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Comparison of the Effectiveness of Series and Parallel Monopolar Electrode Arrangements in Electrocoagulation Reactors for Reducing Color and COD

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A B S T R A C T

Industrial batik wastewater contains dyes and organic compounds at high concentrations, posing a potential threat to aquatic environments. This study aims to evaluate the effectiveness of electrocoagulation using series and parallel monopolar electrode configurations in reducing the levels of methylene blue, methyl red, and chemical oxygen demand (COD) in batik wastewater. The process was carried out in batches, with variations in electrode configuration, voltages of 6 and 9 volts, and contact times of 30–90 minutes, using aluminium and iron electrodes. Color concentration analysis was performed using UV–Vis spectrophotometry, while COD was analyzed using the closed reflux method. The results showed that increasing the voltage and contact time improved the removal efficiency of all parameters. The parallel monopolar configuration provided the best performance, with reduction efficiencies of 95.23% for methylene blue, 90.02% for methyl red, and 71.21% for COD. This was influenced by a more even current distribution and more effective coagulant formation. Parallel monopolar electrocoagulation has the potential to be applied as an alternative method for treating batik wastewater.

Contribution to Sustainable Development Goals (SDGs):
SDG 3: Good Health and Well-Being
SDG 6: Clean Water and Sanitation
SDG 11: Sustainable Cities and Communities
SDG 14: Life Below Water

1. INTRODUCTION

1.1. Research Background

Batik is one of Indonesia's cultural heritages that has been designated by UNESCO as Intangible Cultural Heritage in 2009. The batik industry in Indonesia is generally classified as small and medium-sized enterprises (SMEs) that play an important role in supporting the national economy. The manufacturing process involves several stages, including motif design, fabric painting, white area covering, dyeing, re-coating with wax using a canting tool, wax removal (nglorot), and batik fabric washing [1].

Despite providing significant economic and cultural benefits, batik production activities also have the potential to cause environmental pollution. The liquid waste produced by the batik industry has characteristics such as high temperature, unstable pH, and high biological oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). In addition, this waste contains a fairly high concentration of dyes. Therefore, it is necessary to treat batik industry wastewater before it is discharged into water bodies so as not to pollute the environment.

One effective method for treating batik wastewater is electrocoagulation, an electrochemical process that works by destabilizing pollutant charges using an electric current that triggers electrode dissolution [2]. This method involves a combination of various electrochemical, chemical, and physical mechanisms that occur in series or in parallel [3]. Metals from dissolved electrodes form coagulants that destabilize and capture pollutant particles in wastewater, forming flocs that then settle [4].

In an electrocoagulation system, electrodes act as conductors of electrical current into the solution to trigger chemical reactions. Electrodes can be arranged in series or parallel configurations, as well as monopolar or bipolar. In general, monopolar systems require lower voltage but need greater electrical current, while bipolar systems operate with lower current but at higher voltage. In terms of advantages, the monopolar configuration is more recommended because it has lower operating costs, easier maintenance, and good energy efficiency in removing pollutants [5].

The arrangement of series monopolar electrodes has the advantage of lower electrode consumption and operating costs, while parallel monopolar electrodes require lower voltage and allow for more even current distribution. This electrode arrangement can affect pollutant reduction efficiency [6] because differences in current and voltage distribution also determine the amount of coagulant ions formed. However, the effectiveness of the electrocoagulation process is also influenced by contact time and the characteristics of the pollutants being treated. Based on this description, this study was conducted to compare the effectiveness of series and parallel monopolar electrode configurations in electrocoagulation reactors in reducing color levels (Methylene Blue and Methyl Red) and COD in batik industry wastewater in Jetis, Sidoarjo.

1.2. Literature Review

1.2.1. Characteristics of Batik Industry Wastewater

The batik-making process consists of various stages. Some stages require materials such as wax and dyes. Therefore, batik wastewater has characteristics such as high temperature, pH, biological oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). In addition, batik industrial wastewater has a high dye content.

In general, dyes are classified into two types: natural and synthetic. The dyes used are generally synthetic, which are difficult to break down because they are easily available and produce bright colors. One of the dyes used in the batik industry is methylene blue and methyl red.

Colorants in water can actually decompose naturally with the help of sunlight. However, this process is relatively slow due to the low intensity of UV light reaching the earth's surface, meaning that the accumulation of colorants at the bottom of the water or in the soil is faster than their photodegradation. This can potentially increase the chemical oxygen demand [7].

1.2.2. Methylene Blue Dye

Methylene blue is the most common cationic dye and is often used in the fabric dyeing process. Among various dyes, cationic dyes are considered the most toxic. In addition to its high toxicity, methylene blue also inhibits photosynthesis in aquatic plants, thereby disrupting the balance of aquatic ecosystems [8]. The following are the physical and chemical properties of methylene blue [9].

Table 1. Physical and Chemical Properties of Methylene Blue

Description	Value
Chemical Formula	$C_{16}H_{18}ClN_3S$
Molar Mass	319.85 g/mol
Density	1.325 g/cm^3
Melting Point	105℃
UV – Vis (λ max)	650 nm

1.2.3. Methyl Red Dye

Methyl red is one of the most reactive synthetic dyes used in dyeing fabrics containing azo dyes. Azo compounds are characterized by the general structure R–N=N–R′, in which R and R′ may consist of identical or different organic groups. The —N═N— element in this compound is known as the azo structure. Azo compounds can be classified as aromatic or aliphatic. Aromatic azo compounds tend to be stable and have striking colors. When the temperature increases or irradiation occurs, the bond between nitrogen and carbon can break simultaneously, releasing nitrogen gas and radicals. Therefore, some aliphatic azo compounds are used as radical initiators. The following are the physical and chemical properties of methyl red [10].

Table 2. Physical and Chemical Properties of Methyl Red

Description	Value
Chemical Formula	$C_{15}H_{15}N_3O_2$
Molar Mass	269,304 g/mol
Density	0,791 g/cm^3
Melting Point	179℃ – 182℃
UV – Vis (λ max)	420 nm

1.2.4. Chemical Oxygen Demand

Chemical Oxygen Demand (COD) represents the quantity of oxygen needed to oxidize organic substances present in water; therefore, COD indicates the level of organic matter that can undergo oxidation. COD measurements include all oxidized compounds that are biodegradable and non-biodegradable [11]. The oxygen demand during oxidation processes is influenced not only by organic substances but also by the presence of oxidizable inorganic constituents. Therefore, COD measurements are generally combined with BOD values, as this quantity allows for the evaluation of the fraction of carbon compounds that can be decomposed in water [12].

1.2.5. Electrocoagulation

The electrocoagulation method is based on the principle of reduction and oxidation (redox) reactions. Electrodes in electrocoagulation function as conductors of electric current into the solution to trigger chemical reactions. The reactions that occur in electrocoagulation involve reduction and oxidation as a result of direct current (DC) flow. Within an electrocoagulation reactor, oxidation takes place at the positively charged electrode (anode), whereas reduction reactions occur at the negatively charged electrode (cathode). In this process, the dissolved anode forms a coagulant that destabilizes and captures wastewater pollutants in the form of suspended particles that will form flocs [4], and the cathode produces hydrogen gas bubbles that help lift impurities to the surface of the wastewater, while the rest settle to the bottom. The debris carried by the hydrogen bubbles will form small flocs that will then grow larger [13].

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1.2.6. Electrode Arrangement Type

In the electrocoagulation process, electrodes can be arranged in series and parallel, as well as monopolar and bipolar. The arrangement of electrodes used can also affect the efficiency of pollutant reduction [14]. Monopolar electrodes arranged in parallel have a smaller potential difference compared to series monopolar electrodes. This is because the current will be divided in a parallel arrangement.

In a monopolar system, all electrodes are electrically connected. In a bipolar configuration, only the outer electrodes are directly connected to the power supply, while the electric current is transmitted through the intermediate electrodes. Under this condition, the electrode surface facing the anode becomes negatively polarized, whereas the surface facing the cathode becomes positively polarized. In general, monopolar configurations have lower operating costs, but higher pollutant removal is usually achieved with bipolar configurations. The following are various types of electrode arrangements in the electrocoagulation process [15].

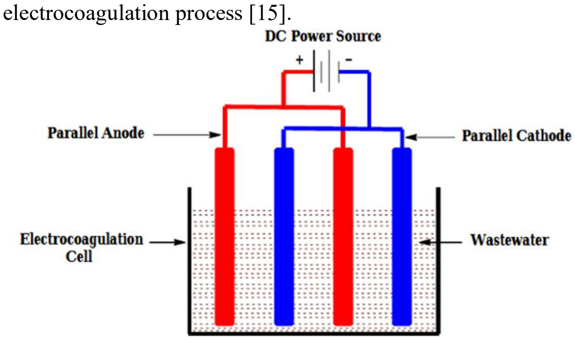

Fig. 1. Monopolar Parallel Electrode Arrangement

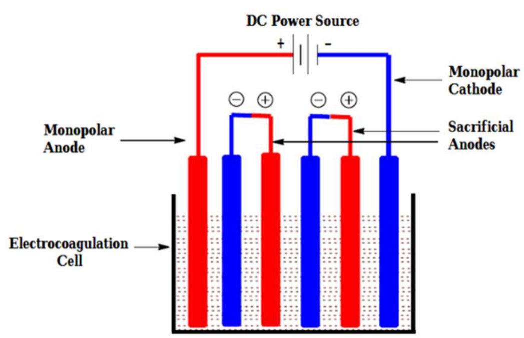

Fig. 2. Monopolar Series Electrode Arrangement

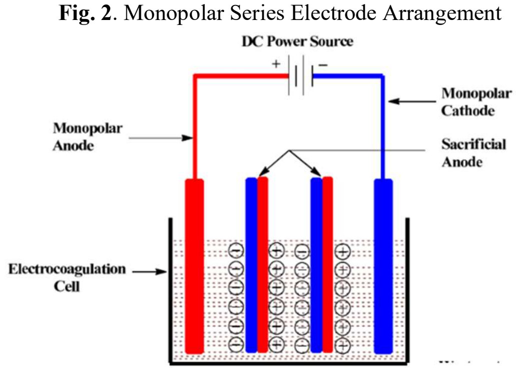

Fig. 3. Bipolar Series Electrode Arrangement

1.3. Research Objective

This study aims to analyze the comparative effectiveness of series and parallel monopolar electrode arrangements in electrocoagulation reactors for reducing color (Methylene Blue; Methyl Red) and COD levels in batik industry wastewater.

2. MATERIALS AND METHODS

2.1. Research Location

This research was conducted at the Environmental Engineering Research Laboratory of the Veteran National Development University in East Java.

2.2. Tools and Materials

The equipment required includes a DC power supply as a current source, aluminum and iron electrodes measuring 8 x 15 cm, a cable circuit to connect the electrodes, a waste container, a flow control tank, an electrocoagulation reactor, a sedimentation reactor, sampling bottles, a submersible pump, ½ inch PVC pipes, ½ inch PVC elbows, and water taps. Meanwhile, the materials required for this study are industrial batik waste from Jetis in Sidoarjo.

2.3. Research Procedure

The research procedure began with taking samples of Jetis batik wastewater and placing the samples in an initial storage tank. Next, electrodes were attached to the media that had been prepared for hanging the electrodes. Previously, the electrodes were washed first using distilled water. This was followed by flowing the wastewater from the storage tank to the flow control tank, then continuing to the main reactor, namely the electrocoagulation reactor. Three liters of wastewater were flowed to the main reactor. After that, the cables were connected to the electrodes according to the desired configuration and the DC power supply was turned on. The electrocoagulation process is carried out according to the desired contact time. Once the contact time has been met, sedimentation is carried out in the sedimentation reactor for 30 minutes. Once the sedimentation time has been met, sampling is carried out from the sedimentation reactor. The following is an illustration of the device design.

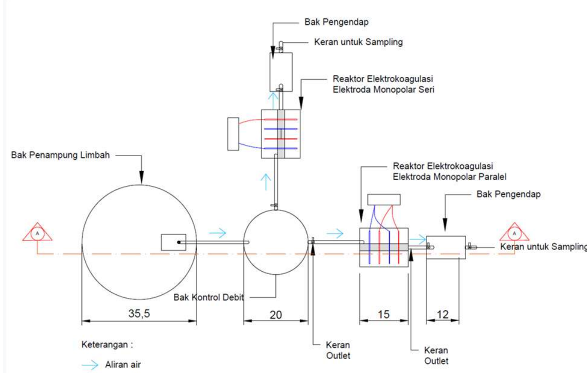

Fig. 4. Reactor Layout

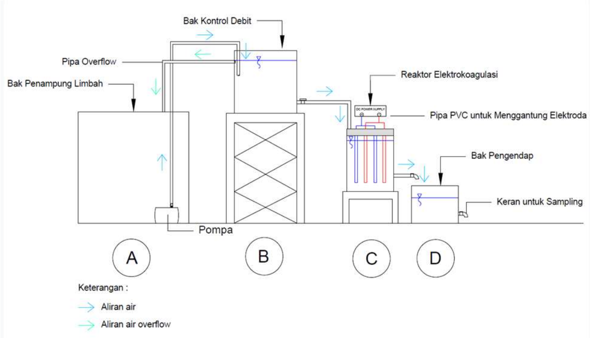

Fig. 5. Reactor Segment

3. RESULT AND DISCUSSION

3.1. *Initial Characteristics of Batik Waste from Jetis, Sidoarjo*

The waste underwent initial characteristic testing before proceeding to the main study. The purpose of this characteristic testing was to determine the initial levels of color parameters (methylene blue; methyl red) and COD so that they could be compared with the final results after undergoing the treatment process. The following are the preliminary test results, which can be seen in the Table 3.

Table 3. Characteristics of Jetis Batik Wastewater

No	Parameters	Units	Waste Content
1	Methylene Blue	mg/L	80.9
2	Methyl Red	mg/L	244.75
3	Chemical Oxygen Demand	mg/L	3584

Source: research results, 2025

3.2. *Comparison of the Effectiveness of Series and Parallel Monopolar Electrode Arrangements on Color Reduction (Methylene Blue; Methyl Red) and Chemical Oxygen Demand (COD)*

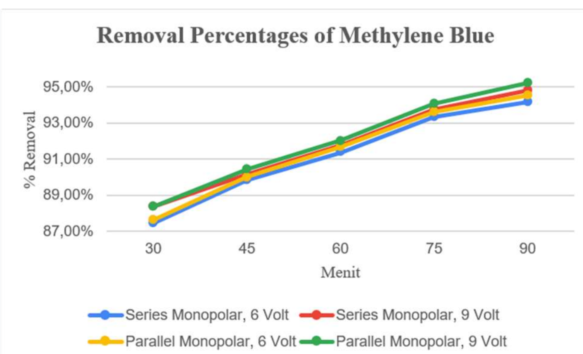

Fig. 6. Percentage Removal Graph of Methylene Blue

From the graph above, it can be observed that the percentage of methylene blue removal increases with contact time. This is because more pollutant particles undergo coagulation, resulting in an increase in the effectiveness of methylene blue removal [8].

This increase in efficiency is related to the amount of coagulant formed during the electrocoagulation process, which is influenced by the electrical voltage used. Higher voltages can produce more coagulant ions, thereby increasing the efficiency of contaminant adsorption [16][17]. The flocs formed tend to settle at the bottom or float on the water surface. This process not only reduces the methylene blue content but also contributes to improving overall water quality by reducing various types of contaminants.

At the 30th minute, the removal percentage ranged from 87.46% to 88.39%. This value continued to increase until the 90th minute, reaching more than 94%. This increase in removal percentage indicates that the electrocoagulation reaction was effective in reducing the methylene blue colour level in batik wastewater. When comparing the series monopolar electrode configuration with the parallel monopolar configuration, both showed almost identical increases in removal percentage. However, the parallel monopolar configuration with a voltage of 9 volts produced the highest removal percentage of 95.23% at the 90th minute. This is in line with the literature, which states that in a parallel monopolar configuration, the current distribution across each electrode is more even, so that oxidation at the anode and reduction at the cathode occur more optimally [18]. Meanwhile, at 6 volts, the colour reduction was still quite high, though not as effective as at 9 volts. Higher voltage increases current strength, thereby accelerating the formation of Al3+ ions from dissolved anode species and hydrogen at the cathode, which promotes floc formation capable of reducing colourants through precipitation or adsorption mechanisms.

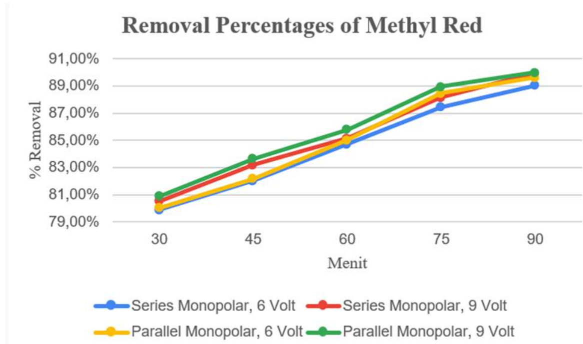

Fig. 7. Percentage Removal Graph of Methyl Red

Based on the research results, the decrease in methyl red concentration increases with increasing contact time. This is because more pollutant particles undergo coagulation, thereby increasing methyl red removal effectiveness [8]

At 30 minutes, the removal percentage ranged from 79.88% to 80.88%. This value continued to increase until 90 minutes and reached more than 89%. This increase in the removal percentage indicates that the electrocoagulation reaction is effective at reducing the concentration of methyl red in batik wastewater. A comparison of configurations shows that the 9-volt parallel monopolar configuration provides the highest efficiency, around 90.02% at the 90th minute, followed by the 9-volt series monopolar, 6-volt parallel monopolar, and 6-volt series monopolar.

In general, the results for methyl red follow the same pattern as for methylene blue, but with slightly lower efficiency. This is due to differences in the chemical characteristics of the two dyes. Methylene blue is cationic, making it easier to interact with negatively charged ions in flocs, whereas methyl red is anionic and tends to form complex interactions with metal coagulants.

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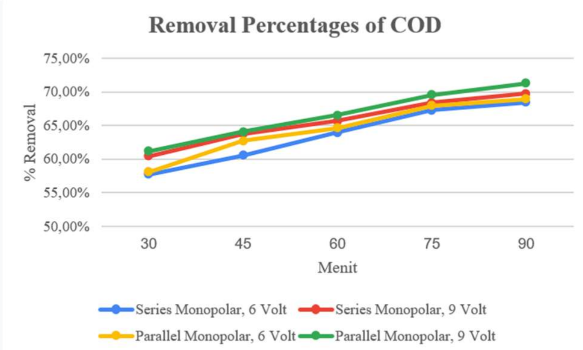

Fig. 8. Percentage Removal Graph of COD

Based on the research results obtained, it can be seen that the COD reduction value increases with increasing contact time. This increase indicates that the longer the electrocoagulation process lasts, the more metal ions are released from the anode and act as coagulants. This is in line with what was stated by Rakhmania, 2022, that as the contact time increases, the metal ions produced will be higher, thus causing higher pollutant removal [19]. However, at a certain point in time, the removal rate will slow down. This is due to electrode saturation that occurs when the process is run for a long time [20].

From 30 to 90 minutes, the COD removal percentage increased from around 58–61% to 70–72%. The parallel monopolar configuration at 9 volts showed the highest removal value throughout the contact time, followed by the 9-volt series monopolar, then the 6-volt parallel and 6-volt series. This pattern indicates that higher voltages also accelerate the rate of in situ coagulant ion formation, thereby strengthening the flocculation and adsorption processes of organic compounds in wastewater. In addition, color concentration also affects chemical oxygen demand concentration. Therefore, the chemical oxygen demand value decreases because the color concentration in the wastewater is significantly removed.

3.3. Differences in Conditions in Monopolar Series and Parallel Configuration Treated Water

There are several differences in the conditions of treated water using series and parallel monopolar configurations. Treated water using a series monopolar configuration tends to have the same temperature as the initial temperature, while treated water using a parallel monopolar configuration tends to feel warm or even hot. This is caused by a greater total electric current and a higher electrochemical reaction rate, which increases local heating. In addition, treated water in a series monopolar configuration has more flocs that settle than float. Conversely, treated water in a parallel monopolar configuration has more flocs that float than settle. This difference is caused by differences in the distribution of electric current and the intensity of hydrogen gas formation. In a series monopolar configuration, lower currents produce denser and more stable flocs that tend to settle. Conversely, a parallel monopolar configuration produces greater currents and intense hydrogen gas formation, causing the flocs to be lighter and pushed to the surface through the mechanism of electroflotation.

4. CONCLUSION

From the experiments conducted, it can be concluded that the electrocoagulation process is effective in reducing colour levels (methylene blue and methyl red) and COD in batik industry wastewater. The parallel monopolar electrode configuration was more effective than the series monopolar configuration. In addition, increases in voltage and contact time were directly proportional to increases in removal efficiency. Higher voltage accelerated the electrochemical reaction, thereby increasing the amount of in situ coagulant formed. Meanwhile, longer contact time led to more pollutants binding to Fe(OH)3, which eventually formed flocs.

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