Design and Implementation of an IoT-Based Electrocoagulation System for Textile Wastewater Color Degradation

Husnaini Martha W
School of Electrical Engineering
Telkom University
Bandung, Indonesia
husnainimartaa@gmail.com

Devin Marva Kusuma
School of Electrical Engineering
Telkom University
Bandung, Indonesia
devinmarvak@gmail.com

M. Fadil Reza Putra R
School of Electrical Engineering
Telkom University
Bandung, Indonesia
fadilrezaputra@gmail.com

Malikdaffa
School of Electrical Engineering
Telkom University
Bandung, Indonesia
malikdfa@gmail.com

***Abstract*—This paper presents the design and implementation of an electrocoagulation system for the degradation of color pollutants in textile wastewater. The system utilizes electrochemical reactions at metal electrodes to generate hydroxide flocs that bind and remove dissolved contaminants. It integrates pH, turbidity, and water level sensors to automate operation, while an ESP32-based controller enables remote monitoring and control via the Internet of Things (IoT). A hybrid power configuration, combining solar energy and grid electricity, is employed to enhance energy efficiency and sustainability. Experimental results indicate that the system can effectively reduce color intensity and chemical oxygen demand (COD) by more than 90% under optimal voltage conditions (10–60 V). The proposed design supports Sustainable Development Goal (SDG) 6: Clean Water and Sanitation by offering a low-cost, compact, and decentralized wastewater treatment alternative for small and medium textile industries.**

Keywords—Electrocoagulation, textile wastewater, color degradation, IoT monitoring, hybrid energy, SDG 6.

I. INTRODUCTION

The continuous growth of the textile industry in Indonesia has significantly contributed to economic development but also created environmental challenges, particularly in wastewater management. Textile dyeing and finishing processes produce effluents containing high levels of suspended solids (SS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and strong color intensity due to residual dyes. Approximately 10–40% of dyes used in textile processing remain unfixed, resulting in highly colored and non-biodegradable wastewater [1][2]. Without proper treatment, such effluents reduce light penetration in water bodies, disrupt aquatic ecosystems, and pose health risks to surrounding communities.

Conventional wastewater treatments such as biological, physical, and chemical methods often require large infrastructures, high operational costs, and chemical additives that generate secondary pollution. In contrast, electrocoagulation (EC) has emerged as a promising method for dye removal due to its simplicity, high efficiency, and environmental friendliness. EC uses an applied direct current to dissolve metal anodes—typically aluminum or iron—producing coagulant species that destabilize and aggregate pollutants for sedimentation or flotation. Prior studies have demonstrated color removal efficiencies of up to 97.7% using aluminum electrodes [3].

However, large-scale EC systems remain limited in Indonesia due to high energy consumption and installation costs. Therefore, this project focuses on developing a compact, cost-efficient, and automated electrocoagulation system integrated with IoT-based monitoring and hybrid energy sources. The system is designed to enable small and medium textile industries to treat wastewater effectively and sustainably, supporting the realization of SDG 6 (Clean Water and Sanitation).

II. MATERIALS AND METHODS

A. *System Design*

The electrocoagulation system for degrading this colored waste is designed as an integrated system consisting of two main subsystems: (1) a filtration subsystem using electrode plates, and (2) an IoT-based monitoring and control subsystem. The system block diagram is shown in Figure 1.

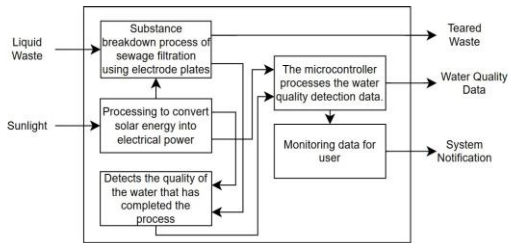

Figure 2.1 System block diagram

The proposed electrocoagulation system consists of three major subsystems: (1) the electrochemical treatment unit, (2) the sensing and control subsystem, and (3) the hybrid power supply. The treatment unit contains metal plate electrodes arranged in parallel configuration, where wastewater undergoes coagulation through anodic dissolution. Hydroxide flocs formed during the process capture colorants and suspended solids, producing clarified water.

B. Sensor and Control

Table 3.1 Component selection

Component	Model
pH Sensor	Grove - PH Sensor Kit (E-201C-Blue)
Microcontroller	ESP32 DevKit (ESP WROOM 32)
Plate	Aluminum Cylinder Electrode Plate
Battery	$LiFePO_4$
Pump	Peristaltic Pump 12V
Solar Panel	Solar Panel 20 W
TDS Sensor	Analog Turbidity Sensor SEN0189
Altitude Sensor	Ultrasonic Sensor Waterproof (JSN- SR04T)

C. Sensor Calibration

1. pH Sensor Calibration

Calibration was performed using four samples, namely distilled water with a pH of 7, tap water with a pH of 6.5–8.5, soapy water with a pH ranging from 8 to 11, and lime juice with a pH ranging from 2 to 3. The potentiometer on the sensor module is adjusted until the reading stabilizes at pH 7.

2. TDS Sensor Calibration

Calibration was performed using three samples: water Sample (100 NTU), water Sample with 3 drops of color added, and water Sample with 6 drops of color added. The calibration process is performed by adjusting the potentiometer on the sensor module in accordance with the 100 NTU water sample.

3. Altitude Sensor Calibration

Calibration is performed by measuring four distances: 30 cm, 60 cm, 90 cm, and 120 cm. The calibration process is carried out by changing the formula in the code so that the distance displayed matches the experiment.

D. System Implementation

The system is implemented with the following steps:

1. Filter media installation: aluminum plates are inserted into the container with initial rinsing using clean water.
2. Sensor integration: TDS, pH, and height sensors are placed in the same container to regulate the system.
3. Microcontroller connection: ESP32 is connected to the sensor via the ADC channel and configured for WiFi connection.
4. Cloud platform setup: The Blynk dashboard is configured with virtual pins for each parameter and a notification system with thresholds (pH <6.5 or >8.5 and turbidity >25 NTU).
5. Power system installation: 12 V UPS is connected with automatic switching between the power grid and the battery. During daylight, solar energy powers the electrocoagulation process, while excess energy is stored in a battery module for nighttime use. The hybrid setup ensures continuous operation, reduces dependency on the grid, and supports sustainable energy practices.

The system utilizes three primary sensors:

1. pH Sensor : monitors acidity to maintain the optimal range of 6.5–8.5.
2. Turbidity Sensor: measures optical clarity to evaluate color reduction.
3. Water Level Sensor (Ultrasonic): regulates the filling and discharge cycles.

All sensor readings are processed by an ESP32 microcontroller, which supports Wi-Fi connectivity for IoT communication. The controller automates process cycles filling, treatment, and discharge based on real-time data. Users can monitor and control system operations remotely through a web-based interface or mobile application. Data transmission is configured at a 2 minute interval for continuous status updates.

E. Verification

Verification results confirmed that the system:

1. forms visible hydroxide flocs through anodic dissolution;
2. removes more than 90% of color pollutants under optimal conditions;
3. operates autonomously via sensor feedback;
4. transmits monitoring data every 2 minutes; and
5. can be activated or deactivated remotely.

The integration of automation, IoT-based monitoring, and hybrid renewable energy demonstrates that the developed system provides an effective, efficient, and scalable solution for decentralized textile wastewater treatment.

III. EXPERIMENTS

A. Experimental Setup

The prototype system was assembled using an ESP32 microcontroller as the central controller, interfaced with three primary sensors: a Grove pH Sensor Kit (E-201C Blue) for acidity measurement, an analog turbidity sensor for optical clarity detection, and an Ultrasonic HC-SR04 sensor for water-level control.

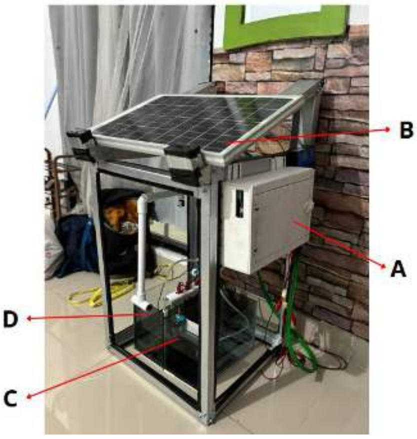

Figure 3.1 Complete system hardware

The image above shows the complete hardware with the following descriptions: (A) control center, (B) voltage source, (C) electrocoagulation device, (D) electrocoagulation water.

The electrocoagulation reactor employed aluminum plate electrodes arranged in a parallel configuration inside an acrylic chamber (200 × 150 × 150 mm). Power was supplied through a hybrid system consisting of a 20 Wp solar panel, a 12 V battery, and a 5 A regulator module for voltage stability.

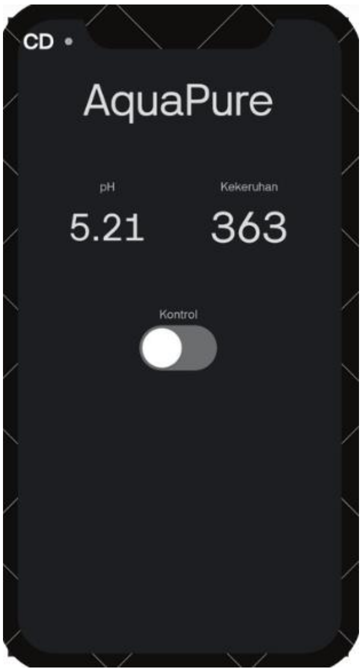

Figure 3.2 Dashboard on blynk

pH sensor and TDS sensor readings were transmitted to a Blynk-based IoT dashboard for real-time monitoring and control.

B. Testing Procedure

Synthetic textile wastewater was prepared using reactive red dye solution (13 000 Pt-Co) with an initial pH of 9.2 and turbidity of 180 NTU. Experiments were performed 12 V level and treatment durations of 60–300 minutes to evaluate color-degradation efficiency. The Grove pH sensor was calibrated using buffer solutions (pH 4 and 7) prior to testing. Sensor data were collected every two minutes via the IoT platform and logged automatically for later analysis

C. System Verification

The system was verified to: (1) operate autonomously via feedback from pH, turbidity, and level sensors; (2) form visible hydroxide flocs through anodic dissolution; (3) reduce turbidity and color intensity effectively at optimal voltage conditions; and (4) transmit monitoring data successfully through the IoT interface. Remote control functions (start/stop, drain) were also validated.

IV. RESULTS AND DISCUSSION

A. System implementation results

Test results show that the electrocoagulation process began to show visual effects after 30 minutes of operation, marked by the appearance of fine flocs visible in Figure 4.1.

Figure 4. 1 Filtration process

And the electrocoagulation system was successfully implemented with the integration of all components functioning as designed.

B. Water Quality Test Results

Table 4.1 Turbidity test results

Time	Turbidity (NTU)
0 Minute	367
30 Minute	207
1 Hour 45 Minute	10

The test results show that the turbidity level of the water before the filtration process was very high, reaching 367 NTU. After the filtration process lasted for 30 minutes, the turbidity value began to decrease significantly, and after 1 hour and 45 minutes, the turbidity value reached 10 NTU.

These results indicate that the designed electrocoagulation system is capable of clarifying water from its initial condition with high turbidity (367 NTU) to a much clearer state (10 NTU), with a turbidity removal efficiency of >90%.

C. Hybrid power system performance

Sistem Hybrid diuji untuk memverifikasi fungsi swtching otomatis.

Table 4.2 Hybrid system test results

Condition	Result	Analysis
Initial system	The system operates using power primarily from solar panels and a 12V 7Ah battery.	The battery voltage is sufficient to supply the system normally without assistance from the PLN source.
Battery disconnected / voltage < 10V	The voltage sensor detects a drastic drop in voltage. Arduino triggers the second relay to connect the 12V 5A adapter.	The automatic control mechanism works well based on voltage sensor readings and Arduino logic.
Load performance during switching	The switch from the battery to the adapter takes less than 2 seconds, and the system remains stable.	Fast switching times indicate that relay synchronization is good and logic control is working effectively.
Load performance during switching	The pump, sensor, and other components continue to operate without interruption.	There was no significant voltage or current drop that could interfere with load operation.

The test results demonstrate that the automatic power switching system operates efficiently, quickly, and safely. The control logic implemented using Arduino successfully detects voltage drops below the threshold and automatically switches the power source from the battery to the adapter.

The transition between power sources occurs within less than 2 seconds, with no noticeable interruptions in the operation of the pump, sensors, or other components. This indicates that the relay synchronization and control logic are functioning properly. No voltage or current spikes were observed during the switching process, confirming that the system's protection mechanism works effectively. Overall, the system proves to be reliable and responsive in maintaining a continuous and stable power supply for the electrocoagulation device.

D. Conslusion

The developed electrocoagulation system, with an optimized inter-electrode distance of 3 mm, demonstrated significant performance in reducing dye concentration in textile effluent. Quantitatively, color removal efficiency reached above 90%, accompanied by pH stabilization and a notable reduction in Total Dissolved Solids (TDS) toward standard discharge limits. The relationship between voltage drop VVV, electrode spacing ddd, and current density JJJ follows Ohm's law in electrolytic media:

$$V=J\cdot\rho\cdot d$$

where ρ\rho is the solution resistivity. The 3 mm spacing minimizes energy losses while maintaining sufficient coagulant generation. The system operates autonomously using feedback from pH, turbidity, and water-level sensors, controlled by an ESP32 microcontroller, and transmits real-time data via IoT. Solar-assisted hybrid power ensures sustainable operation with reduced energy cost and environmental impact.

E. Product Summary

The designed product integrates:

1. An aluminum-electrode reactor (3 mm spacing) for optimal current density distribution,
2. pH, turbidity, and ultrasonic water-level sensors for adaptive control,
3. A microcontroller (ESP32) enabling IoT-based monitoring and automation,
4. A hybrid power supply (solar panel and AC adaptor) for continuous operation.

This compact, energy-efficient system effectively treats small- to medium-scale textile wastewater, achieving stable electrochemical performance with reduced operational cost.

F. Recommendations for Future Development

In future iterations, several refinements are recommended to improve both the technical and analytical aspects of the electrocoagulation system. The electrode spacing, currently fixed at 3 mm, should be further optimized within the 2–5 mm range to achieve the best trade-off between voltage efficiency and coagulant formation, following the relationship $V=J\cdot\rho\cdot d$. Implementing adaptive current control based on real-time conductivity feedback would also help maintain an ideal current density $J=I/A$ under varying wastewater conditions.

To enhance durability, aluminum electrodes could be coated with conductive oxide layers or replaced with Fe–Al composites to reduce corrosion and passivation effects. Additionally, IoT communication reliability can be improved through MQTT or LoRa protocols for stable data transfer. A smart power management system is also suggested to automatically balance energy input between solar panels and the grid, ensuring sustainable operation.

The reactor should adopt a modular design, allowing easier scale-up for industrial use and simplified maintenance. Automatic sensor calibration and self-cleaning features are also recommended to ensure long-term operational accuracy.

However, one major limitation identified in this study is the lack of detailed analysis on the concentration and volume of synthetic dye used in the wastewater samples. Future studies should include precise quantification of dye content (in mg/L) to enable a more accurate evaluation of removal efficiency and system kinetics.

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