

# Treatment of Polluted River Water with Electrocoagulation Using Waste Aluminium Cans Based on Green Technology

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River pollution caused by domestic and industrial discharges has become a major environmental concern. Conventional water treatment often requires large amounts of chemical, generates substantial sludge, and incurs high operational costs, while the use of low-cost recycled electrodes in electrocoagulation remains insufficiently explored. Therefore, green alternatives are needed to improve water quality. Electrocoagulation is a water treatment process that forms coagulants to remove pollutants from wastewater by applying an electric current offers an alternative solution as a green technology for the treatment of polluted river water. The aim of this study was to develop and evaluate the efficiency of electrocoagulation using aluminum electrodes from canned drinks as a green technology method for river water quality and to determine optimum operating conditions. In this study, river water was treated by electrocoagulation method using eight aluminum plates electrode from canned drinks measuring 6x6 cm, and a reactor measuring 12x6x8 cm. The electrocoagulation process was carried out under varying contact times (10-45 minutes), electrode distances (1-2 cm), and applied voltages (6 to 12 V). The optimum operating conditions were obtained at a contact time of 40 min, an electrode distance of 1 cm, and an applied voltage of 12 V. Under these conditions, the electrocoagulation process effectively reduced dissolved solids and conductivity while maintaining favorable pH conditions for floc formation. Kinetic analysis showed that the pseudo-first-order model ( $R^2 = 0.9611$ ) described the electrocoagulation process better than the pseudo-second-order model ( $R^2 = 0.8940$ ), suggesting that the removal process was predominantly governed by physical adsorption onto aluminum hydroxide flocs. In addition, the proposed system demonstrated lower energy consumption and substantially lower estimated operating and equipment costs than a representative conventional laboratory-scale electrocoagulation system, highlighting its potential as a low-cost and environmentally friendly approach for small-scale river water treatment.

**Keywords:** Electrocoagulation, green chemistry, river water, clean water

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River water quality is greatly influenced by the social environment such as population density and social activities. Various human activities in fulfilling their daily needs originating from industrial activities, factories, settlements and agriculture will produce waste which contributes to the decline in river water quality [1]. Modern industries such as mining, metallurgy, chemical industry, metal industry, discharge various pollutants, including organic and inorganic ions, into the environment, which causes water to become polluted [2] Pollutants in the form of heavy metal ions consist of mercury, lead, cadmium, arsenic, copper, chromium, nickel and zinc [3]. These heavy metal ions damage the ecosystem because they are not biodegraded and accumulate in plants and animals [4].

Preview research by Mamun et al [5] on the Geum River in South Korea, the concentrations

of five-day Biochemical Oxygen Demand (BOD<sub>5</sub>) and Chemical Oxygen Demand (COD) ranged from 0.76-7 mg/L and 3-18 mg/L, respectively. The maximum BOD<sub>5</sub> and COD concentrations exceeded the WHO guideline limits of 5 mg/L and 10 mg/L, respectively. These findings indicate the presence of organic pollution that may contribute to the deterioration of river water quality. The study further identified intensive agricultural activities and built-up areas as the primary sources of nutrient inputs and organic pollutants, particularly in the downstream sections of the river [6]. Deterioration of water quality is indicated by changes in color and odor, and the high COD and BOD values [7].

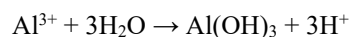
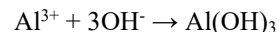
According to United States Environmental Protection Agency (US EPA), the recommended total dissolved solids (TDS) limit for drinking water is 500 mg/L, while the Bureau of Indian Standards

[8] specifies a maximum permissible limit of 2000 mg/L. The highest TDS concentration recorded in the Gambia River. Boussouga et al [9] reported that the Gambia River in West Africa was polluted with pesticides, pharmaceutical waste, and polyfluoroalkyl compounds with a concentration of 1500 ng/L. Meanwhile, the TDS ranging from 0.02-33 g/L. The Gambia River is located near agricultural land and pharmaceutical industrial areas, allowing pesticide-contaminated groundwater and untreated pharmaceutical wastewater into the river, resulting in elevated levels of TDS.

Various methods have been developed as an effort to overcome river water pollution, such as electrocoagulation [10, 11], ceramic membranes [12], adsorption [11], coagulation [13] and ultrafiltration [14]. Among these methods, electrocoagulation (EC) is emerging as a promising alternative due to its advantages that overcome the limitations of conventional treatment methods [15]. EC produces coagulant in situ by applying an electric current to metal electrodes, easy installation and operation, short maintenance time, and the ability to remove very fine particles, as these fine particles are more easily attracted to an electric field [16]. In addition, EC does not require chemical additives because the coagulant is produced directly from the eroded sacrificial electrodes, thus minimizing secondary pollution and reducing sludge production [17]. Therefore, the EC method is classified as a green technology for water and wastewater treatment [18]. According to Manahan [19], chemical experiments which aim to minimize the formation of waste are included in the green chemistry category and are in accordance with sustainable development goals [20]. Bassie [21] further describe green chemistry as the redesign of chemical products and processes with the aim of reducing or eliminating negative impacts on the environment and human health.

Electrocoagulation is an electrochemical process in which coagulants are generated in situ by applying an electric current to a sacrificial metallic anode, leading to the destabilization of suspended pollutants. At the same time, hydrogen gas produced at the cathode aids in floating contaminants to the surface [22]. The type of coagulant formed depends on the electrode material, which is selected based on pollutant characteristics, material cost, and oxidation potential. Among the various materials reported, aluminum is widely recognized as one of the most effective electrode materials for EC [23] and therefore it is used in the present study. When an electric current flows through the Al electrodes, the anode undergoes corrosion and releases metal cations that rapidly transform into polymeric metal hydroxides, functioning similarly to coagulant salts in conventional chemical coagulation [24]. These reactions can be summarized as follows:

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



The  $\text{OH}^-$  ions from the base will undergo oxidation to form oxygen gas ( $\text{O}_2$ ),



Cathode reactions:  $2\text{H}_2\text{O} + 2\text{e}^- \rightleftharpoons \text{H}_2 + 2\text{OH}^-$

From these reaction,  $\text{O}_2$  gas will be produced at the anode, and  $\text{Al(OH)}_3$  formed in the solution acts as a coagulant that binds suspended pollutants to form flocs. These flocs then settle or float, resulting in the separation of clean water from contaminants. The performance of the electrocoagulation process is commonly evaluated based on its separation efficiency, which is calculated using the following equation:

$$\% \text{ Efficiency} = \frac{C_o - C_t}{C_o} \times 100\%$$

Where:  $C_o$  = initial concentration of the target pollutant (mg/L)

$C_t$  = concentration of the target pollutant after electrocoagulation (mg/L)

One of the primary environmental advantages of electrocoagulation is its minimal reliance on external chemical coagulants. In conventional coagulation processes, chemicals such as aluminum sulfate (alum) or ferric chloride are added to water to promote contaminant removal, often resulting in chemical residues and secondary pollution. In contrast, EC employs sacrificial electrodes to generate metal ions directly within the treatment system, significantly reducing or even eliminating the need for additional chemical coagulants. This approach minimizes the chemical footprint of the treatment process and improves water quality by preventing residual chemical contamination [25].

Compared with chemical coagulation (CC), EC produces significantly lower volumes of sludge. A study conducted by Gasmi et al [26], the sludge concentration generated by CC reached 395 mg/L, whereas EC produced only 256 mg/L. The in-situ generation of coagulants promotes efficient floc formation, yielding denser sludge with lower water content, which is easier to handle and dispose of. This reduction in sludge volume decreases disposal challenges and associated environmental impacts. Furthermore, the lower chemical content of EC-generated sludge enables safer handling and potential reuse in agricultural or construction applications, contributing to waste minimization and circular economy principles [27].

Early electrocoagulation systems were often limited by high energy consumption, restricting

their widespread application. However, modern innovations have enhanced the energy efficiency of these systems. Advances in power management, optimized reactor designs, and the integration of renewable energy sources such as solar and wind have made EC more sustainable. Additionally, pulse current and intermittent power supply techniques have reduced energy requirements without compromising treatment performance. These improvements align EC technology with energy conservation goals, making it more cost-effective and environmentally friendly [27].

This study presents a low-cost and environmentally friendly electrocoagulation system that utilizes recycled aluminum beverage cans as sacrificial electrodes, commercially available iron nails as iron electrodes, and magnesium metal as a galvanic current source for water treatment. The system was evaluated in terms of treatment efficiency and economic feasibility relative to conventional chemical coagulation. By integrating recycled materials with inexpensive electrode components, the proposed system embodies key green chemistry principles, including waste prevention, resource reutilization, and cost-effective water treatment.

## EXPERIMENTAL

### Chemicals and Materials

Water samples were collected from the Ciliwung River due to its exposure to multiple anthropogenic pollution sources, including domestic wastewater, agricultural runoff, commercial activities, industrial discharges, and land use changes. River water from the Ciliwung River was collected using pre-cleaned polyethylene bottles and analyzed immediately. Aluminum and iron electrodes ( $3 \times 6$  cm) prepared from recycled Al cans and mild steel sheets were installed in a 50 mL electrocoagulation cell powered by a 9 V DC source. Water quality parameters (pH, TDS, and conductivity) were measured using calibrated portable meters, and all reagents were analytical grade. All experiments were performed at room temperature (25°C) with measurements conducted in triplicate.

### River Water Sampling

River water samples were collected from the Ciliwung River located on Jalan Rawasari, Cempaka Putih Timur Subdistrict, Cempaka Putih District, Central Jakarta (6°07'04" S, 106°49'43" E). River water flows through residential areas. River water samples were

collected at four sampling points located 100, 120, 140, and 160 m downstream of a restaurant wastewater disposal outlet. Samples were collected using polyethylene bottles. Prior to sampling, polyethylene bottles were rinsed with 10% HNO<sub>3</sub>, followed by distilled water, and finally conditioned with river water. Samples were taken at a depth of approximately 50 cm below the water surface. Sample collection is carried out at 4 points. Each bottle is labeled according to the sampling point. Samples from the four points were mixed and analyzed for TDS, pH and conductivity. Composite sampling was performed to obtain a representative sample that reflects the average water quality of the study area and minimizes spatial variability.

### pH Measurement

The pH of river water was measured using a calibrated digital pH meter (IONIX pH meter). Calibration was performed prior to measurement using standard buffer solutions of pH 4 and pH 7. Measurements were conducted at room temperature, and the pH value was recorded.

### Electrical Conductivity

Electrical conductivity was measured using a conductivity meter (Lutron CD-4301) calibrated with deionized water and a standard conductivity solution. The electrode was immersed in the sample until a stable reading was obtained, and the value was recorded in  $\mu\text{S/cm}$ .

### Total Dissolved Solids (TDS)

TDS was measured using a digital TDS meter (Lutron CD-4301) according to standard protocols. The instrument was calibrated before measurement, and the electrode was immersed in the sample until a stable reading was obtained. Each sample was measured three times, and the average value was reported.

### Electrocoagulation Treatment

Electrocoagulation experiments were conducted using a mini container plastic which functions as an electrolysis cell with a volume of 50 mL. As electrodes, aluminum from used beverage cans was cut to dimensions of  $3 \times 6$  cm. Electrode spacing was adjusted to 1.0, 1.5, and 2.0 cm for optimization. A 9 V DC battery served as the power source. The arrangement of the equipment is shown in Figure 1 below.

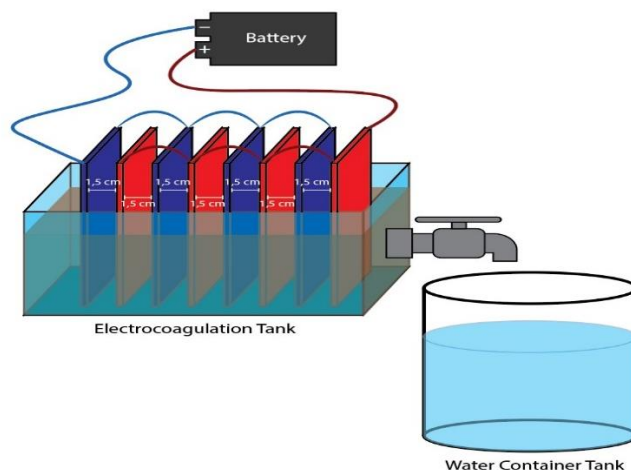


**Figure 1.** Electrocoagulation tank.

**Table 1.** Ciliwung River water quality

| No | Parameter                                | Value |
|----|------------------------------------------|-------|
| 1  | pH                                       | 6.8   |
| 2  | TDS (mg/L)                               | 118   |
| 3  | Conductivity ( $\mu\text{S}/\text{cm}$ ) | 480   |

A 30 mL aliquot of the river water was placed into electrocoagulation cell. A total of eight electrodes were connected to the battery using insulated alligator clips, and electrolysis was carried out for varying durations (10, 20, 25, 30, 35, 40 and 45 minutes). After treatment, electrodes were removed, and the treated water was filtered through Whatman No. 42 filter paper to separate the formed flocs. The filtrate was collected in labeled bottles for subsequent analysis of pH, conductivity, and TDS. All experiments were performed in triplicate, and results were expressed as mean values.

## RESULTS AND DISCUSSION

### Characteristic River Water

The results of chemical analysis of Ciliwung River water are shown in **Table 1**.

Although the pH and Total Dissolved Solids (TDS) values in Ciliwung River water samples still meet the quality standards stipulated in Government Regulation No. 22 of 2021 (pH 6-9 and TDS  $\leq 1,000$  mg/L) [28] these two parameters are not sufficient to represent the overall water quality conditions. Various studies have shown that the Ciliwung River still faces pollution pressure from contaminants that are not always reflected in basic physical parameters. One contaminant that has received much attention is

microplastics. Mahendra et al. [29] reported that the abundance of microplastics in Ciliwung River water ranged from 320-741 particles/L, while in sediment it reached 6,560-10,630 particles/kg, with the dominant form being fragments (97%). In addition, Wilyalodia et al[30] found that microplastic abundance exhibited significant seasonal variation, increasing from an average of 530 particles/L in the dry season to 1,111 particles/L in the rainy season, while in sediment it increased from 859 to 1,583 particles/100 g. These findings indicate the presence of significant anthropogenic pollution pressure even though basic water quality parameters remained within the standard range. On the other hand, the initial physicochemical characteristics of the Ciliwung River water provide favorable conditions for the application of the electrocoagulation process. The pH value in the neutral range (6-8) and conductivity of around 480  $\mu\text{S}/\text{cm}$  indicate sufficient electrolyte availability to support the release of coagulant ions ( $\text{Al}^{3+}$  or  $\text{Fe}^{2+}/\text{Fe}^{3+}$ ) from the electrode without requiring the addition of external electrolytes. This condition is important because electrocoagulation efficiency is strongly influenced by the pH and conductivity of the solution. Various studies have reported that the electrocoagulation process generally works optimally in the conductivity range of 200-1500  $\mu\text{S}/\text{cm}$ , which allows for effective charge transfer and efficient coagulant floc formation. Therefore, although the Ciliwung River still contains various contaminants

that require further treatment, the initial characteristics of its water show good suitability for kinetic studies and optimization of electrocoagulation process parameters

### Effect of Time Electrocoagulation on Water Quality

Changes in water quality parameters based on the electrocoagulation process time can be used to evaluate the effectiveness of system performance in reducing the concentration of dissolved solids and dissociated ions. The 10-45 minutes range was chosen based on previous studies. Lulesa et al. [31] used a reaction time range of 20-50 minutes in surface water treatment and reported that increasing the process time consistently increased the removal of COD, BOD, TDS, phosphate, and TSS. Meanwhile, Alam et al. [32] used a contact time range of 0-45 minutes in acid mine drainage treatment and found that increasing the electrocoagulation time to 45 minutes effectively increased the removal of heavy metals, particularly Fe and Mn. Thus, although Lulesa et al [31] began their observations at 20 minutes, Alam et al.'s (2024) study makes the 10-45 minutes range an appropriate choice because it covers the initial reaction phase (10 minutes) to near-optimal conditions (45 minutes)

where pollutant removal continues to increase. **Figure 2** below shows the effect of electrocoagulation time on pH, TDS, and river water conductivity.

**Figure 2** shows that as the electrocoagulation time increases, the pH tends to increase, while the TDS and conductivity values decrease. However, after a certain time, the changes in these three parameters become relatively small. **Figure 2a** showed that the pH value increases from 6.8 at the 10<sup>th</sup> minute to 8.0 at the 40<sup>th</sup> minute and remains constant until the 45<sup>th</sup> minute. At the same time in **Figure 2b**, the TDS value decreases from 98 mg/L to 64 mg/L at the 40<sup>th</sup> minute and only decreases to 62 mg/L at the 45<sup>th</sup> minute, while the conductivity in **Figure 2c** decreases from 423  $\mu$ S/cm to 185  $\mu$ S/cm at the 40<sup>th</sup> minute and then only decreases to 180  $\mu$ S/cm at the 45<sup>th</sup> minute. The decrease in TDS and conductivity from 40 to 45 minutes is only 3.1% and 2.7%, respectively, indicating that most of the coagulation and dissolved species removal processes have occurred before the 40<sup>th</sup> minute. Therefore, a contact time of 40 minutes can be considered the optimum operating time, as increasing the process time no longer provides a significant performance increase compared to the additional electrical energy required.

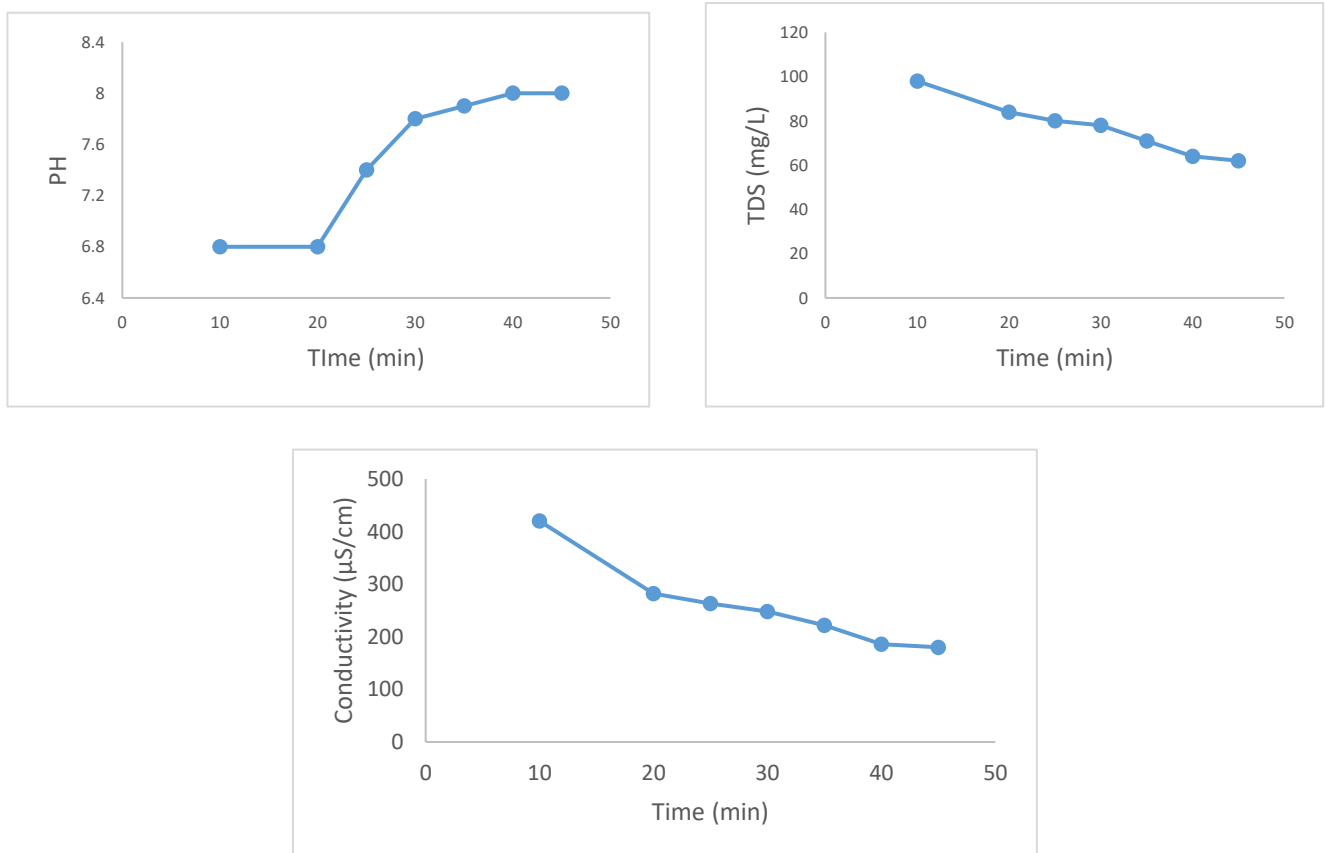


**Figure 2.** Effect of electrocoagulation time on (a) pH water (b) TDS (c) Conductivity.

The study observed an increase in pH during the electrocoagulation process. This occurs due to the water reduction reaction at the cathode, which produces hydroxide ions ( $\text{OH}^-$ ) and hydrogen gas ( $\text{H}_2$ ). The accumulation of  $\text{OH}^-$  ions in the solution increases the alkalinity and pH of the water. Furthermore, the formation of hydrogen bubbles can facilitate the release of dissolved carbon dioxide, thus contributing to the increase in pH. This phenomenon has been widely reported in various electrocoagulation applications using aluminum and iron electrodes [33].

The decrease in TDS and conductivity values occurs because metal ions released from the anode undergo hydrolysis and form hydroxide flocs, which act as coagulants. These flocs can adsorb and aggregate colloidal particles, organic matter, and dissolved ions in the water. As contact time increases, more solute is removed from the liquid phase, causing the TDS value to decrease. Since electrical conductivity depends on the concentration of free ions in solution, a decrease in the number of dissolved ions also causes a decrease in conductivity. Once most of the contaminants have been removed and the number of consumable ions becomes limited, the rate of change in pH, TDS, and conductivity decreases, so the system tends to reach a steady state [33, 34].

#### Influence of Electrode Type

The influence of electrode type on river water quality, particularly pH, TDS, and conductivity, is determined by the electrochemical characteristics of the metal used as the electrode. In this study, aluminum (Al) and iron (Fe) electrodes were chosen because they are the most used materials in electrocoagulation processes for water and wastewater treatment. In addition to being relatively inexpensive and readily available, the  $\text{Al}^{3+}$  and  $\text{Fe}^{2+}/\text{Fe}^{3+}$  ions produced during the electrolysis process can form hydroxide flocs that was effective in adsorbing and precipitating various

contaminants. Although copper (Cu) electrodes have also been reported to be used in electrocoagulation, the release of  $\text{Cu}^{2+}$  ions have the potential to cause secondary heavy metal contamination in the treated water, so their use is more limited compared to Al and Fe electrodes. A study by Zaher et al. [35] comparing Al, Fe, and Cu electrodes also showed that aluminum electrodes provide higher pollutant removal performance than the other two electrodes. Table 2 below shows the relationship between electrode type and water quality.

Based on **Table 2**, the Al-Al electrode produced the lowest TDS and conductivity values compared to other electrode combinations. This superior performance is likely related to the formation of  $\text{Al}(\text{OH})_3$  flocs, which are more effective as coagulants. Aluminum hydroxide flocs possess a large surface area and high adsorption capacity, enabling them to bind suspended particles and dissolved species more efficiently. These results consistent with research by Zaher et al. [35], reported that aluminum electrodes provided the highest xanthate removal efficiency compared to iron and copper electrodes. Furthermore, Rangseesuriyachai T, et al [36] also reported that the Al-Al electrode configuration produced higher TDS removal efficiency than Fe-Fe configuration during the electrocoagulation treatment of hospital wastewater.

However, the differences in TDS and conductivity values obtained in this study were relatively small. Because the experiment was not replicated to allow for statistical analysis, these differences cannot be declared statistically significant. Therefore, the results of this study only indicate a tendency that Al-Al electrodes provide better water quality than Al-Fe and Fe-Fe under the operating conditions used. Further research with sufficient repetitions and statistical analysis, such as ANOVA, is needed to confirm the significance of these differences.

**Table 2.** Effect of electrode type on river water quality at 40 minutes.

| No | Electrode | pH  | TDS (mg/L) | Conductivity ( $\mu\text{S}/\text{cm}$ ) |
|----|-----------|-----|------------|------------------------------------------|
| 1  | Al-Fe     | 7.8 | 74         | 210                                      |
| 2  | Al-Al     | 8.0 | 68         | 180                                      |
| 3  | Fe-Fe     | 7.8 | 76         | 195                                      |

**Table 3** Effect of electrode distance on river water quality at 40 minutes with Al-Al electrode.

| No | Electrode distance (cm) | pH  | TDS (mg/L) | Conductivity ( $\mu\text{S}/\text{cm}$ ) |
|----|-------------------------|-----|------------|------------------------------------------|
| 1  | 1                       | 6.8 | 74         | 208                                      |
| 2  | 1.5                     | 7.2 | 78         | 212                                      |
| 3  | 2                       | 7.2 | 82         | 220                                      |

### Influence of Electrode Distance

The distance between electrodes is a critical operating parameter affecting energy consumption, electric field distribution, mass transfer, and pollutant removal efficiency during the electrocoagulation process [33, 34]. Table 3 shows the effect of varying electrode spacing using an Al-Al configuration at a contact time of 40 minutes on river water quality. Table 3 below shows the effect of electrode spacing using Al-Al electrodes with a time of minutes on river water quality.

Based on Table 3, lower electrode spacing resulted in lower TDS and conductivity values. The lowest TDS (74 mg/L) and conductivity (208  $\mu\text{S/cm}$ ) were obtained at an electrode spacing of 1 cm, whereas the highest values were observed at 2 cm. These results indicate that increasing the electrode spacing tends to reduce the removal efficiency of dissolved species during electrocoagulation.

This phenomenon is associated with the increase in ohmic resistance as the distance between electrodes becomes larger. A shorter electrode spacing provides a shorter ion migration pathway, thereby reducing electrical resistance and enhancing charge transfer within the solution. Consequently, anodic dissolution and the generation of  $\text{Al}^{3+}$  ions are promoted, leading to more effective formation of  $\text{Al}(\text{OH})_3$  flocs that act as coagulants. In contrast, larger electrode spacing weakens the electric field and slows the migration of metal ions toward hydroxide ions ( $\text{OH}^-$ ), resulting in a lower floc formation rate and reduced electrocoagulation efficiency [33, 37].

In this study, electrode spacings of 1.0, 1.5, and 2.0 cm were selected based on the commonly reported operating range for laboratory-scale electrocoagulation systems. Distances below 1 cm were not investigated because they may increase the risk of short-circuiting, hinder gas bubble release, and promote excessive floc accumulation on the electrode surface, which can accelerate electrode fouling and reduce operational stability. Conversely, electrode spacings greater than

2 cm were not evaluated because larger gaps generally increase ohmic resistance and energy consumption while reducing treatment efficiency [33, 34].

Among the investigated conditions, an electrode spacing of 1 cm produced the lowest TDS and conductivity values and was therefore selected as the optimum electrode spacing for subsequent experiments. This optimum condition was subsequently used to evaluate the effect of applied voltage and to investigate the electrocoagulation kinetics of river water treatment.

### The Effect of Voltage on River Water Quality

The selection of voltage variations of 6, 9, and 12 V was based on scientific and technical considerations. This voltage range is widely used in electrocoagulation research for water and wastewater treatment, allowing for comparison of results with previous research [38]. Furthermore, voltages below 6 V generally produce low current densities, resulting in less effective anode dissolution and floc formation [39]. Conversely, applying too high a voltage, such as 15 V, can significantly increase energy consumption without a corresponding increase in removal efficiency and affect the characteristics of the aluminum hydroxide flocs formed [38]. Therefore, the range of 6-12 V was chosen as the operating conditions expected to provide a balance between process efficiency and energy requirements. The upper limit of 12 V is also adjusted to the specifications of the DC power supply available in the laboratory so that all experiments can be carried out stably and consistently. The effect of voltage was measured on electrode distance, Al-Al electrode type and minute time shown in Table 4.

Based on Table 4, increasing the applied voltage from 6 to 12 V resulted in lower TDS and conductivity values, whereas only minor changes were observed in pH. The TDS decreased from 102 mg/L at 6 V to 97 mg/L at 12 V, while conductivity decreased from 212 to 154  $\mu\text{S/cm}$ . These results suggest that a higher applied voltage enhanced the removal of dissolved species during the electrocoagulation process.

**Table 4.** Effect of voltage on river water quality at 40 minutes with Al-Al electrode and electrode distance 1 cm.

| No | Voltage (Volt) | pH  | TDS (mg/l) | Conductivity ( $\mu\text{S/cm}$ ) |
|----|----------------|-----|------------|-----------------------------------|
| 1  | 6              | 6.8 | 102        | 212                               |
| 2  | 9              | 6.8 | 98         | 186                               |
| 3  | 12             | 6.9 | 97         | 154                               |

The improved performance at higher voltages can be attributed to the increase in current density within the electrochemical system. According to Faraday's law, the amount of metal ions released from the sacrificial anode is proportional to the electric charge passing through the cell. Consequently, increasing the applied voltage promotes the dissolution of aluminum and increases the production of  $\text{Al}^{3+}$  ions. These ions subsequently undergo hydrolysis to form  $\text{Al}(\text{OH})_3$  flocs, which act as effective coagulants for the adsorption and aggregation of dissolved and suspended contaminants. As a result, the concentrations of dissolved species decrease, leading to lower TDS and conductivity values. Similar observations have been reported in previous electrocoagulation studies, where higher operating voltages enhanced coagulant generation and pollutant removal efficiency [40, 41].

Only a slight increase in pH was observed, from 6.8 at 6 and 9 V to 6.9 at 12 V. This trend is associated with the cathodic reduction of water, which generates hydroxide ions ( $\text{OH}^-$ ) and hydrogen gas ( $\text{H}_2$ ). The formation of  $\text{OH}^-$  contributes to an increase in solution alkalinity and consequently raises the pH. However, the magnitude of the pH change was relatively small, indicating that the amount of  $\text{OH}^-$  generated during the process was insufficient to substantially alter the acid-base equilibrium of the river water under the investigated conditions.

Among the tested conditions, 12 V produced the lowest TDS and conductivity values and was therefore selected as the optimum operating voltage for subsequent experiments, including the electrocoagulation kinetic study.

### Kinetic Study of River Water Electrocoagulation

During the electrocoagulation process, the aluminum anode undergoes electrochemical dissolution in Ciliwung River water, which serves as the electrolyte medium. The released  $\text{Al}^{3+}$  ions subsequently undergo hydrolysis to form aluminum hydroxide species, predominantly  $\text{Al}(\text{OH})_3$ . These hydroxide flocs act as

active coagulants with a large surface area capable of removing contaminants through adsorption, charge neutralization, and sweep flocculation mechanisms [42].

To investigate the removal mechanism during electrocoagulation, the TDS removal data were analyzed using pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models. These models were selected because they are among the most commonly applied kinetic approaches for describing adsorption processes in water treatment systems and can provide insight into the dominant removal mechanism [43, 44]. In addition, comparison of the two models helps to determine whether the removal process is mainly governed by physical adsorption or by more complex surface interactions.

The linear form of the pseudo-first-order model is expressed as:

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t$$

whereas the pseudo-second-order model is represented by:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

where  $q_t$  represents the amount of TDS removed at time  $t$ ,  $q_e$  is the amount of TDS removed at equilibrium,  $k_1$  is the pseudo-first-order rate constant, and  $k_2$  is the pseudo-second-order rate constant.

The kinetic analysis was performed using TDS measurements obtained at electrocoagulation times of 10, 20, 25, 30, 35, 40 dan 45 min under the optimum operating conditions, namely Al-Al electrodes, an electrode spacing of 1 cm, and an applied voltage of 12 V. The value of  $q_t$  was calculated from the amount of TDS removed at each sampling time, while  $q_e$  was estimated from the final experimental condition, which was assumed to approach equilibrium. The linearized kinetic plots are presented in Figure 3.

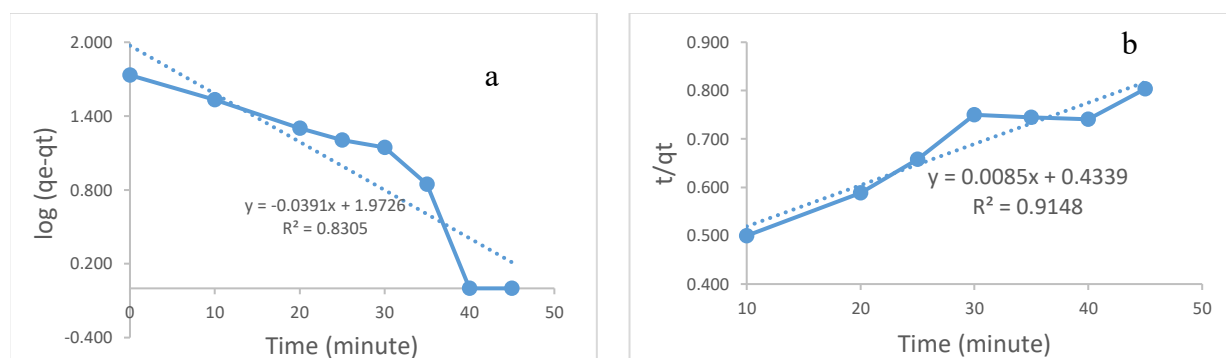


**Figure 3.** Plot the kinetic study data based on (a) Pseudo first Order (b) Pseudo Second Order.

The pseudo-first-order model yielded a coefficient of determination ( $R^2$ ) of 0.9611, which was higher than that obtained for the pseudo-second-order model ( $R^2 = 0.8940$ ). This result indicates that the pseudo-first-order model provides a better description of the experimental data.

The better fit of the pseudo-first-order model suggests that TDS removal during electrocoagulation is predominantly governed by physical adsorption onto the surface of the aluminum hydroxide flocs. This finding is consistent with the interpretation proposed by Simonin (2016), who reported that pseudo-first-order kinetics commonly provide a good representation of adsorption systems controlled by external mass transfer and physical interactions between the adsorbate and the adsorbent surface.

### Study of Operating Cost Electrocoagulation

Evaluating the operating cost of electrocoagulation is essential to assess the feasibility of its practical application. In this study, a simplified electrocoagulation system employing recycled aluminum beverage cans as sacrificial electrodes and a low-voltage battery was

developed to demonstrate a low-cost green chemistry alternative. Electrical energy consumption was calculated from the applied voltage, current, and operating time, whereas electricity costs were estimated using the Indonesian electricity tariff. The conventional electrocoagulation system was included as a representative laboratory-scale reference to compare the potential economic advantages of the proposed system. The comparison of electricity consumption and estimated equipment costs is presented in Tables 5 and 6. Equipment costs were estimated based on retail prices obtained from Indonesian laboratory suppliers and commercial online marketplaces.

As shown in Table 5, the proposed small-scale electrocoagulation system consumed only 0.00225 kWh, corresponding to an estimated electricity cost of approximately USD 0.00017 per operation. In comparison, the representative conventional electrocoagulation configuration required 0.024 kWh, with an estimated electricity cost of approximately USD 0.0020. The lower energy consumption mainly resulted from the lower operating voltage (9 V) and current (0.5 A) used in the proposed system.

**Table 5.** Electrical cost.

| Cost Component           | Conventional Method |           | Small-Scale Method |           |
|--------------------------|---------------------|-----------|--------------------|-----------|
|                          | Value               | Cost      | Value              | Cost      |
| Voltage(V)               | 24                  |           | 9                  |           |
| Current(A)               | 2                   |           | 0.5                |           |
| Power(watt)              | 48                  |           | 4.5                |           |
| Operating Time(jam)      | 0.5                 |           | 0.5                |           |
| Energy Consumption (kWh) | 0.024               | 1.444/kWh | 0.00225            | 1.444/kWh |
| Electricity Cost (USD)   |                     | 0.0020    |                    | 0.00017   |

**Table 6.** Cost Comparison Between Conventional Method and Green Chemistry Approach.

| No. | Conventional laboratory-scale electrocoagulation | Estimated Cost (USD) | Proposed green chemistry electrocoagulation | Estimated Cost (USD) |
|-----|--------------------------------------------------|----------------------|---------------------------------------------|----------------------|
| 1   | Glass beaker (500 mL)                            | 5.15                 | Acrylic reactor (10 × 8 × 8 cm)             | 5.21                 |
| 2   | Commercial aluminum plate electrode (2 pieces)   | 0.61                 | Recycled aluminum beverage cans (2 pieces)  | 0                    |
| 3   | DC laboratory power supply (30 V, 5 A)           | 44.48                | 9 V alkaline battery                        | 1.97                 |
| 4   | Electrical operating cost per batch              | 0.0020               | Electrical operating cost per batch         | 0.00017              |
| 5   | -                                                | -                    | Alligator clips (2 pieces)                  | 0.77                 |
|     | Total estimated cost                             | 50.242               |                                             | 7.95017              |

Table 6 presents an estimated comparison of the initial equipment and operating costs between a representative laboratory-scale electrocoagulation system and the proposed green chemistry configuration. The estimated costs were based on representative retail prices obtained from laboratory suppliers and commercial online marketplaces in Indonesia. As shown, the proposed system requires a substantially lower initial investment (approximately USD 7.95) than the conventional laboratory setup (approximately USD 50.24). The reduction in cost is mainly attributed to the use of recycled aluminum beverage cans as sacrificial electrodes and a low-cost battery instead of a laboratory DC power supply. In addition, the lower operating voltage resulted in a significantly lower electricity consumption (Table 5). These findings suggest that the proposed electrocoagulation system is a promising low-cost alternative for educational purposes and small-scale water treatment applications.

### CONCLUSION

The electrocoagulation process has proven to be an effective alternative to address river water quality issues. The use of Al-Al electrodes can increase the efficiency of reducing key parameters such as TDS and stabilize pH to near neutral levels. Experimental results indicate that determining optimum conditions, including process time and electrode spacing, plays a crucial role in improving floc separation performance and accelerating the water clarification process. Small-scale electrocoagulation systems that apply green chemistry principles offer operational advantages due to low energy consumption, no chemical additives required, and reduced sludge production. Overall, this method offers an economical, environmentally friendly, and adaptable solution for improving river water quality in various field conditions.

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