Electrocoagulation for drinking water treatment: a review

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**Abstract.** In this era, raw water pollution often occurs, and conventional processing can sometimes not treat it. Raw water as a water source for drinking water has to meet physical, chemical, and biological parameters in accordance with a predetermined standard. One of the parts of the advanced electrochemical process is electrocoagulation, which has been widely used to treat various types of wastewater and water. Chemical coagulation and electrocoagulation had the same process but a different mechanism. The way aluminum or iron is delivered is the difference in the mechanism. This article focuses on the effects of various operating parameters and recent developments in the electrocoagulation for the drinking water treatment process. Their optimum ranges for maximum pollutant removal and various pollutants removed by this process are observed.

1. **Introduction**

Raw water is widely used by people to meet various daily needs, including bathing, washing, toilet activities, industry, and commerce. Along with the growth of settlements and industry, the quality of raw water has decreased due to the disposal of domestic and industrial waste, which is directly released into the river without any responsible treatment [1]. The use of raw water as a source of water for clean and drinking water needs to meet physical, chemical, and biological parameters in accordance with predetermined standards, including the Regulation of the Minister of Health of the Republic of Indonesia No.492/MENKES/IV/2010 concerning Requirements for Drinking Water Quality.

Generally, the process of treating river water into raw water is carried out by purifying water using chemical coagulants in the coagulation and flocculation processes [2]. Water treatment technology by electrochemical is seen as an environmentally friendly alternative with fewer sludge yields, does not required additional chemicals without reducing the quality of water produced [3,4]. The advantage of the electrocoagulation process is no addition of chemicals, so no by-products of high concentration chemical pollutants. But the electrocoagulation process needs periodic replacement of the electrodes due to the decaying of the anode, the passivation at the cathode, and required high conductivity [5]. This article will investigate and discuss electrocoagulation for drinking water treatment, the affecting factors, and its' technology application. Electrocoagulation discussed in this article is electrocoagulation for drinking water treatment. This technology is used to remove TSS parameters, turbidity, and organic matter.
2. Electrocoagulation

Electrocoagulation is a water treatment technology with an electrochemical approach to treat several sources of water or contaminated water [3]. Electrocoagulation and chemical coagulation have a similar process of removing pollutants but different in their mechanisms [5]. In electrocoagulation, Al$^{3+}$ is released from the electrode (anode) and forms an Al(OH) floc, which is able to bind contaminants and particles in the water [6]. At the anode, an active coagulant in the form of metal ions (usually aluminum or iron) is released into the solution, while at the cathode, there is an electrolytic reaction in the form of releasing hydrogen gas [7]. Electrocoagulation using a direct current that causes ions from the anode decay to remove contaminants through a chemical reaction. The DC current that is flowed will release metal ions at the anode and H$_2$ gas also OH$^-$ ion [5].

\[
\begin{align*}
\text{At Anode:} & \\
M & \rightarrow M \text{ (aq) } n^+ + ne^- & (1) \\
2H_2O (l) & \rightarrow 4H^+ (aq) + O_2 (g) + 4e^- & (2)
\end{align*}
\]

\[
\begin{align*}
\text{At Cathode:} & \\
M & \rightarrow M \text{ (aq) } n^+ + ne^- & (3) \\
2H_2O (l) + 2e^- & \rightarrow H_2 (g) + 2OH^- & (4)
\end{align*}
\]

The electrocoagulation with Al and Fe electrode has efficiency of 52.4-100% to remove colour [8], [9], has efficiency of 64-96% to treat turbidity [8-12], has an efficiency of more than 85% to remove TSS [13], and has an efficiency of 63-96% to remove organic matter [12-14]. In the process of electrocoagulation, there are several affecting factors that influence the process.

3. Affecting Factors

3.1. Solution conductivity

The conductivity of the solution is an important parameter in the electrocoagulation process. The efficiency of the current density used to decay the coagulant is based on the conductivity of the solution [15]. Conductivity efficiency can also reduce the processing time required. If the conductivity of the water treated is low, it is necessary to add a salt solution because the conductivity depends on the type and concentration of the electrolyte solution. There are several types of solutions, including NaCl, BaCl$_2$, KCl, Na$_2$SO$_4$, and KI. Generally, NaCl is used to increase conductivity in water [16]. The addition of Cl$^-$ can reduce the negative effects of CO$_3^{2-}$ and SO$_4^{2-}$, where these ions can cause the decomposition of Ca$^{2+}$ and Mg$^{2+}$ ions. The decomposition of these ions results in the formation of an oxide layer, which reduces the efficiency of the electric current. To increase the efficiency of the electrocoagulation process, it is recommended to use an electrolyte solution containing Cl$^-$ more than 200 mg/L [7].

3.2. Electrode arrangement

The electrode arrangement in the electrocoagulation is divided into two monopolar and bipolar electrode arrangements. In a parallel monopolar arrangement in which the anode and cathode are connected in parallel, each pair of electrodes has a positive and negative charge. The bipolar system has a single power connection system, and there is no electrical connection on the inner electrodes. The bipolar system has a more effective efficiency for iron and aluminum electrodes [17].

![Figure 1. Monopolar system and bipolar system.](image-url)
Using a bipolar arrangement could reduce organic matter with an efficiency of 83% while using a monopolar arrangement could reduce organic matter with an efficiency of 71.1% \cite{18, 19}. The shape of the electrodes has an effect on the electrocoagulation process in its efficiency. The electrode type that has a hole (mesh) has a higher efficiency in removing pollutants than a flat electrode. Electrodes that have this hole can increase or release the current 1.2 times than the flat electrode.

3.3. Type of current used
In the electrocoagulation process, hydroxide ions are generated by the electrolysis process from the use of the anode. The hydroxide ion acts as a coagulant and removes pollutants from the solution. Some studies explained that the electrocoagulation process uses direct current (DC). The use of DC leads to the formation of corrosion at the anode due to the oxidation process. In the study explained that the effect of alternating AC and DC currents on the removal of cadmium from water using an anode and cathode aluminium electrode configuration obtained 97.5% and 96.3% allowances with a current density of 0.2 A using AC and DC systems \cite{20}. Electrode corrosion formation can be reduced by using an AC system rather than a DC system in electrocoagulation.

3.4. PH
Pollutant settled start at a certain pH. The efficiency of pollutant removal decreases with increasing or decreasing pH of a solution \cite{21}. Under certain conditions, complex compounds and polymers can be formed through the hydrolysis process and the electrochemical Al\(^{3+}\) polymerization reaction. At pH 4-9, using an Al anode electrode will form Al(OH)\(^{2+}\), Al(OH)\(^{3+}\), Al\(_5\)(OH)\(_4\)\(^{4+}\), Al(OH)\(_3\), and Al\(_{13}\)(OH)\(_{32}\)\(^{7+}\). At pH above 10 Al(OH)\(_4\)\(^-\) is very dominant, then the coagulant production process will continuously decrease. Meanwhile, the iron electrode in the pH range 5-9 Fe(OH)\(_3\) will form. Fe\(^{2+}\) is oxidized to Fe\(^{3+}\) at a pH above 5, and the oxidation process occurs completely in the pH range 8-9 \cite{22}.

\[
\begin{align*}
\text{Fe}_{(s)} & \rightarrow \text{Fe}^{2+}_{(aq)} + \text{ne}^{-} \quad (5) \\
4\text{Fe}^{2+}_{(aq)} + 10\text{H}_2\text{O} + \text{O}_{2(aq)} & \rightarrow 4\text{Fe(OH)}_{3(s)} + 8\text{H}^{+} \quad (6) \\
\text{Fe}^{2+}_{(aq)} + 2\text{OH}^{-} & \rightarrow \text{Fe(OH)}_{2(s)} \quad (7) \\
\text{Al}_{(s)} & \rightarrow \text{Al}^{3+}_{(aq)} + 3\text{e}^{-} \quad (8) \\
\text{Al}^{3+}_{(aq)} + \text{nH}_2\text{O} & \rightarrow \text{Al(OH)}_{n}^{3-n} + \text{nH}^{+} \quad (9)
\end{align*}
\]

3.5. Current density
The current density determines the coagulant dose rate, the hydrogen bubble production rate, the floc size, and growth, which can affect the electrocoagulation efficiency. Asselin et al. (2008) used a current of 0.3A and a processing time of 60 or 90 minutes \cite{23}. The results of TSS reduction efficiency were 90% for turbidity and 89% for TSS. Hakizimana et al. (2017) used a current density of 10 A/m\(^2\) at a pH of 7.9 and a contact time of 3 minutes \cite{16}. The removal that occurs in the turbidity parameter has an efficiency of 99% for Al and 96% for Fe. The current determines the dose of coagulant decayed at the anode and the change in hydrogen gas at the cathode. Faraday's law explains that the amount of mass-produced by an electrode is directly proportional to the amount of electricity used. The voltage used in electrocoagulation is not only based on the strength of the current used but also by the conductivity of the solution and the distance between the electrodes, where the conductivity of the solution is inversely proportional to resistance. There is an optimum value in current density according to the processed load \cite{3}.

3.6. Gap electrode
The pollutant maximum removal efficiency is obtained by maintaining the optimal gap between the electrodes. At the minimum distance between the electrodes, the efficiency of pollutant removal is low. This is because the metal hydroxide produced, which acts as a floc is degraded by the collision between the flocs due to the high electrostatic attraction \cite{24}. The pollutant removal efficiency increased with increasing the distance between the electrodes. This is because as the distance between the electrodes increases, there is a decrease in the electrostatic effect resulting in slower motion of the ion produced.
This provides more time for the metal hydroxide to form to agglomerate the floc, resulting in an increase in pollutant removal efficiency [25]. At distances of 3, 5, and 9 mm, the voltage required also increased by 2.4, 4.2, and 6.8 V. This shows that as the electrode gap increases, the energy demand required will also increase [26].

3.7. Time electrolysis
The pollutant removal efficiency increases with increasing electrolysis time. For a fixed current density, the amount of metal hydroxide produced increases with increasing electrolysis time. For electrolysis time outside the optimal electrolysis time, the efficiency of pollutant removal does not increase because the number of available flocs is insufficient to remove pollutants [25]. The TSS decreased, and the turbidity decreased with increasing contact time [27]. The initial concentration of 64 mg/L TSS pollutant load and 63.8 NTU turbidity and treated for 10, 15, and 20 minutes can reduce TSS parameters by 86%, 90%, and 93%. Meanwhile, the reduction in turbidity was 94%, 95%, and 95.6%. At pH, it shows an increase from the initial concentration of 6.8 to 7.13; 7.39; 7.42.

4. Applications

4.1. Removal TSS and turbidity
The turbidity parameter is closely related to the levels of suspended substances or TSS because water turbidity is caused by the presence of particles or suspended substances in the water. Asselin et al. (2008) conducted research with electrocoagulation with the bipolar configuration of Fe electrodes using a current density of 0.3A and a processing time of 60 or 90 minutes [23]. Gain a TSS reduction efficiency of 90% and 89% for TSS. With continuous electrocoagulation processing with a voltage of 12 volts, the reduction in turbidity reached an efficiency of 95.9% at the contact time of 20 minutes [27]. The contact time will affect the decrease in turbidity and TSS. The current density and voltage also affected the efficiency of the reduction. The higher the current density and voltage, the higher the efficiency, but at a certain current density or voltage, it can increase or decrease the pH so that it requires optimum current density and voltage [28].

4.2. Removal color
Color in water is caused by the presence of natural metal ions (iron and manganese), humus, plankton, plants around the water, domestic waste, decaying organic matter, and industrial waste. The electrocoagulation process is considered one of the technologies that could remove the color from water that is treated. Research with electrocoagulation with monopolar configuration of Al electrodes using a current density of 0.48 mA/m², and a processing time 12 minutes with the concentration influent 61.8 PtCo [28]. Gain a color higher reduction of 94%. The highest color reduction efficiency with electrocoagulation processing using aluminum and iron electrodes was 96.5% and 90%. The mechanisms for reducing color concentration are precipitation and adsorption. The reaction is as followed by:

Precipitation:
\[
\text{Color} + \text{Monomer Al} \rightarrow \text{Color Monomer Al}_{(s)} , \text{pH} = 4 – 5 \quad (10)
\]
\[
\text{Color} + \text{Polimer Al} \rightarrow \text{Color Polymer Al}_{(s)} , \text{pH} = 5 – 6 \quad (11)
\]

Adsorption:
\[
\text{Color} + \text{Al(OH)}_{3(\text{s})} \rightarrow \text{Particle} \quad (12)
\]
\[
\text{Color Polymer Al}_{(s)} + \text{Al(OH)}_{3} \rightarrow \text{Particle} \quad (13)
\]

4.3. Removal of organic matter
The increase and transport of organic contaminants results in other unwanted products becomes a vessel for photochemical processes and naturally exhibits the properties of organic substances in water referred to as NOM (Natural Organic Matter). The process of removing organic pollutants is carried out in
several mechanisms, namely destabilization, complexation, entrapment, and adsorption [3]. The complexation reaction is as followed by:

\[
\text{Organic Matter} + (\text{HO})\text{Al(s)} \rightarrow \text{Organic Matter-OAl(s)} + \text{H}_2\text{O} \tag{14}
\]

Vepsalainen et al. (2009) used a current of 0.1 A with a current density of 0.48 mA/cm\(^2\) for 4-12 minutes with the influent concentration 16 mg/L showed a decrease in organic matter with Al electrodes by 75\% [28]. Mcbeath (2020) operated continuously with voltages 0-10 V and 0-29V, currents 0-12.4A and 0-57.7A with the influent concentration up to 10.72 mg/L [29]. The distance between the electrodes is 1 mm, the density is 27.6 mA/cm\(^2\), and the speed being pumped is 0.22 m/sec. Percentage reduction of 79\%. Asselin et al. (2008) with Fe electrodes with 6 pairs of bipolar configuration, current of 0.3A, and processing time of 60 - 90 minutes [23]. The results of the reduction efficiency of Organic Substance (BOD) by 86\% and grease oil by 99\%. Ulu et al. (2015) used Al, Fe, and Al-Fe electrodes, 10 mm distance between electrodes, and a stirring speed of 150 rpm resulting in removal efficiency of 71 % for Al, 59.8\% for Fe, and 68.8\% for Al-Fe [19].

4.4. Case study

The case study that will be discussed is a case study related to electrocoagulation processing design using secondary data from PDAM X. Secondary data is carried out with a design calculation approach using the data in table 5. Raw water quality data will be compared with Regulation No. 492/Menkes/Per/IV/2010 concerning Drinking Water Requirements. From table 1, it can be seen that the parameters of color, turbidity, organic matter do not meet the required quality standards, so the design as mention in table 2.

| No | Parameter      | Unit | Result | Regulations No 492/2010 | Ket   |
|----|----------------|------|--------|-------------------------|-------|
| 1  | Temperature    | °C   | 283    | 25 ± 3                  | Conform |
| 2  | Color          | TCU  | 23.5   | 15                      | Not Conform |
| 3  | Turbidity      | NTU  | 75.19  | 5                       | Not Conform |
| 4  | TSS            | mg/L | 120.93 | 50*                     | Not Conform |
| 5  | Organic Matter | mg/L | 12.8   | 10                      | Not Conform |
| 6  | pH             |      | 7.75   | 6.5-8.5                 | Conform |

Source: PDAM X, 2020 and Regulation No.492 - 2010, *PP No 82 - 2001

| Data          | Result | Unit     | Data     | Result | Unit |
|---------------|--------|----------|----------|--------|------|
| Flow rate     | 110    | m\(^3\)/day | Depth    | 1.3    | m    |
| Volume       | 3.333333 | m\(^3\)  | Length   | 2.6    | m    |
| Contact Time | 20     | minute   | Width    | 1.3    | m    |
| Current      | 75.1   | A        | mE Al    | 25.1   | g/m\(^3\) |
| Voltage      | 1,682.9 | V       | Energy Consumption | 126.3 | kWh/L |

Table 1. Quality of raw water.

Table 2. Result design.
Determination of current strength based on pollutant load and flow rate. In Ngatin et al. (2010), the current strength obtained was 4.8 A [30]. Contact time for 15-20 minutes with a processed load of 312 grams/hour was able to produce a reduction efficiency of 90% TSS, 85.2% Organic substances, and 95% turbidity. The planned raw water discharge is 10 m³/hour, the processed load is 1209.3 grams/hour, then the current is obtained by comparing the ratio between the current strength and the processing load. Current obtained 18.8 A for each pair of electrodes.

The required energy consumption is calculated based on voltage. The voltage approach uses TDS concentration. TDS is connected with conductance to determine the value of Gk (Mho). The conductance is opposite of the value of R (ohms). The mho value used is 0.0446 Mho/m. This voltage for 20 minutes of operation with a current of 75.1 A, is:

\[ V = I \times R \]
\[ V = I \times (1/Gk) = 75.1 \times (1/0.0446) = 1,682.9 \text{ V} \]
\[ P = V \times I \times h /1000 \]

P as electric power (kWh), V as voltage (V), I as current (amperes), and has a time (hours). The electric power obtained is 126.3 kWh.

5. Conclusion
The application of electrocoagulation for drinking water treatment in reducing TSS, turbidity, color, and organic matter has high efficiency, making it a promising technology. These need to pay attention to operating parameters such as the solution’s conductivity, electrode settings, the type of current used, pH, current density, electrode distance, and electrolysis time. Electrocoagulation for drinking water treatment with a bipolar arrangement is preferred over monopolar. The use of aluminum electrodes is more efficient with a wide pH range. The current that used must be adjusted to the pollution load to be processed because each raw water has a different processing load. The conductivity of the solution in raw water tends to be small by looking at the TDS value so that the energy requirements required are quite high, the addition of electrolyte solutions is a solution to increase electrolyte conductivity.

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