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Original Research Article

Electrocoagulation Performance for Salinity Total Dissolved Solids and Conductivity Removal in Aqueous Systems

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Abstract

In the midst of an abundance of water, coastal communities cannot enjoy it because the seeping seawater has boosted salt levels, TDS, and conductivity. This crisis is getting worse along with excessive exploitation of groundwater, land level dropping, and rising sea levels slowly but surely. Conventional desalination technology is difficult to apply to community-scale needs because it requires large energy, high costs, and complicated operational procedures. This study assessed the ability of electrocoagulation in reducing salinity, TDS, and conductivity in brackish water in the coastal area of Pekalongan through observation at several points for 14 days. The experiment utilizes aluminium electrodes in a batch system reactor with a processing duration of 90 minutes. Samples taken from wells and rivers were analysed for salinity, TDS, conductivity, pH, dissolved oxygen (DO), and temperature, both before and after the treatment process. As a result, the maximum efficiency of salinity reduction and TDS reached 49%, but the average efficiency was only in the range of 4–5% with a high degree of variation. On the other hand, dissolved oxygen levels actually fell more stablely, averaging around 20.2%. The best results were obtained on July 20, 2025, while the worst results occurred on July 26, 2025 because the pH dropped quite drastically. The process of disappearance itself is generally already running within the first hour. Although electrocoagulation shows potential, this method still needs refinement given its sensitivity to raw water characteristics and pH values. The novelty of this study is not in the introduction of new technologies, but in field trials that observe the stability and recurrence of electrocoagulation in dynamic coastal brackish water conditions. These findings reveal the gap between controlled laboratory results and real-world applications, as seen from the low average efficiency, the emergence of negative efficiency, and the very significant influence of pH.

Keywords: Electrocoagulation; Water Treatment; Salinity Removal

1. Introduction

Coastal areas worldwide face a paradoxical clean-water crisis (Boschken, 2013; Barbier, 2019). On the one hand, water resources are abundant; on the other hand, their quality is degraded by natural and anthropogenic hydrogeological processes. Seawater intrusion is a primary threat, contaminating freshwater aquifers with saline water and transforming groundwater into brackish water (Hussain et al., 2019; Perumal et al. 2024). The geographical and hydrological characteristics of coastal regions, such as

low-lying areas and groundwater basins directly adjacent to the sea, make it highly susceptible to this phenomenon. For instance, research in the Pasuruan Groundwater Basin showed that seawater intrusion can extend hundreds of meters inland, contaminating residents' shallow wells. Closer to the focus area, the coastal region of Pekalongan, known for land subsidence and tidal flooding, experiences a high level of vulnerability to seawater intrusion. This process significantly increases the concentration of dissolved salts, measured as total dissolved solids (TDS), and salinity in groundwater (Adji et al., 2022). Elevated TDS and salinity levels have serious implications for domestic water quality and the environment. Brackish water is unsuitable for consumption, as it can lead to health issues such as skin diseases and metabolic disorders, and it is also inappropriate for agricultural irrigation because high salt concentrations inhibit plant growth (Chakraborty et al., 2019; Costopoulos et al., 2025). Furthermore, water with high TDS and hardness can cause scaling in cooking utensils and water distribution systems (Shams et al., 2019). Unfortunately, conventional treatment technologies, such as simple filtration using sand, activated carbon, or zeolite, are often ineffective for treating brackish water (Abdiyev et al., 2023). Although filtration can reduce TDS levels, its performance remains suboptimal and typically requires pre-treatment processes such as coagulation–flocculation to achieve better results. Membrane technologies, such as reverse osmosis (RO), are highly effective; however, it has several limitations, including susceptibility to chlorine damage and the high cost of membrane replacement, making it less feasible for small-scale or remote applications. In response to these limitations, electrocoagulation has emerged as a promising alternative for brackish water treatment.

The fundamental mechanism of E involves an electrochemical process in which a direct electric current is passed through metal electrodes (typically iron or aluminum) immersed in water (Garcia-Segura et al., 2017; Moussa et al., 2017; Rahman et al., 2023). At the anode, oxidation occurs, releasing active metal ions, such as aluminum (Al^{3+}) or iron (Fe^{2+}) that function as in-situ coagulants (Li et al., 2023). These ions subsequently react with hydroxyl ions (OH^-) generated at the cathode to form metal hydroxide flocs. These flocs effectively bind and adsorb various pollutants, including ions responsible for hardness, TDS, and chloride. The resulting aggregates either settle or float to the surface due to hydrogen gas bubbles produced during the process (Kobya et al., 2020; Rahman et al., 2023). Recent studies have demonstrated the effectiveness of EC, such as in seawater desalination with significant TDS reduction (Hakizimana et al., 2017), and in the treatment of brackish peat water in coastal wetlands, achieving salinity reduction efficiencies of up to 91.78 percent (%) at relatively low cost (Rahman et al., 2023). Although laboratory studies have demonstrated the effectiveness of electrocoagulation, several significant research gaps remain. First, there is a lack of multi-location studies that apply this technology to brackish water under varying geographical and hydrogeological conditions, particularly in densely populated coastal areas such as Pekalongan, which exhibit complex environmental dynamics (Rahman et al., 2023). Second, there is a notable scarcity of multi-day field investigations. Most existing studies are limited to batch-scale or short-term laboratory experiments, which do not adequately capture the operational performance and long-term reliability of electrocoagulation systems under fluctuating raw water conditions in real-world settings (Rahman et al., 2023).

Although electrocoagulation has become known as a water treatment method, the extent to which this technology can be relied upon when applied in dynamic coastal environments is still a big question. Most of the existing studies rely on laboratory settings with parameters that are kept stable, in stark contrast to actual coastal conditions affected by tides, rainfall, landslides, groundwater uptake, and human activity, all of which can change salinity, TDS, conductivity, and water holding power in a short period of time. Against that background, this study does not aim to create a new electrocoagulation technology, but rather to test the extent to which this process can work consistently, repeatable, and how sensitive it is to changes in field conditions. Through observations at various points and times in the Pekalongan area, this study presents an overview of the gap between the results obtained in the laboratory and the reality in the field, especially for the brackish water treatment needs used by the community. The purpose of this study was to measure how effective electrocoagulation was in reducing the TDS and

salinity of brackish water in Pekalongan, with an observational approach conducted in many locations and over several days. The results of this research are expected to be the foundation for the development of water treatment technology that is practical, durable, and easy to imitate by coastal communities to meet their daily clean water needs. This research itself will be held in Pekalongan, Indonesia, in 2025.

Therefore, this study aims to evaluate the effectiveness of electrocoagulation technology in reducing TDS and salinity levels in brackish water within the coastal region of Pekalongan through a multi-location and multi-day observational approach. The findings of this study are expected to contribute to the development of appropriate, sustainable, and scalable water treatment technologies that can be readily adopted by coastal communities to meet their domestic clean water needs. This study was conducted in Pekalongan, Indonesia, in 2025.

2. Methods

2.1 Study Area

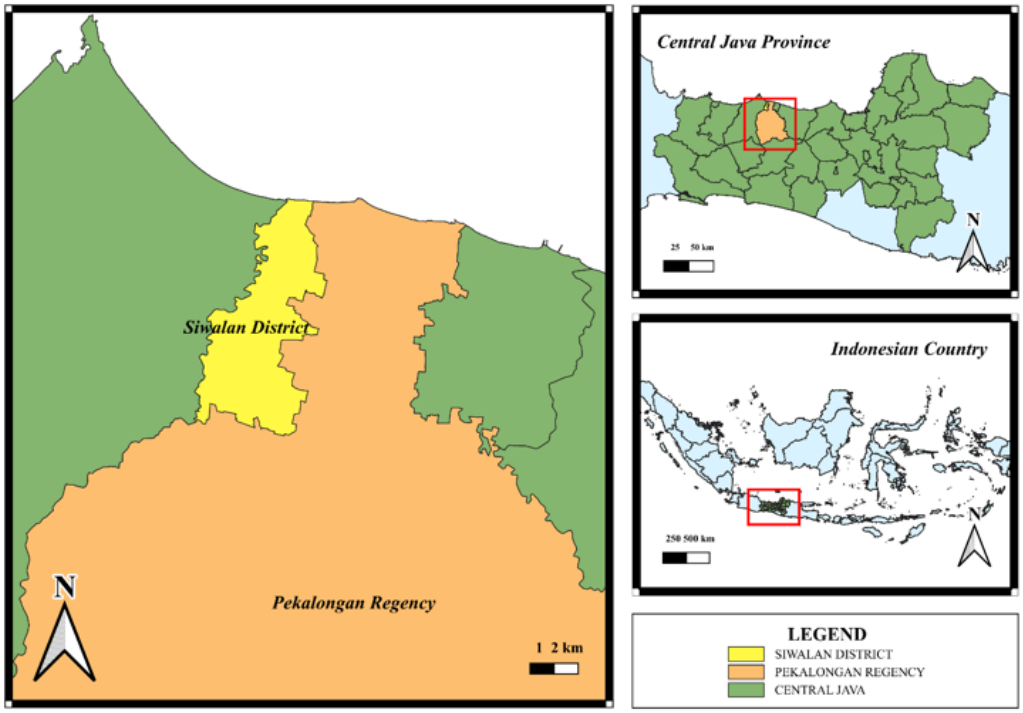


Figure 1. Geographical location of the study area of Siwalan District, Pekalongan Regency, Central Java, Indonesia

This study was conducted in Siwalan District, Pekalongan Regency, Central Java Province, Indonesia, located along the northern coast of Java Island (Figure 1). This coastal region is characterized by low-relief plains that are highly vulnerable to seawater intrusion, tidal flooding, and groundwater salinization. As a result, local communities face significant challenges due to limited access to freshwater for domestic use. Geographically, Siwalan District consists of extensive low-lying alluvial plains with elevations close to sea level. The shallow groundwater system in this coastal area is strongly influenced by interactions between freshwater and seawater, driven by the dynamics of the Java Sea.

The Pekalongan coastal zone is also affected by land subsidence and recurrent tidal flooding, which further accelerates seawater intrusion into shallow aquifers. Consequently, the groundwater sources used by residents have elevated salinity and are often classified as brackish. In this study, water samples were collected from multiple sources representing groundwater and surface water conditions in the coastal area of Pekalongan. Groundwater samples were collected from six shallow community wells

distributed across residential and coastal settlement areas. These groundwater sources included wells located near residential areas, community activity areas, coastal settlements, and community facilities, representing domestic water sources commonly used by local residents. Surface water samples were obtained from a river channel within the study area, representing surface water conditions influenced by tidal dynamics, drainage systems, and surrounding human activities. The sampling locations were selected to represent variations in water quality, water sources, and environmental influences associated with seawater intrusion, tidal fluctuations, and anthropogenic activities. By including distributed groundwater and surface water sources across the coastal area, this study provides a representative assessment of brackish water conditions in Pekalongan and supports the evaluation of electrocoagulation performance under field-relevant conditions.

Sampling locations were selected using a grid-based spatial sampling approach to capture variations in water quality across the coastal area of Siwalan Village, Pekalongan Regency. The study area was divided into nine spatial zones, with one sampling point designated within each zone. This approach was intended to provide spatial coverage of areas affected by persistent tidal flooding, seawater intrusion, and surrounding residential activities. The selected locations represented different environmental conditions within the coastal settlement, including groundwater and surface water sources. By distributing sampling points across the study area, the sampling strategy aimed to capture spatial heterogeneity in brackish water characteristics rather than relying on a single water source. However, the selected sites should not be interpreted as statistically representative of the entire Pekalongan coastal region.

2.2 Experimental Procedures and Water Quality Analysis

Sampling was conducted over 14 observation days, from July 20 to August 2, 2025. The observations included shallow-well groundwater and river water collected under varying coastal environmental conditions. Each sampling date represented a separate field observation, and observations conducted on different dates or at different locations were not treated as parallel experimental replicates. The experimental setup for electrocoagulation used a laboratory-scale batch reactor which had a rectangular design that measured 45 cm by 25 cm by 25 cm and could hold up to 22 liters of water. The reactor contained seven zinc (Zn) electrodes which measured 20 cm by 5 cm by 0.2 cm and which spread out with three-centimeter gaps between each electrode. The geometric surface area of each electrode was 100 cm^2 per face, corresponding to 200 cm^2 for both major faces, although the actual effective submerged area depends on the electrode immersion depth. The electrodes operated through a direct-current power source which delivered 12 volts at 5 amps according to the specified values. The experimental documentation showed that the current density reached 500 A/m^2 during the testing process. The value needs to be validated through comparison with actual submerged anode areas together with their specific electrode arrangement. The treatment process operated without any external mechanical stirring so the electrolysis-generated gas bubbles created the primary method for mixing liquids. The reactor and electrode assembly were constructed using locally available materials, and no specific manufacturer or model was documented for the reactor components.

The measured water quality parameters include salinity, total dissolved solids (TDS), electrical conductivity, pH, dissolved oxygen (DO), and temperature. Salinity is measured by the salinity of a brand/model portable meter (a certain range and accuracy). TDS is measured by a digital TDS meter, conductivity with brand/model meter conductivity, pH with portable pH meter, DO with DO meter, and temperature with brand/model digital thermometer. All instruments are calibrated before use according to the manufacturer's guidelines. pH meters are calibrated with a standard buffer solution of pH 4.00; 7,00; and 10.00. The conductivity and TDS meters are calibrated with a standard conductivity solution (e.g. 1413 µS/cm or 12.88 mS/cm). The salinity meter is verified with salinity standards, while the DO meter is calibrated using an air-saturated water/solution without oxygen/factory standard. The temperature measurement is matched with the reference thermometer. All measurements were taken in

the field or immediately after sampling to minimize changes in water quality prior to analysis (Bartram et al., 1996). The analysis procedure follows the standard protocol for monitoring environmental water quality. The collected data is then processed with descriptive statistics to determine the minimum, maximum, average, standard deviation, and percentage of allowance for each parameter. The efficiency of the dispensation was calculated by comparing the initial and final concentrations after treatment. The experimental flow diagram is presented in Figure 2, while the operating conditions and analysis instruments are summarized in Table 1.



Figure 2. The study flow diagram

Table 1. Parameter and units

No.	Parameter	Unit	Method
1	Salinity	%	Salinity meter
2	Total Dissolved Solids	ppm	TDS meter
3	Conductivity	mS/cm	Conductivity meter
4	pH	-	pH meter
5	Dissolved oxygen	mg/L	DO meter
6	Temperature	°C	Thermometer

2.3 Statistical Analysis

All measurement data were statistically analyzed using descriptive and inferential methods. Through descriptive statistics, minimum, maximum, average, standard deviation, and coefficient of variation are calculated to provide an overview of the distribution of raw water quality data and the effectiveness of the treatment process. The efficiency of the dispensing for each parameter is determined by comparing the concentrations before and after processing, using the formula:

Removal efficiency (%) = $[(C_0 - Ct) / C_0] \times 100$

where C_0 is the initial concentration and Ct is the concentration after processing. To measure the reliability level of the results, a 95% confidence interval was created for the average efficiency of salinity allowance, TDS, conductivity, and DO. Before the significance test is carried out, the normality of the difference between the initial and final values is first tested. For normally distributed data, paired t-tests are used; while for abnormal data, the Wilcoxon test was selected as a non-parametric test. The significance threshold used was $p < 0.05$. Because this research is carried out in the field with all its dynamics, the experimental design emphasizes more on monitoring performance in actual situations, rather than on strict control of variables as in the laboratory. Therefore, this study does not include a control reactor without treatment or direct comparison with other technologies. These limitations are considered in interpreting the findings, while comparisons with alternative methods are carried out through a literature review.

The statistical analysis should be interpreted considering the observational field design of this study. The measurements obtained from different dates and locations represent independent field observations under different raw-water conditions rather than true experimental replicates. Therefore, the statistical tests describe the variability and consistency of observed treatment performance but cannot fully separate treatment effects from natural variations in raw-water characteristics. The absence of parallel replication and untreated controls limits causal interpretation, and the statistical results should be considered exploratory rather than confirmatory.

2.4 Data Availability and Operational Feasibility

To ensure transparency and reproducibility of the research findings, all the raw data of the experiments are compiled and presented in additional appendices. This supporting data includes initial values and time series measurement results at each observation interval (minutes 0, 15, 30, 45, 60, 75, and 90) for salinity, TDS, conductivity, pH, DO, and temperature parameters, grouped by sampling date and location. In addition, additional data also includes the calculated allowance efficiency, reactor operational conditions, and documentation of procedures in the field. The design of this study is an observational study in the field over several days, rather than a laboratory experiment designed for optimization with controlled replication. Because raw water quality varies naturally, each sampling location and day was treated as an independent field observation rather than an experimental replicate. Therefore, the observed differences reflect both electrocoagulation performance and variations in raw-water characteristics. The absence of parallel replication limits the ability to quantify experimental uncertainty and should be considered when interpreting statistical outcomes. However, no parallel replication was carried out for each sample, so the reliability and reproducibility aspects of the results need to be interpreted taking into account these limitations. For follow-up research, it is recommended that three repeats be performed for each condition, and include empty reactors, no-treatment controls, and comparative tests with other processing systems. Energy consumption estimation is carried out based on voltage, current, treatment duration, and water volume, using the formula:

Energy consumption (kWh/m^3) = $(U \times I \times t) / V$

with U (voltage, V), I (current, A), t (time, hour), and V (volume, m^3; if volume in litres, converted first). Meanwhile, the consumption of aluminium electrodes is theoretically calculated with Faraday's Law:

Electrode consumption (g) = $(I \times t \times M) / (z \times F)$

with M = molar mass of aluminum, z = 3 (number of electrons involved), and F = 96.485 C/mol. The results of the electrode consumption calculation are then normalized to the volume of treated water and expressed in g/m³ or kg/m³.

2.5 Control and Comparative Assessment

This study did not include a parallel untreated control reactor or direct side-by-side experiments with conventional treatment methods during the original field campaign. Therefore, the actual treatment benefit of electrocoagulation was evaluated by comparing the initial and final water quality values before and after electrocoagulation treatment. In addition, a literature-based comparison with conventional water treatment methods, such as simple filtration, adsorption, and membrane-based desalination, was included to provide a broader interpretation of the practical advantages and limitations of electrocoagulation. The comparison focused on treatment performance, operational complexity, suitability for small-scale application, and relevance for brackish-water treatment in coastal communities. This approach was used to support the interpretation of electrocoagulation performance under field conditions, while the absence of untreated control and direct comparative experiments was acknowledged as a study limitation.

3. Result and Discussion

3.1 Initial Water Quality Analysis

Understanding the initial quality of raw water is fundamental for evaluating the effectiveness of any treatment technology, including electrocoagulation. The characterization of brackish water samples collected from various locations in the coastal region of Pekalongan revealed significant variations in both physical and chemical parameters. Descriptive statistics summarizing the minimum, maximum, mean, and standard deviation values for key water quality parameters are presented in Table 2**.**

Table 2. Descriptive statistics of initial water quality parameters in brackish water samples

Parameter	Min.	Max.	Mean	Standard deviation (SD)
Salinity (%)	0.33	0.87	0.47	0.13
TDS (ppm)	4,000	10,490	5,687.86	1,566.10
Conductivity (mS/cm)	6.00	15.70	8.51	2.34
pH	6.26	7.29	6.81	0.33
Temperature (°C)	26.50	30.70	29.63	1.14
DO (mg/L)	13.10	17.70	15.15	1.51

The data in Table 2 demonstrates a wide range of water quality, indicating heterogeneous conditions across the study area. The mean salinity and TDS values were 0.47% and 5,687.86 ppm, respectively, confirming that the sampled water sources were within the brackish water category, as water with TDS between 1,000–10,000 ppm is generally classified as brackish. The variation in TDS and conductivity values indicates substantial differences in water characteristics among sampling locations. The minimum TDS value of 4,000 ppm and maximum value of 10,490 ppm indicate considerable variation in saline influence among sampling locations. The higher TDS concentration observed at certain sampling points suggests stronger influence from seawater intrusion and tidal processes. This prominent variation underscores the necessity of a multi-location study, as a single treatment approach may not be universally effective. When comparing groundwater and river water sources, the data implies that groundwater in coastal Pekalongan is more susceptible to high salinity. This observation aligns with previous studies (Custodio et al., 1987; Adji et al., 2022), which report that shallow unconfined aquifers in coastal areas are highly vulnerable to saltwater intrusion due to their direct hydraulic connection with the sea (Bear et al.,

1999). The elevated TDS and salinity levels have important implications for water treatment. High salinity water is known to cause scaling in distribution systems and household appliances, and its consumption may lead to adverse health effects such as hypertension and kidney disorders (Chakraborty et al., 2019). Furthermore, elevated TDS presents a challenge for conventional treatment methods, such as simple filtration, which are generally ineffective in removing dissolved ions. This condition justifies the exploration of advanced technologies such as EC, which has demonstrated potential in reducing ionic contaminants in brackish water (Rahman et al., 2023). The pH values ranged from slightly acidic (6.26) to moderately alkaline (7.29). Although the reported standard deviation (0.33) appears, this range remains plausible for natural waters influenced by organic matter decomposition and seawater mixing (Stumm et al., 2013). The temperature ranged from 26.50°C to 30.70°C, which is typical of tropical surface and groundwater conditions. Notably, the DO data indicates a potential anomaly. The dissolved oxygen values ranged from 13.10 to 17.70 mg/L, where the maximum solubility is approximately 9 mg/L (American Public Health, 2020; Manahan, 2017). This discrepancy suggests a possible data entry or unit error. If the intended measurement refers to percentage saturation (%), the observed range would be more realistic. The minimum DO value of 5 mg/L indicates relatively oxygenated conditions at certain sites, while the variability reflects differences in organic pollution levels and aquifer recharge processes. Overall, the high variability across all parameters confirms that raw water quality in coastal Pekalongan is highly dynamic. This reinforces the need for a robust and adaptable treatment solution, such as electrocoagulation, to effectively address fluctuating water quality conditions.

3.2 Electrocoagulation Performance on Salinity

The effectiveness of the electrocoagulation system in reducing salinity was evaluated by measuring the percentage removal of salinity after 90 minutes of treatment across multiple days and locations. The daily removal efficiencies are summarized in Table 3, while Figure 3 illustrates the trend of salinity reduction over the treatment duration.

Table 3. Daily salinity removal efficiency during electrocoagulation treatment at different sampling locations

Date	Location	Initial salinity (%)	Salinity after 90 minutes (%)	Removal (%)
20-Jul-25	Shallow Well	0.87	0.44	49%
21-Jul-25	River	0.45	0.45	0%
22-Jul-25	River	0.44	0.42	5%
23-Jul-25	River	0.44	0.45	-2%
24-Jul-25	River	0.42	0.4	5%
25-Jul-25	Shallow Well	0.42	0.43	-2%
26-Jul-25	River	0.6	0.69	-15%
27-Jul-25	River	0.52	0.46	12%
28-Jul-25	River	0.44	0.44	0%
29-Jul-25	River	0.41	0.4	2%
30-Jul-25	River	0.41	0.41	0%
31-Jul-25	River	0.41	0.42	-2%
01-Aug-25	Shallow well	0.42	0.42	0%
02-Aug-25	River	0.33	0.27	18%

Figure 3 illustrates the variation in salinity concentration throughout the 90-minute electrocoagulation process across different sampling days. In general, a decreasing trend in salinity was observed as the treatment progressed. This finding is consistent with the fundamental mechanism of EC, in which dissolved ions are removed through adsorption, co-precipitation, and flotation by metal hydroxide flocs (Vepsäläinen and Sillanpää, 2020). The most significant reduction typically occurred within the first 30 to 60 minutes of operation, after which the removal rate tended to plateau. This pattern aligns with previous studies (Vepsäläinen and Sillanpää, 2020), which reported that ion removal kinetics in electrocoagulation are rapid during the initial phase due to the high availability of coagulant species and the abundance of free ions in solution. As the reaction progresses, the driving force for mass transfer decreases, resulting in a slower removal rate. For the detailed data, it can be seen in Supplementary File.

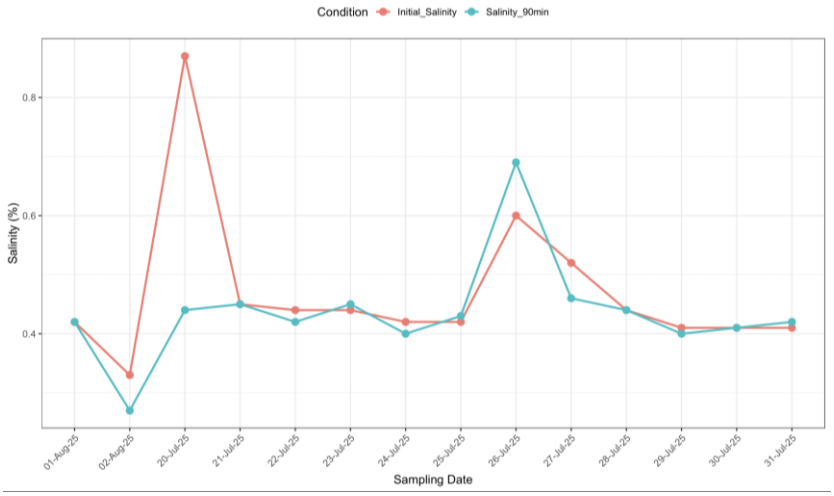


Figure 3. Temporal variation of salinity during the 90-minute electrocoagulation treatment process

The electrocoagulation system demonstrated variable performance across different days, with removal efficiency ranging from –15% to 49%. The highest removal efficiency of 49% was achieved on July 20, 2025, at the shallow well location, which also had the highest initial salinity (0.87%). This suggests that the electrocoagulation process can be highly effective under specific conditions, particularly when the initial contaminant concentration provides a sufficient driving force for electrochemical reactions. A removal efficiency of 18% on August 2, 2025, also indicates satisfactory performance under moderate initial salinity conditions. Conversely, negative removal efficiencies were observed on several days, most notably on July 26, 2025, at the river location, where salinity increased by 15% after treatment. Negative removal, in which the final concentration exceeds the initial concentration, can occur for several reasons. One possible explanation is the desorption or re-dissolution of previously removed ions back into the solution, particularly if operating conditions (such as current density or pH) are not optimally maintained (Merzouk et al., 2009). Additionally, fluctuations in raw water quality, including variations in ionic composition and conductivity, can influence electrochemical processes and lead to inconsistent results (Kobya et al., 2020). The negative removal observed on July 23 and 25, 2025, although smaller (–2%), further emphasizes the sensitivity of the electrocoagulation process to changes in feed water characteristics. The data revealed considerable instability in the electrocoagulation process, with many days showing zero or negligible removal (e.g., July 21, 28, 30, and August 1, 2025). This variability highlights the challenges of implementing electrocoagulation technology under real field conditions with fluctuating water quality. The inconsistent performance may be attributed to variations in raw water parameters such as pH, temperature, and the specific ionic matrix, all of which significantly affect coagulation efficiency and floc formation (Linares-Hernández et al., 2010). The river location, sampled on multiple days, exhibited highly variable results (from –15% to 18% removal), underscoring the dynamic nature of surface water quality influenced by tides, rainfall, and anthropogenic activities. Based on the observed temporal trends, the most pronounced salinity reduction generally occurred within the first 30–

60 minutes of treatment, after which additional changes were relatively limited. This period should be interpreted as an observed treatment range rather than a formally determined optimum, as no optimization experiment was conducted in this study. This finding is consistent with previous studies (Kobya et al., 2020), which recommend an optimal electrolysis time of 50–60 minutes to balance energy consumption and removal efficiency. Identifying an optimal treatment time is crucial for practical applications, as it helps minimize operational costs while achieving acceptable water-quality improvements. In summary, while electrocoagulation demonstrates potential for salinity reduction, with peak efficiencies approaching 50%, its performance remains highly variable and sensitive to changes in raw water quality. The occurrence of negative removals and frequent zero-efficiency days indicates that process optimization and robust control strategies are necessary before this technology can be reliably deployed for community-scale brackish water treatment in coastal Pekalongan.

The temporal variation during the 90-minute electrocoagulation process indicates that the most significant salinity reduction generally occurred within the first 30–60 minutes of treatment, followed by a slower reduction rate. Although extending the treatment duration to 90 minutes provided additional reaction time, the improvement in salinity reduction became less pronounced in most observations. This suggests that treatment duration should be optimized by considering the balance between removal performance and operational requirements. The reduction in salinity confirms that electrocoagulation can improve the quality of brackish water by decreasing dissolved ionic components. However, because salinity represents the main characteristic of seawater intrusion in coastal water sources, additional treatment processes may still be required to achieve drinking water quality requirements.

3.3 Electrocoagulation Performance on Total Dissolved Solids

The removal of TDS is a key performance metric in brackish water desalination. Table 4 and Figure 4 summarize the TDS removal performance of the electrocoagulation system over multiple days and sampling locations.

Table 4. Daily TDS removal efficiency during electrocoagulation treatment at different sampling locations

Date	Location	Initial TDS (ppm)	TDS after 90 minutes (ppm)	Removal (%)
20-Jul-25	Shallow Well	10,490	5,360	49%
21-Jul-25	River	5,460	5,490	-1%
22-Jul-25	River	5,370	5,150	4%
23-Jul-25	River	5,410	5,530	-2%
24-Jul-25	River	5,100	4,860	5%
25-Jul-25	Shallow well	5,120	5,280	-3%
26-Jul-25	River	7,290	8,360	-15%
27-Jul-25	River	6,240	5,640	10%
28-Jul-25	River	4,910	5,380	-10%
29-Jul-25	River	5,070	4,860	4%
30-Jul-25	River	5,010	5,000	0%
31-Jul-25	River	4,980	5,140	-3%
01-Aug-25	Shallow well	5,180	5,130	1%
02-Aug-25	River	4,000	3,260	19%

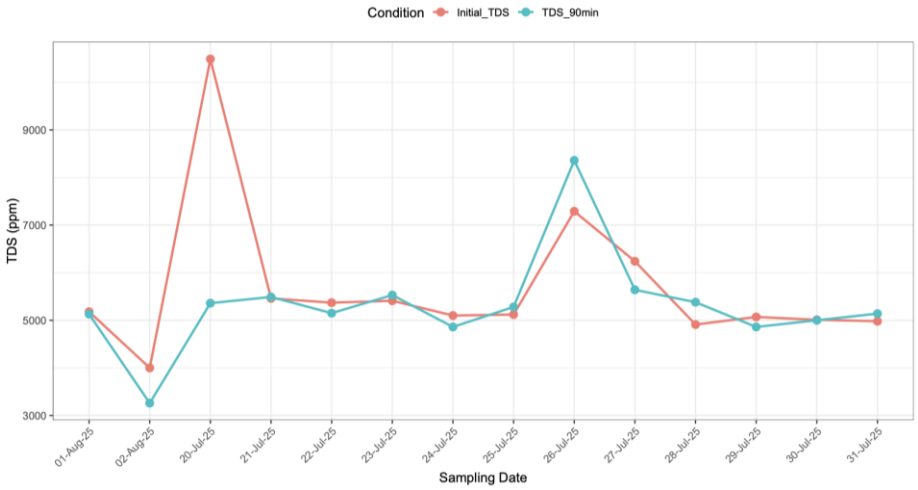


Figure 4. Temporal variation of TDS concentration during the 90-minute electrocoagulation treatment process

As shown in Table 4 and Figure 4, over the 14-day observation period, the Electrocoagulation system exhibited TDS removal efficiencies ranging from -15% to 49% (Kabdaşlı et al., 2012). The highest removal efficiency (49%) was achieved on July 20 at the shallow well, with an initial TDS of 10,490 ppm. This result demonstrates the potential of electrocoagulation under high contaminant concentrations, where a stronger driving force enhances electrochemical reactions. A substantial removal efficiency (19%) was also observed on August 2 in the river, despite a lower initial TDS (4,000 ppm), indicating that reasonable performance can still be achieved under moderate conditions. Performance varied significantly by location. The shallow well exhibited mixed results (49% to -3%), reflecting temporal variations in groundwater quality influenced by tidal intrusion and aquifer recharge dynamics. In contrast, the river showed the widest range of removal efficiencies (-15% to 19%), indicating highly variable surface water quality driven by rainfall, tidal mixing, and anthropogenic activities. Negative TDS removal was observed on several days, particularly on July 26 (-15%) and July 28 (-10%), indicating an increase in dissolved solids after treatment. This phenomenon can be explained by three main factors. First, aluminum ion dissolution under suboptimal pH conditions may result in Al^{3+} remaining in solution rather than precipitating as hydroxides, thereby increasing TDS (Moussa et al., 2017). Residual aluminum becomes particularly significant at pH values around 8 (Garcia-Segura et al., 2017). Second, overcurrent conditions may generate excessive coagulant ions that remain dissolved, leading to increased TDS while also wasting energy and reducing treatment efficiency (Hakizimana et al., 2017). Third, electrode over-dissolution due to localized corrosion and non-uniform current distribution may cause actual metal dissolution to exceed theoretical predictions, thereby increasing dissolved solids. Therefore, electrode consumption must be carefully controlled to balance pollutant removal and avoid counterproductive outcomes (Kobya et al., 2011). From a kinetic perspective, effective treatment days showed a rapid decline in TDS within the first 30–60 minutes, followed by a plateau phase. This behavior is consistent with first-order kinetics, in which readily available coagulant species drive the rapid initial removal. In contrast, during negative removal events, TDS initially decreased and then increased, suggesting that while early-stage coagulation removed some ions, prolonged electrolysis under unfavorable conditions led to the accumulation of dissolved aluminum. The optimal contact time for TDS removal was approximately 60 minutes (Rahman et al., 2023), representing a balance between removal efficiency and energy consumption. The observed temporal pattern indicates that most TDS reduction occurred within approximately 30–60 minutes, followed by relatively limited additional improvement. However, this range represents an observed treatment trend rather than a formally optimized contact time. The relatively low or negative removal efficiencies observed on certain days highlight the discrepancy between controlled laboratory conditions and real-world field applications of electrocoagulation technology. For

coastal communities in Pekalongan, where water quality fluctuates due to seasonal, tidal, and rainfall influences, effective electrocoagulation implementation requires adaptive control strategies that respond to real-time variations in raw water quality rather than relying on fixed operational parameters.

The influence of treatment duration on TDS reduction showed a similar trend, with rapid improvement occurring during the first 30–60 minutes followed by a stabilization phase. The observed 30–60-minute range showed the most pronounced TDS reduction, whereas extending treatment to 90 minutes generally provided limited additional improvement. However, the 90-minute treatment duration used in this study provided sufficient reaction time to evaluate the electrocoagulation performance under field-relevant brackish water conditions. The final TDS concentrations remained above the applicable drinking-water requirement in most treatment runs, despite reductions observed under certain conditions. Therefore, electrocoagulation under the tested conditions was insufficient to consistently produce water suitable for direct consumption. Additional treatment would be required to further reduce dissolved solids and achieve drinking-water quality requirements.

3.4 pH Variation and Reaction Mechanism

The pH of the solution is a critical parameter in electrocoagulation processes, as it influences the speciation of coagulant species, the solubility of metal hydroxides, and ultimately the efficiency of pollutant removal. Monitoring pH changes throughout the treatment provides valuable insights into the underlying electrochemical reactions and dominant coagulation mechanisms. Table 5 presents the initial pH, final pH after 90 minutes of treatment, and the change in pH (ΔpH) for each experimental run, while Figure 5 illustrates the temporal variation of pH during the treatment process.

Table 5. Initial pH, final pH after 90 minutes of electrocoagulation treatment, and corresponding pH change (ΔpH)

Date	Location	Initial pH	pH (90 min)	ΔpH
20-Jul-25	Shallow Well	7.29	6.79	-0.5
21-Jul-25	River	6.98	6.32	-0.66
22-Jul-25	River	7.07	6.74	-0.33
23-Jul-25	River	7.05	6.3	-0.75
24-Jul-25	River	6.77	6.23	-0.54
25-Jul-25	Shallow well	7.13	6.92	-0.21
26-Jul-25	River	6.69	3.73	-2.96
27-Jul-25	River	6.26	4.82	-1.44
28-Jul-25	River	6.43	4.58	-1.85
29-Jul-25	River	6.33	6.13	-0.2
30-Jul-25	River	6.46	5.84	-0.62
31-Jul-25	River	6.89	6.84	-0.05
01-Aug-25	Shallow well	7.14	6.73	-0.41
02-Aug-25	River	6.91	4.88	-2.03

pH significantly affects electrocoagulation performance by influencing coagulant speciation, metal hydroxide solubility, and pollutant removal efficiency (Garcia-Segura et al., 2017; Moussa et al., 2017). Table 6 presents the initial pH, final pH after 90 minutes, and pH change (ΔpH) for each experimental run, while Figure 5 illustrates pH variation during treatment. The data support the hypothesis that pH is the most critical variable influencing electrocoagulation performance, as operation outside the optimal pH range significantly reduces treatment efficiency and may lead to process failure.

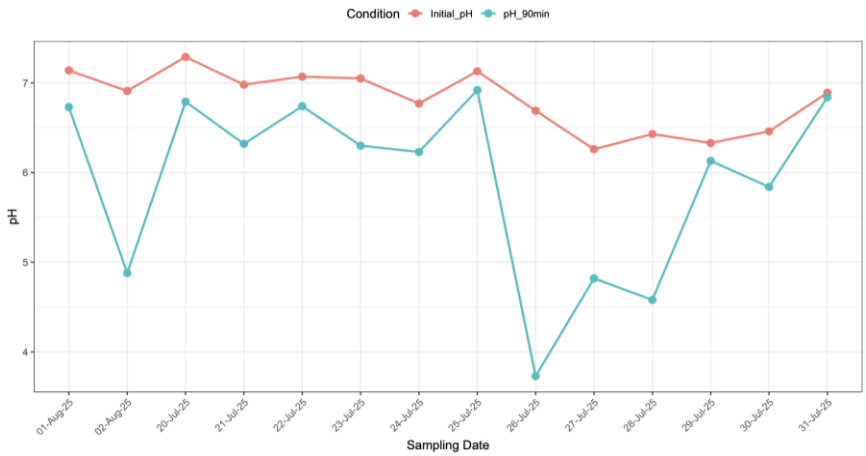


Figure 5. Temporal variation of pH during the electrocoagulation treatment process

All treatment runs exhibited a consistent decrease in pH, with ΔpH values ranging from –0.05 to –2.96. This behavior is commonly observed in Electrocoagulation systems employing aluminum electrodes (Kobya et al., 2011). At the anode, aluminum oxidation ($Al \rightarrow Al^{3+} + 3e^-$) releases Al^{3+} ions, while the cathode generates hydroxide ions through water reduction ($2H_2O + 2e^- \rightarrow H_2 + 2OH^-$). Although cathodic OH^- production would be expected to increase pH, the released Al^{3+} ions undergo sequential hydrolysis in the bulk solution, consuming hydroxide ions and producing protons: $Al^{3+} + H_2O \rightarrow$ monohydroxoaluminum $[Al(OH)^{2+}] + H^+$; $Al(OH)^{2+} + H_2O \rightarrow Al(OH)_2^+ + H^+$; $Al(OH)_2^+ + H_2O \rightarrow$ aluminum hydroxide $[Al(OH)_3] + H^+$. This proton generation explains the observed pH decline and demonstrates that electrocoagulation reactions inherently drive the system toward acidic conditions, potentially limiting effectiveness without appropriate control measures (Jiménez et al., 2012). The largest pH decrease was recorded on July 26 at the river site (6.69 to 3.73; ΔpH = –2.96). Significant decreases were also observed on August 2 (ΔpH = –2.03), July 27 (ΔpH = –1.44), and July 28 (ΔpH = –1.85). These substantial pH reductions coincided with negative TDS removal efficiencies, notably on July 26 (–15%) and July 28 (–10%), indicating non-optimal electrocoagulation conditions. This may be attributed to excessive current density or prolonged electrolysis exceeding the buffering capacity of the water. These findings highlight the critical role of buffering capacity in electrocoagulation performance. Aluminum hydroxide solubility increases significantly at pH values below 5 (Hakizimana et al., 2017). Under acidic conditions, aluminum predominantly exists in soluble forms (Al^{3+} and $Al(OH)^{2+}$) rather than as solid flocs, resulting in increased dissolved aluminum and TDS concentrations and explaining the observed reduction in removal efficiency. Aluminum hydroxide is amphoteric, with minimum solubility near neutral pH (6–7) and increased solubility under both acidic and alkaline conditions. At pH values below 5, as recorded on July 26 (3.73), July 27 (4.82), July 28 (4.58), and August 2 (4.88), aluminum species are not conducive to effective floc formation. In contrast, within the optimal pH range of 6–7, hydrolysis leads to the formation of gelatinous, insoluble $Al(OH)_3$ flocs with high surface area and adsorption capacity. Contaminant removal occurs via adsorption onto floc surfaces and sweeps coagulation. For example, a pH of 6.79 on July 20 resulted in the highest TDS removal efficiency (49%). This observation supports the hypothesis that maintaining near-neutral pH is essential for effective treatment, and even short-term deviations can significantly impair performance. A strong correlation was observed between final pH and treatment performance. Final pH values between 6.0 and 7.0 corresponded to positive removal efficiencies, whereas pH values below 5 resulted in poor or negative removal. Two anomalies were identified: July 27 (10% removal, final pH 4.82) and August 2 (19% removal, final pH 4.88). These results suggest that coagulation may have occurred during an intermediate period when pH was within the optimal range, followed by late-stage acidification. This indicates that treatment duration is a critical parameter, and earlier termination may have improved outcomes (Rahman et al., 2023). These anomalies further highlight that pH history, defined as the temporal evolution of pH during treatment, is as

important as the final pH. Therefore, process duration must be carefully optimized to prevent late-stage acidification from counteracting earlier treatment gains. At pH values above 8, aluminum redissolves as tetrahydroxoaluminate [$Al(OH)_4^-$] ions, further emphasizing the importance of maintaining an optimal pH range for stable floc formation (Garcia-Segura et al., 2017). The strong dependence of removal efficiency on pH underscores the necessity of continuous pH monitoring in electrocoagulation systems. The significant pH decreases observed during low-efficiency runs indicate that these systems are prone to acidification, particularly when treating low-alkalinity waters. This is especially relevant in coastal brackish environments such as Pekalongan, where seawater mixing creates a complex ionic matrix with limited buffering capacity against protons generated during aluminum hydrolysis. Continuous monitoring is therefore essential to detect unfavorable conditions before it compromises treatment performance. The narrow optimal pH range (6–7) presents a significant challenge for electrocoagulation system design. Fixed operating conditions based solely on treatment time or current are insufficient for waters with variable characteristics. Recommended operational strategies include optimizing current density according to water alkalinity, limiting treatment duration to prevent excessive acidification, and applying alkaline dosing when initial alkalinity is low. The relationships between pH trajectories and treatment outcomes support the hypothesis that successful electrocoagulation implementation in coastal environments requires a transition from fixed methods to adaptive feedback control systems. The rapid acidification observed in Pekalongan's brackish water indicates that raw water characterization should extend beyond initial contaminant concentrations to include buffering capacity. Future studies should investigate predictive models for real-time pH monitoring and automated current density adjustment, combined with low-dose pH control to maintain optimal conditions (Bazrafshan et al., 2015). These improvements would further support the hypothesis that adaptive management, rather than treatment intensification, is key to realizing the full potential of electrocoagulation for community-scale desalination in variable coastal environments (Kabdaşlı et al., 2012; Kuokkanen et al., 2013). Overall, the findings reinforce the importance of real-time pH monitoring and adaptive control for reliable electrocoagulation performance under changing field conditions. This positions electrocoagulation as a practical solution for coastal communities facing brackish-water challenges, rather than merely a laboratory-based technique. Furthermore, integrating real-time pH monitoring with adaptive control systems enhances field operability, demonstrating that such approaches effectively bridge the gap between optimal laboratory conditions and the operational reliability required in complex environments such as Pekalongan.

The pH variation during the 90-minute treatment period provides additional insight into the electrochemical reactions occurring during electrocoagulation. The continuous decrease in pH observed during treatment indicates the influence of aluminum hydrolysis and electrochemical reactions on solution chemistry. Therefore, monitoring treatment duration and pH variation is important to maintain effective coagulation conditions and avoid deterioration of treatment performance. The final pH values also varied considerably, with several treatment runs falling below the acceptable drinking-water range. This indicates that pH adjustment would be required for those treatment conditions. Furthermore, because microbiological and other chemical drinking-water parameters were not evaluated in this study, compliance with drinking-water standards cannot be established based solely on the measured parameters. Consequently, the treated water should be considered unsuitable for direct consumption under the tested conditions and would require additional treatment and comprehensive water-quality verification before use as drinking water. Considering the combined effects of electrocoagulation on dissolved solids, salinity, and pH variation, these findings indicate that electrocoagulation is an effective technology for improving coastal brackish water quality. However, electrocoagulation alone may not be sufficient as a standalone treatment for producing potable water under the tested conditions. Therefore, EC is more appropriately applied as a pre-treatment process that can be integrated with subsequent purification technologies to achieve drinking water standards.

3.5 Reproducibility and Sustainability Analysis

The scientific value of this study lies in the disparity observed between the efficiency of peak removal and the average performance in field conditions Although electrocoagulation is able to reduce salinity and TDS by up to 49% under optimal conditions, the average efficiency achieved is relatively low with significant variations. Therefore, the maximum removal value represents a specific favorable condition rather than the general performance of the system during field operation. These findings indicate that reliance on maximum elimination values may result in overestimation of the operational feasibility of electrocoagulation. Process stability, pH control, and raw water quality heterogeneity are proven to be the main determinants of successful application in the field. Thus, this study provides an understanding that the implementation of electrocoagulation in real life requires an adaptive operating strategy, rather than simply following a fixed protocol from laboratory results.

In the perspective of community-scale implementation, water treatment technologies must meet the criteria of effectiveness, consistency, and reproducibility amid variations in water quality (Crittenden et al., 2012; Metcalf et al., 2014). This dataset collected from various times and location points is one of the first field studies to evaluate electrocoagulation in brackish water under actual conditions. A statistical summary of the efficiency of the 14-day allowance is presented in Table 6, while Figure 6 shows the distribution of the data using a boxplot.

Table 6. Statistical summary of removal efficiencies for key water quality parameters during electrocoagulation treatment

Parameter	n	Mean removal (%)	Min (%)	Max (%)	SD (%)	95% CI of mean removal (%)
Salinity	14	4.91	-15.00	49.43	14.83	-3.65 to 13.48
TDS	14	4.13	-14.68	48.90	15.13	-4.61 to 12.86
Conductivity	14	4.10	-15.11	49.04	15.25	-4.70 to 12.91
DO	10	20.15	9.16	36.63	9.51	13.35 to 26.95

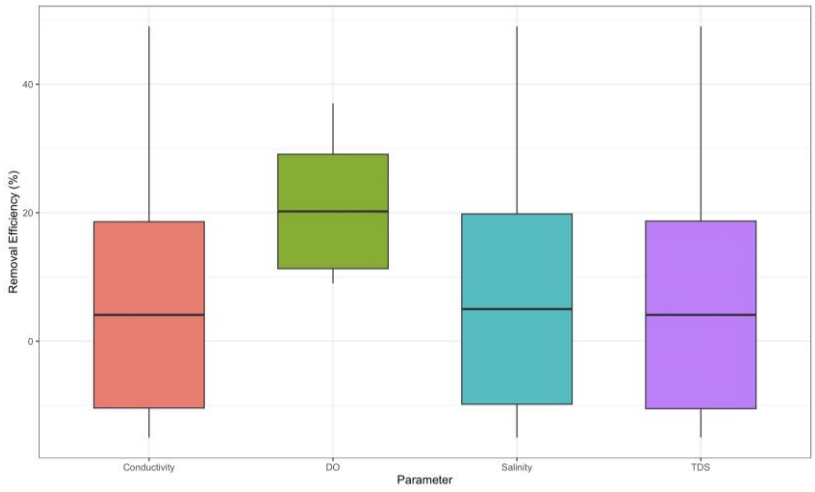


Figure 6. Distribution of removal efficiencies for selected water quality parameters over 14 days of electrocoagulation experiments

Most removal efficiencies were relatively low, with average removal values of 4.91% for salinity, 4.13% for TDS, and 4.10% for conductivity. In some instances, removal efficiencies approached zero. DO, however, showed a decrease after electrocoagulation treatment (20.15%, n = 10). This change should not be interpreted as pollutant removal efficiency because dissolved oxygen is an indicator of water oxygen conditions rather than a target contaminant. The observed decrease may reflect changes in oxygen transfer, electrochemical reactions, and water chemistry during the treatment process (Moussa et al., 2017). The observed variability in electrocoagulation performance indicates selective contaminant

removal, where adsorption-driven removal of organic matter is more effective than coagulation-based removal of ionic species. The substantial gap between mean removal (4–5%) and peak removal (49%) highlights the discrepancy between ideal and real-world operating conditions. This aligns with previous field studies reporting lower efficiencies due to uncontrollable environmental factors (Drogui et al., 2007; Jiménez et al., 2012). In contrast, laboratory studies typically report higher removal efficiency. The high standard deviations for salinity (14.83%), TDS (15.13%), and conductivity (15.25%) indicate substantial variability and poor reproducibility of electrocoagulation performance under field conditions. The high coefficient of variation values for salinity, TDS, and conductivity further confirm the instability of the system, indicating that electrocoagulation performance was highly sensitive to fluctuations in raw water characteristics (Hakizimana et al., 2017). In contrast, the observed DO change (SD = 9.51%) was relatively more stable, indicating that dissolved oxygen conditions were less variable during treatment compared with dissolved ionic parameters. However, this change reflects variation in water chemistry rather than removal efficiency (Garcia-Segura et al., 2017). Negative removal was observed on July 26, 2025, at the river site, coinciding with a pH drop to 3.73. This indicates a complete process failure, likely caused by unfavorable raw water characteristics and suboptimal operating conditions (Kobya et al., 2011). Conversely, the maximum removal efficiency of 49% was recorded on July 20 at the shallow well (pH 7.29; TDS 10,490 ppm), demonstrating the operational potential of electrocoagulation under optimal conditions. Overall, the wide performance range (–15% to 49%) underscores the lack of reproducibility and limits the reliability of electrocoagulation for consistent treatment under variable field conditions. Given that positive removal occurred in only 64% of observations, while 36% exhibited negative removal below –5%, such performance is unacceptable for a community-scale water supply system (Edition, 2011; Rahman et al., 2023). This inconsistency introduces significant health risks, particularly in the absence of post-treatment monitoring. A potential electrocoagulation application incorporating front-end RO or membrane distillation (MD) could be combined with an internal electrocoagulation unit for each MD stack column, serving as a pre-EC/RO module. This configuration could provide non- electrocoagulation pretreatment for MD or enhance electrocoagulation operation, particularly regarding any recirculation of the MD concentrate stream. Furthermore, recirculation of the MD concentrate could be optimized, potentially enabling a more compact electrocoagulation configuration. This approach may also improve organic load degradation, especially if MD is preceded by a dissolved air flotation unit or a similar process for organic removal. However, in analyzing electrocoagulation field performance, operational control should be considered as a real-time balancing of performance parameters to achieve optimal control or to revert to a more passive control mode. For MD operational performance, both pre- and post- electrocoagulation conditions can be evaluated using a mesh membrane. Pre electrocoagulation performance establishes conditions for a relatively passive or quasi-steady-state MD operation by regulating retention time. When a persistent operational state is achieved, MD operation approaches steady state, and the passive pre- electrocoagulation condition is likely maintained within the overall electrocoagulation control mechanism. This operational stability may be further enhanced by removing the membrane anti-wetting control fluid from the MD system, as well as by adopting a more compact electrocoagulation configuration. This observation is further illustrated in Figure 7, which shows the distribution of removal efficiencies, highlighting the dominance of positive removal for TDS, mixed outcomes for salinity, and the relatively balanced contribution of key parameters to overall variability.

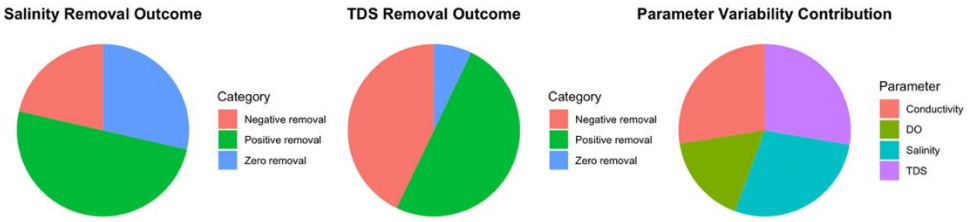


Figure 7. Distribution of removal efficiencies for selected water quality parameters over 14 days of electrocoagulation experiments

3.6 Feasibility Indicators

The evaluation of the feasibility of the electrocoagulation process was carried out through a series of field observations over several days, time series monitoring, and testing on various water sources. The collected dataset includes successful and unsuccessful treatment results, providing a realistic reflection of the performance of this technology in dynamic coastal brackish water conditions. The provision of raw data of the time series as an attachment strengthens the transparency aspect and allows independent validation of the efficiency of the provisioning presented. On the other hand, this feasibility assessment also highlights a number of limitations. First, the study did not involve parallel experimental replication for each sampling point and time. As a result, the observed variability does reflect fluctuations in raw water quality and process instability, but the element of uncertainty from the repetition of the experiment cannot be separated. Second, power consumption and electrode consumption are not measured directly, but are estimated through theoretical calculations based on operational parameters and Faraday's laws. This approach was taken in view of the importance of this operational aspect in determining feasibility, given that the efficiency of the dispensing alone is not enough, a process with high energy requirements or a fast electrode corrosion rate will reduce its competitiveness in the field. Thus, future feasibility studies should integrate measurements of actual power consumption, electrode mass loss, sludge production, and cost analysis to more accurately assess the potential application of these technologies at a community scale.

3.7 Statistical Reliability of Removal Performance

Testing the reliability of electrocoagulation results was carried out through the determination of confidence intervals and statistical hypothesis tests, as a complement to descriptive statistics. Based on 14-day data, the 95% confidence intervals for salinity removal (-3.65% to 13.48%), TDS removal (-4.61% to 12.86%), and conductivity removal (-4.70% to 12.91%) included zero values. This indicates that the overall removal performance of electrocoagulation for dissolved ionic parameters was not statistically consistent across the observation period. Therefore, electrocoagulation performance under the tested conditions should be interpreted as variable field performance rather than as a consistently effective desalination process. In contrast, the observed DO decrease showed a narrower confidence interval (13.35% to 26.95%), indicating a relatively consistent change in dissolved oxygen conditions during treatment. However, this change does not represent contaminant removal performance. However, these statistical results should be interpreted with caution because the observations were obtained from different sampling dates and locations rather than repeated measurements under identical experimental conditions. Consequently, the confidence intervals reflect variability across field conditions and do not represent uncertainty derived from experimental replication. Paired t-tests between initial and late concentrations showed that the difference for salinity and TDS was not significant at $p < 0.05$. This confirms that, despite the existence of days of high dispensing efficiency, overall the processing effect was inconsistent across the entire set of observations. These findings reinforce the conclusion that the performance of electrocoagulation in dynamic coastal environments is highly dependent on raw water quality, pH fluctuations, and operational stability. Although a maximum efficiency of 49% indicates promising potential, wide confidence intervals,

statistical insignificance, and the emergence of negative efficiencies indicate that this process is not mature enough for community-scale applications without further refinement. Therefore, future implementation should integrate a real-time control system, responsive pH adjustment, and validation through repeated tests with adequate control.

3.8 Control and Comparative Assessment

A direct untreated control reactor and side-by-side comparison with conventional treatment methods were not included in the original field campaign. Therefore, the benefit of electrocoagulation was assessed by comparing initial and final water quality values and by providing a qualitative comparison with commonly used treatment methods based on previous studies. The comparison is summarized in Table 7. Based on this comparison, electrocoagulation shows potential as a small-scale treatment option or pretreatment process for coastal brackish water. However, because the removal performance in this study was highly variable, electrocoagulation should not be considered a reliable stand-alone desalination method without further optimization, untreated control testing, and direct comparison with conventional or hybrid treatment systems.

Table 7. Comparative assessment of electrocoagulation and alternative treatment approaches

Treatment approach	Main function	Expected performance for salinity/TDS	Practical advantages	Main limitations
Untreated condition	No active treatment	Very limited removal; changes may occur only due to natural settling or storage effects	No energy or chemical input	Cannot remove dissolved salts effectively
Simple filtration	Removes suspended solids and turbidity	Low effectiveness for dissolved ions such as salinity and TDS	Simple, low cost, easy to operate	Not suitable as a stand-alone desalination method
Adsorption	Removes selected pollutants and organic compounds	Limited and material-dependent removal of dissolved ions	Flexible and relatively simple	Requires adsorbent replacement or regeneration
Reverse osmosis / membrane treatment	Removes dissolved salts and ions	High salt rejection	Effective for desalination	High pressure, energy demand, membrane fouling, and maintenance cost
Electrocoagulation	Generates coagulants in situ through aluminum electrode dissolution	Variable removal; maximum salinity and TDS removal	No external chemical coagulant, simple reactor design,	Sensitive to pH, raw water quality, current density, and electrode condition

Treatment approach	Main function	Expected performance for salinity/TDS	Practical advantages	Main limitations
		reached 49% in this study	potential for small-scale use	

To further evaluate the applicability and future development potential of electrocoagulation technology for coastal brackish water treatment, a SWOT analysis was conducted based on the experimental findings, operational performance, and comparison with other treatment approaches. This analysis identifies the key strengths and limitations of electrocoagulation, as well as the opportunities and challenges associated with its implementation in real-world applications. The SWOT assessment provides a broader perspective on the feasibility of electrocoagulation as a potential treatment strategy, particularly for improving water quality in coastal areas affected by seawater intrusion.

Table 8. SWOT analysis of electrocoagulation technology

Aspect	Analysis
Strengths	Electrocoagulation generates coagulants in situ through aluminum electrode dissolution, does not require external chemical coagulants, uses a relatively simple reactor configuration, and demonstrated maximum salinity and TDS removal of 49% in this study.
Weaknesses	Treatment performance was highly variable under field conditions, with average removal efficiencies of only 4–5%. The process was sensitive to pH variation, raw water characteristics, and electrode conditions.
Opportunities	EC has potential as a small-scale pre-treatment technology for coastal communities affected by seawater intrusion. Integration with membrane filtration, adsorption, or other polishing processes may improve reliability.
Threats	Practical implementation may be affected by fluctuating coastal water quality, energy requirements, electrode consumption, maintenance needs, and the absence of direct comparison with optimized hybrid systems.

The SWOT analysis indicates that electrocoagulation has potential as a decentralized treatment approach for coastal brackish water, particularly due to its simple configuration and ability to improve water quality without external chemical coagulants. However, the observed variability in field performance highlights the need for adaptive operation and integration with complementary treatment technologies before large-scale implementation.

3.9 Limitations

As with field research in general, this study is not without a number of limitations that need to be considered in interpreting the findings. First, the observational research design in the field using raw water from shallow wells and rivers causes the quality of treated water to vary greatly from one day to the next and from one location to another. This natural variability certainly affects the consistency level of the processing results achieved. Second, in the implementation of the experiment, no control reactor that runs in parallel without electrocoagulation treatment is included. As a result, changes in water parameters that may arise from natural processes such as precipitation, evaporation, or temperature changes cannot be expressly distinguished from the influence of the electrocoagulation process itself. Third, this study did not conduct direct comparison tests with other water treatment technologies, such as conventional filtration, adsorption, reverse osmosis, or membrane technology. Therefore, discussions about the advantages or disadvantages of electrocoagulation relative to other technologies refer only to literature reviews, not to equivalent experimental data. To overcome these limitations, future research is

recommended to design experiments with adequate repeatability, including no-treatment control, performing blank tests, and directly comparing electrocoagulation with alternative or hybrid treatment systems. These measures are important to strengthen statistical validity and strengthen the practical evidence regarding the application of electrocoagulation to coastal brackish water treatment.

4. Conclusions

This study evaluated the effectiveness and operational stability of electrocoagulation for reducing salinity and TDS in brackish water from coastal Pekalongan through multi-location and multi-day field observations. The results demonstrate that electrocoagulation has the potential to improve brackish water quality; however, its performance under fluctuating field conditions remains highly variable. The electrocoagulation system achieved maximum removal efficiencies of approximately 49% for salinity and TDS in individual treatment runs; however, the overall average removal efficiencies were only 4–5%, indicating variable performance under field conditions. However, the recalculated average removal efficiencies were 4.91% for salinity, 4.13% for TDS, and 4.10% for conductivity, while DO showed an average removal efficiency of 20.15%. These results reflect the influence of multiple days with minimal or negative removal performance. Changes in DO concentration were also observed during treatment, with an average decrease of 20.15%. However, this decrease reflects changes in dissolved oxygen conditions during electrocoagulation and should not be interpreted as evidence of oxygen-demanding substance removal. The analysis also revealed substantial variability in treatment performance. Standard deviation values for salinity, TDS, and conductivity were approximately three times higher than their respective means, indicating poor reproducibility of the electrocoagulation process over the 14-day observation period. Several experimental runs exhibited negative removal efficiencies, particularly when the final pH dropped below 5. Under such acidic conditions, aluminum hydroxide flocs tend to redissolve into soluble aluminum species, thereby reducing coagulation efficiency and increasing dissolved solids in the treated water. Variations in pH during the electrocoagulation process provide important insights into the underlying reaction mechanisms. The consistent decrease in pH across all experimental runs confirms that aluminum hydrolysis reactions dominated the system chemistry, producing protons and resulting in net acidification. Optimal treatment performance generally occurred when the final pH remained near neutral (6–7), where insoluble aluminum hydroxide flocs formed most effectively. Significant pH drops below this range were associated with decreased removal efficiency and, in some cases, deterioration of water quality. Based on comparison with the applicable drinking-water requirements and the limited set of water-quality parameters evaluated in this study, the electrocoagulation-treated water cannot be considered suitable for direct consumption. Additional treatment and comprehensive testing of drinking-water quality parameters are required before the treated water can be considered potable. The most pronounced changes generally occurred within the first 30–60 minutes of treatment. However, this range should not be interpreted as a formally determined optimum because no optimization experiment was conducted. Extending the process to 90 minutes often yielded only marginal improvements or even reduced performance, due to excessive electrode dissolution and increased acidification. Overall, the findings highlight a significant gap between the potential performance of electrocoagulation under controlled conditions and its operational stability under real field conditions. While electrocoagulation demonstrated promising peak removal efficiencies, the high variability and frequent process upsets indicate that further optimization and control strategies are required before the technology can be reliably implemented for community-scale brackish water treatment in coastal areas. Future work should focus on improving process stability through adaptive control of current density, treatment duration, and pH regulation. Additionally, integrating Electrocoagulation with complementary polishing technologies, such as membrane filtration or adsorption, may enhance system reliability and provide a more sustainable solution to address clean water challenges in coastal communities, such as Pekalongan. Statistical reliability analysis showed that the average salinity, TDS, and conductivity reductions were accompanied by wide confidence intervals that included zero values, confirming that electrocoagulation performance

in general was statistically inconsistent even though high efficiency could be achieved under certain conditions. The main contribution of this research is the mapping of the potential and limitations of electrocoagulation in the context of coastal brackish water fields. Further research should include experimental replication, treatment less control, blank assays, and direct comparisons with alternative or hybrid systems to strengthen the reliability and applied validity of the findings.

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Ethics Statement

No human clinical interventions or animal experiments were conducted as part of this research.

CRediT Author Statement

Wildan Herwindo: Idea Development, Research Design, Program Development. **Ingerawati Sekar Bumi**: Resources, Manuscript Draft Preparation, Project Administration. **Annisa Sila Puspita**: Visualization, Supervision. **Anis Sulistianingsih**: Resources, Manuscript Draft Preparation, Project Administration.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used Chat GPT-3.0 to improve readability and language understanding. After utilizing this AI technology, the author(s) meticulously reviewed and amended the content as required, ensuring its accuracy and completeness. The author(s) assume(s) complete accountability for the content of the publication.

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