increasing the starting level caused larger variations in pH than increasing the applied voltage. The treated water was alkaline at starting quantities ≥ 10 mg/L. The findings are comparable with those for nitrate [22]. Few research using EC and fluoride have looked at the impact of beginning pH on end pH levels. Abdullah *et al*. (2023) all found that EC treatment led to a rise in final pH.
b. Whenever the initial pH is acidic, the treated solution pH (final pH) increases to around 7, whereas if the original pH is alkaline, the final pH decreases to around 7, as indicated in Table 2. Abdullah *et al*. (2023), Gupta and Sharma (2023), Sandoval *et al*. (2024) observed comparable findings while treating restaurant effluent by EC and distilled water laced with clay (kaolinite) [23-25].

The study discovered that the pH level that remains following treatment varies depending on the initial level of pollutants and type. These findings have important consequences regarding removing fluoride from drinking water. Fluoride contents in Indian groundwater can reach up to 15 mg/L in West Bengal [26]. However, doubtful that pH changes will have a substantial impact on F levels in Indian ground waters or their treatment. Initial pH may play a significant role in removing F from sewage in significant amounts.

Two experiments were conducted using double distilled water and groundwater, with the identical settings of 25 V applied voltage and an initial fluoride content of 10 mg/L. The mean level of fluoride in groundwater is 0.493 mg/L, with a further 10 mg/L applied for EC studies. The groundwater sample exhibited an initial pH of 9.17, 122.63 mg/L of total dissolved solids, and 7.7 NTU of turbidity. Figure 4 shows no significant difference in fluoride removal effectiveness between double-distilled and groundwater. The results show a minor elimination of fluoride from distilled water.

The results showed no significant difference in fluoride elimination efficiency between double distilled and groundwater, as illustrated in Figure 4. The results show that distilled water has a slightly greater fluoride elimination percentage (84.9%) than GW. Groundwater elimination rate reached 79.7% using an initial concentration of 10 mg/L and a final concentration of 2.03 mg/L. Groundwater elimination rate is slightly lower than double distilled water due to the existence of additional anions besides fluoride.

Table 1: Summary of results for fluoride removal in an EC batch reactor.

Experiment Number	Applied Voltage (V)	Co (mg/L)	Cf (mg/L)	F Removal efficiency %	Initial pH	Final pH	Change in pH	Initial Turbidity (NTU)	Final Turbidity (NTU)	Electrode Consumption (mg Fe/L)	Iron dissolved (mg Fe/mg F removed)	Sludge Production (kg/m^3)
Distilled water												
1	10	10	4.3	57	6.53	7.1	0.57	0	1.4	70	12.28	0.13
2	15	10	3.21	67.9	6.7	7.11	0.41	0	2.3	70	10.31	0.06
3	20	10	2.72	72.8	6.46	6.87	0.41	0	3.7	60	8.24	0.24
4	25	10	1.51	84.9	6.42	7.26	0.84	0	4.2	120	14.13	0.34
5	25	20	4.83	75.85	6.31	8.43	2.12	0.4	4.2	190	11.96	0.44
6	25	30	8.98	70.07	6.51	8.98	2.47	0.6	5	260	11.52	0.64
7	25	40	13.91	65.23	6.92	9.28	2.36	1.2	5.2	360	11.69	0.58
8	25	50	18.2	63.6	6.6	9.39	2.79	1.1	6.1	670	17.29	0.7
Ground water												
9	25	10	2.04	79.6	7.69	10.97	3.28	4.3	9.1	870	109.3	-

5. ANALYSIS OF ELECTRODE DEPOSITS AND SLUDGE USING

5.1. EDX

Energy-dispersive X-ray spectroscopy (EDS or EDX) determines a sample's composition of elements. Electrode deposits and sludge were analyzed using EDX following EC treatment.

5.1.1. EDX for electrodes

Electrochemical reactions (EC) dissolve the anode and deposit metal oxides on the cathode. After a batch experiment at 25 V with double-distilled water, EDX analysis was performed on the electrode deposits generated by sandpapering the two electrodes to identify their element content. Research indicates that both electrodes experience considerable adsorption of F during EC. The results of our research's

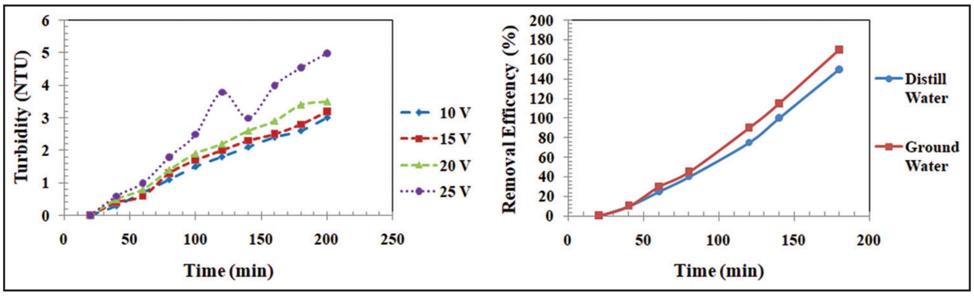

Figure 4: The study investigates the impact of applied voltage on the removal of fluoride in an EC batch reactor, examining the variation in conductivity over time of 10 mg/L.

Table 2: Variation in removal efficiency of fluoride with varying initial pH in an EC batch reactor.

Initial pH	Final pH	Change in pH	F Removal efficiency %	Initial Turbidity (NTU)	Final Turbidity (NTU)	Electrode Consumption (mg Fe/L)	Iron dissolved (mg Fe/mg F removed)	Sludge Production (g/L)
5	7.03	2.03	65.9	10	3.41	150	22.762	0.213
6	6.35	0.35	78.8	10	2.12	140	17.766	0.275
6.42	7.26	0.84	84.9	10	1.51	140	16.49	-
7	7.4	0.4	81.8	10	1.82	-	-	-
8	7.61	0.39	79.6	10	2.04	-	-	-
9	7.96	1.04	73.9	10	2.61	370	50.068	0.263
10	7.4	2.6	69.1	10	3.09	150	15.353	-

spectrum analyses reveal the existence of Fe, O, C, and Si deposits on both electrodes. The cathode deposits had a reported concentration of 0% and showed an F peak. The findings indicate that F levels in electrode deposits fell under the detection limit of 0.1% by weight for both electrodes.

5.1.2. EDX of sludge

After the EC experiment, the reactor fluids had been passed through cellulose filter paper (No. 42, Whatman India) and dried at 110ºC for a single day. The filter's dry solids have been obtained and examined with EDX.

The sludge had four primary substances: Iron, oxygen, fluorine, and sodium. The existence of iron has occurred through electrode dissolving, oxygen by oxide and hydroxide precipitation, and sodium and fluoride by adding sodium fluoride to the original solution. Table 3 summarizes the relative distribution of the elements.

Table 3: EDX of sludge.

Element	Weight %	Atomic %
O	32.1	56.85
F	5.79	8.64
Na	4.15	5.11
Fe	57.95	29.4
Total	100	100

5.2. Mass Balance

A basic mass balance was performed around the EC batch reactor using a 1 L solution. Assume no fluoride was generated or consumed.

$$\text{Mass accumulated in Sludge} = F^{-}\text{mass in} - F^{-}\text{ mass out}$$
$$(\text{supernantant}) - F^{-}\text{mass adsorbed } (\text{both electrodes})$$

Initially, a 10 mg/L fluoride concentration had been produced in double distilled water. The final concentration of fluoride in the supernatant was 1.51 mg/L. The amount of sludge generated was 0.1461 g/L. The EDX results indicate that fluoride made up 5.79% of the sludge weight. The fluoride concentration in the sludge was determined to be 8.459 mg, calculated as

$$0.1461 \times 0.0579 \text{ g } (0.008459 \text{ g})$$

The mass balance calculation indicates that the output contains 9.969 mg of fluoride, compared to a total of 10 mg. By this point in time, there is no major disparity between fluoride input and outcome, indicating that the mass balance is complete. Our analysis found not any significant or quantifiable F adsorption on the electrodes, as evidenced by the mass balance.

5.3. EC in the Continuous Flow Reactor for Fluoride Removal

5.3.1. The effect of applied voltage

Experiments have been performed in a continuous-flow reactor at voltages of 10V, 15V, 20V, and 25V over 6 h, using double-distilled water solutions of fluoride. The findings are outlined in Figure 5. After 6 h, the fluoride elimination rate was 55% at 10 V, resulting in an exit fluoride level of 4.5 mg/L (from an initial level of 10 mg/L). At 25 V, the greatest fluoride elimination rate is 79.4%, resulting in the final level of 2.06 mg/L from an initial level at 10 mg/L.

5.3.2. pH and Turbidity

pH samples are taken at periodically. The initial pH after adding sodium fluoride varied between 6.14 and 6.18. The pH rose slightly, with a value of 6.62–6.8. The primary benefit of EC is that it does not need neutralization following treatment, unlike conventional coagulation. Samples are taken at frequently and evaluated for conductivity. The initial conductivity following applying sodium fluoride was 0.032 mS/cm. The experiment ended with the highest conductivity of 0.051 mS/cm at

Table 4: Summary of results for fluoride removal in a continuous flow EC reactor.

Applied Voltage (V)	Co (mg/L)	Cf (mg/L)	Initial pH	Final pH	F Removal efficiency %	Initial Turbidity (NTU)	Final Turbidity (NTU)	Electrode Consumption (mg Fe/L)	Sludge Production (kg/m^3)	Iron dissolved (mg Fe/mg F removed)
Distilled water										
10	10	4.5	55	6.15	6.62	0.2	2.7	15	0.057	27.27
15	10	3.7	63	6.18	6.8	0.3	3.2	17	0.079	26.98
20	10	2.95	70.5	6.15	6.66	0.3	3.2	19	0.113	26.95
25	10	2.06	79.4	6.14	6.7	0.3	3.7	29	0.129	36.52
Ground water										
25	10	7.13	28.7	9.17	9.27	7.7	1.7	78	0.256	271.8

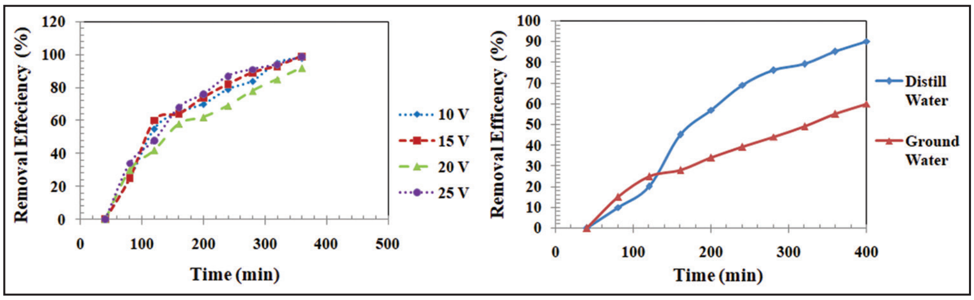

Figure 5: Impact of applied voltage on the removal of fluoride in an EC batch reactor, examining the variation in conductivity over time of 10 mg/L.

25V. As the voltage that was applied grew, the ion concentration of the solution progressively has risen, resulting in a slight rise in conductivity.

Turbidity was determined by collecting samples during periodic times and analyzing them. The initial turbidity after applying sodium fluoride was 0.3 NTU. Turbidity increased over time regardless of applied voltages. The allowable turbidity level for drinking water is 5 NTU. EC and filtration consistently resulted in turbidity levels under this standard.

5.4. A Comparison of Fluoride Removal in Distilled and Ground Water

An additional study compared fluoride elimination effectiveness between double-distilled water and groundwater. Although there was not a substantial difference in the effectiveness of elimination for double distilled water between batch and continuous flow systems, groundwater reduction efficiency differed significantly [25]. The continuous flow reactor significantly reduced fluoride elimination rate in groundwater to 28.7%, compared to the batch procedure [Table 4]. There are two probable explanations regarding this note: 1. The water has high levels of total dissolved solids (122.63 mg/L), turbidity (7.7 NTU), pH (9.17), and other contaminants.

1. GW includes significant amounts of total dissolved solids (122.63 mg/L), turbidity (7.7 NTU), a pH level that is high (9.17), and a variety of additional ions other than fluoride. Hu *et al*. (2003) discovered that when fluoride was not the dominating anion in solution, it had been substituted with different ions, leading to reduced fluoride effectiveness in elimination at the anode. Analyzing groundwater samples revealed typical levels of fluoride, chloride, nitrite, bromide, nitrate, and sulfate at 0.493, 2.03, 0.175, 0.96, 0.6, and 2.3 mg/L, correspondingly. According to Divyadeepika *et al*. [27], anions such as bromide, phosphate, and sulfate lower the effectiveness of F removal, while chloride increases it.
2. The continuous flow reactor exposed the water samples to a lesser efficient coagulant dosage (78 mg Fe/L) than the batch reactor (870 mg Fe/L). In the batch reactor, 1 L of water had been subjected to a potential of 25 V for 3 h, then given 1 h of settling. The continuous flow reactor exposed 10 L of water to a constant voltage for 6 h with a hydraulic residence period of 4 h. Despite having the same residence durations, the continuous flow reactor requires significantly less coagulant. The decreased efficient coagulant dose only influenced F removal from GW, not distilled water. This suggests that the dose was adequate for distilled water yet insufficient for GW.

6. CONCLUSIONS

Fluoride is a frequent naturally occurring groundwater pollutant in India. The present research used EC and filtration to effectively remove fluoride. After EC, filtration was required to attain acceptable turbidity levels in the water. The batch investigations assessed three working variables: applied potential, initial concentrations, and initial pH. The effect of altering applied voltage was tested in continuous flow. We conducted batch and continuous-flow investigations to compare F elimination from distilled and groundwater.

Applied Potential: Increasing the applied voltage led to higher percentages of F elimination in batch and continuous-flow systems. In batch EC experiments, the highest F elimination rate was 84.9% with distilled water and 79.7% using groundwater.

Continuous flow investigations successfully eliminated 79.4% and 28.1% of fluoride from distilled and groundwater, correspondingly. The reduced F elimination efficiency in continuous mode for groundwater is due to interaction with other ions and a lesser efficient coagulant dose when compared to batch tests.

Two pH-related behaviors were observed: (1) At a fluoride dosage of 10 mg/L and an initial pH range of 5–10, there was not a substantial variance in final pH. Fluoride elimination is most effective at a pH of 6.42 in batch systems. (2) The initial F content had a significant impact on the final pH. Increasing the initial F content (≥10 mg/L) led to a rise in pH.

(2) The initial F content had a significant impact on the final pH. As the original F content (≥10 mg/L) risen, the pH of the treated water became more alkaline. As the greatest F contents in ground waters in India vary from as high as 15 mg/L, EC treatment for F removal is unlikely to cause a considerable increase in pH. Therefore, neutralization is not necessary.

Sludge generation: EDX analysis of sludge and electrode deposit samples revealed that 85% of the injected fluoride was trapped in the sludge, according to a mass balance surrounding the batch reactor. The sludge primarily consisted of iron oxides.

7. REFERENCES

1. I. Djekić, B. Velebit, B. Pavlić, P. Putnik, D. Šojić Merkulov, A. Bebek Markovinović, D. Bursać Kovačević, (2023) Food Quality 4.0: Sustainable food manufacturing for the twenty-first century, ***Food Engineering Reviews***, **15:** 577-608.
2. D. Kour, K. L. Rana, N. Yadav, A. N Yadav, A. A. Rastegari, C. Singh, A. K. Saxena, (2019) Technologies for biofuel production: Current development, challenges, and future prospects. In: ***Prospects of Renewable Bioprocessing in Future Energy Systems***, Cham: Springer, p1-50.
3. A. Maione, N. Massarotti, R. Santagata, L. Vanoli, (2022) Environmental assessment of a heating, cooling and electric energy grid from a geothermal source in Southern Italy, ***Journal of Cleaner Production***, **375:** 134198.
4. M. Röck, M.R.M, Saade, M. Balouktsi, F.N. Rasmussen, H. Birgisdottir, R. Frischknecht, A. Passer, (2020) Embodied GHG emissions of buildings-the hidden challenge for effective climate change mitigation, ***Applied Energy***, **258:** 114107.
5. S. Dangar, A. Asoka, V. Mishra, (2021) Causes and implications of groundwater depletion in India: A review, ***Journal of Hydrology***, **596:** 126103.
6. T. Shah, (2020) Climate change and groundwater: India's opportunities for mitigation and adaptation. In: ***Water Resources Policies in South Asia***, India: Routledge, p213-243.
7. A. Dehdar, A. R. Rahmani, G. Azarian, R. Jamshidi, S. Moradi, (2022) Removal of furfural using zero gap electrocoagulation by a scrap iron anode from aqueous solution, ***Journal of Molecular Liquids***, **367:** 120368.
8. V. Devda, K. Chaudhary, S. Varjani, B. Pathak, A. K. Patel, R. R. Singhania, P. Chaturvedi, (2021) Recovery of resources from industrial wastewater employing electrochemical technologies: Status, advancements and perspectives, ***Bioengineered***, **12(1):** 4697-4718.
9. D. Ghernaout, (2020) Electrocoagulation as a pioneering separation technology-electric field role, ***Open Access Library Journal***, **7(8):** 1-19.
10. B. Shahi Khalaf Ansar, E. Kavusi, Z. Dehghanian, J. Pandey, B. Asgari Lajayer, G. W. Price, T. Astatkie, (2023) Removal of organic and inorganic contaminants from the air, soil, and water by algae, ***Environmental Science and Pollution Research,*** **30(55):** 116538-116566.
11. R. Fatima, S. Naseer, M. R. H. S. Gilani, M. Aamir, J. Akhtar, (2023) Metal hydroxides, ***Sustainable Materials for Electrochemical Capacitors***, 33-64.
12. B. A. Lasaki, P. Maurer, H. Schönberger, E. P. Alvarez, (2023) Empowering municipal wastewater treatment: Enhancing particulate organic carbon removal via chemical advanced primary treatment, ***Environmental Technology and Innovation***, **32:** 103436.
13. M. Bharti, P. P. Das, M. K. Purkait, (2023) A review on the treatment of water and wastewater by electrocoagulation process: Advances and emerging applications, ***Journal of Environmental Chemical Engineering***, **11:** 111558.
14. A. Othmani, A. Kadier, R. Singh, C. A. Igwegbe, M. Bouzid, M. O. Aquatar, F. Sher, (2022) A comprehensive review on green perspectives of electrocoagulation integrated with advanced processes for effective pollutants removal from water environment, ***Environmental Research***, **215:** 114294.
15. N. Adimalla, H. Qian, (2023) Evaluation of non-carcinogenic causing health risks (NCHR) associated with exposure of fluoride and nitrate contaminated groundwater from a semi-arid region of south India, ***Environmental Science and Pollution Research***, **30(34):** 81370-81385.
16. V. Duggal, S. Sharma, (2022) Fluoride contamination in drinking water and associated health risk assessment in the Malwa Belt of Punjab, India, ***Environmental Advances***, **8:** 100242.
17. P. Khyalia, S. S. Duhan, J. S. Laura, M. Nandal, (2024) A comprehensive analysis of fluoride contamination in groundwater of rural area with special focus on India. In: ***Water Resources Management for Rural Development***, Netherlands: Elsevier, p201-212.
18. R. Bhardwaj, T. Inderjeet, (2024) Advanced simulation technologies for removal of water fluoride. In: ***Advanced Treatment Technologies for Fluoride Removal in Water: Water Purification***, Cham: Springer Nature Switzerland, p197-212.
19. B. Thomas, C. Vinka, L. Pawan, S. David, (2022) Sustainable groundwater treatment technologies for underserved rural communities in emerging economies, ***Science of the Total Environment***, **813:** 152633.
20. M. Mehralian, M. H. Ehrampoush, A. A. Ebrahimi, A. Dalvand, (2023) Development of electrocoagulation-based continuous-flow reactor for leachate treatment: Performance evaluation, energy consumption, modeling, and optimization, ***Applied Water Science***, **13(8):** 162.
21. B. Biswas, S. Goel, (2022) Electrocoagulation and electrooxidation technologies for pesticide removal from water or wastewater: A review, ***Chemosphere***, **302:** 134709.
22. M. Mantovani, E. Collina, M. Lasagni, F. Marazzi, V. Mezzanotte, (2023) Production of microalgal-based carbon encapsulated iron nanoparticles (ME-nFe) to remove heavy metals in wastewater, ***Environmental Science and Pollution Research***, **30(3):** 6730-6745.
23. A. Z. Abdullah, H. M. Amanullah, M. H. Abdurahman, N. I. Basir, (2023) Treatment of stabilized sanitary landfill leachate using electrocoagulation process equipped with Fe, Al, and Zn electrodes and assisted by cationic polyacrylamide coagulant aid, ***Arabian Journal for Science and Engineering***, **48(7):** 8495-8506.
24. R. Gupta, P. K. Sharma, (2023) A review of groundwater-surface water interaction studies in India, ***Journal of Hydrology***, **621:** 129592.
25. M. A. Sandoval, O. Coreño, V. García, R. Salazar-González, (2024) Enhancing industrial swine slaughterhouse wastewater treatment: Optimization of electrocoagulation technique and

operating mode, ***Journal of Environmental Management***, **349:** 119556.

26. E. Shaji, K. V. Sarath, M. Santosh, P. K. Krishnaprasad, B. K. Arya, M. S. Babu, (2024) Fluoride contamination in groundwater: A global review of the status, processes, challenges, and remedial measures, ***Geoscience Frontiers***, **15(2):** 101734.
27. D. Deepika, K. Yadav, J. Joshi, (2024) Fluoride pollution control techniques and principles. In: ***Advanced Treatment Technologies for Fluoride Removal in Water: Water Purification***, Cham: Springer Nature Switzerland, p43-69.

***Bibliographical Sketch**

Dr. S. Srinivasa Gowd obtained Ph. D. Degree from Sri Venkateswara, Tirupati. He has many publications in the peer reviewed national and international Journals. He is currently working as Associate Professor in the Department of Geology, Yogi Vemana University, Kadapa. He completed more than 15 years of teaching experience in Geology. He worked as CSIR-Research Associate, CSIR-Sr. Research Associate (Scientists' Pool Scheme), and DST-Young Scientist at National Geophysical Research Institute (NGRI), Hyderabad and Sri Venkateswara University, and Tirupati. His research interests are in the areas of Environmental Geochemistry, Hydrogeology, Remote Sensing & GIS and he has supervised many M.Sc. students' projects

Dr. C. Krupavathi completed Ph. D. as DST-Inspire fellow from Department of science and technology, New Delhi. She completed M.Sc., from Yogi Vemana University, Kadapa. She is currently working as Lecturer, Mining department in YSRR Polytechnic College, Pulivendula. She has received DST-Inspire fellow award in the year of 2018. Her research interests are in the areas of Hydrogeology, Water quality, Contamination of Water, Remediation methods. Her contribution has been recognized in many peer-reviewed journals and book chapters.