Experimental investigation and optimization on COD removal efficiency in textile wastewater by solar-photovoltaic electrocoagulation technology

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Abstract. Electrocoagulation is an attractive method for the many types of water and wastewaters treatments due to its advantages such as environmental friendliness, cost effectiveness, energy and high removal efficiency. The goal of this study was to investigate the COD removal rate and energy efficiency of COD parameter from real textile wastewater by solar energy assisted electrocoagulation process using aluminium and iron electrodes. In addition, process optimisation was performed by Monte Carlo Simulation and the relationship between the parameters was investigated by sensitivity analysis. At optimum reaction parameters, COD removal percentage reached 97.51% at aluminium electrode, while the highest removal percentage was 78.70% at iron electrode. The minimum energy consumption and cost for Al and Fe electrode were 1.2 kWh/m^3 and 0.144 \$/m^3, respectively.

1 Introduction

Globally, more than a million tonnes of synthetic pigments and dyes are produced each year. These are extensively utilized in a wide range of industrial domains, including the paper, food, textile, and leather sectors, as well as photo-electrochemical cells. Textile wastewater is treated using physical, chemical, and biological techniques [1]. However, the chemicals used in common biological treatment processes are often ineffective due to the presence of highly structured, low-biodegradable polymers.

Chemical Oxygen Demand (COD) represents the amount of oxygen required for the breakdown of organic matter in water by microorganisms. A high COD indicates a high level of organic matter in the wastewater [2]. This situation has various negative effects such as oxygen depletion in the environment, decrease in water quality and eutrophication, bad odour and environmental disturbance and threat to public health. Removal of COD is important for the protection of the environment and human health. For this reason, wastewater from industrial plants should be brought into compliance with the COD limits specified in the regulations [3].

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Electrochemical technology, particularly in industry, is crucial to the green transformation movement and the clean energy-environment context because of its extensive technological network [4]. Wastewater treatment, process stream recycling, fuel cells, and new batteries are the most popular methods of producing energy. Environmental electrochemistry has been the target of much research in recent years.

Accordingly, the study, electrocoagulation is a clean and efficient way to treat a variety of wastewaters [5], groundwater [6], leachate [7], brine [8], olive oil [9], grey water [10], and contaminants like nitrate, fluoride, and arsenic [4, 11, 12].

The cost of the electrocoagulation (EC) treatment process and the effectiveness of pollutant removal are significantly impacted by the electrode material. Aluminium and iron are particularly effective activators in these processes. In addition, it is more preferred because it is environmentally friendly, relatively non-toxic and cheaper. In essence, an electrocoagulation reactor is an electrochemical cell that uses a metal ion coagulant to dose the contaminated water after reactions (1-3) using a sacrificial metal anode, often made of iron and aluminium [13, 14].

$$\text{Anode } Fe \rightarrow Fe^{2+} + 2e^- \quad (1)$$
$$\text{Cathode } H_2O + 2e^- \rightarrow H_2 + OH^- \quad (2)$$
$$\text{In solution } Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \quad (3)$$

Al as a sacrificial electrode can be used primarily as an electrocoagulation method to remove contaminants from drinking water, surface waters, and paints, among other things [15]. Reactions (4-6) demonstrate how Al coagulant is formed.

$$\text{Anode } Al \rightarrow Al^{3+} + 3e^- \quad (4)$$
$$\text{Cathode } H_2O + 2e^- \rightarrow H_2 + OH^- \quad (5)$$
$$\text{In solution } Al^{3+} + 3OH- \rightarrow Al(OH)_3 \quad (6)$$

Especially in the last 20 years, various electrodes have been designed to improve electrochemical procedures in industrial and wastewater treatment, drinking water purification, and sludge treatment. Electrochemical methods provide great efficiency and low resource consumption as a pre-treatment phase to improve the degradability of a pollutant or as an enhanced treatment method to even more remove color or COD to fulfil specified wastewater standards [16].

The Monte Carlo simulation technique has been used to analyse dose distributions in water and tissue and has provided information on the effects of processes such as electrocoagulation on water quality [17]. This simulation method has been effective in evaluating the efficiency of electrocoagulation processes and their effects on water treatment.

In this study, COD removal from textile wastewater using EC method integrated with solar energy system was aimed. Monte Carlo Simulation (MCA) was used to perform the optimization and Sensitivity Analysis (SA). Six quantitative variables, namely COD concentration, conductivity, amperage, voltage, pH and reaction time, were investigated. In conclusion, electrocoagulation method is a green technology for especially wastewater treatment and proposers a versatile and effective solution to address a wide range of pollutants in different water sources. The use of advanced simulation techniques such as Monte Carlo further enhances the system's applicability and efficiency.

2 Material and Method

2.1 Experimental Setup

Each experimental investigation was carried out in a 1.5 L glassmaking reactor with dimensions of 100 × 100 × 250 mm [4]. Plate electrodes with dimensions of 90 × 200 × 3 mm for Al and 96 × 180 × 1.5 mm for Fe were used in the investigation. The electrodes were linked to a direct current power supply (specifically a Rigol DP832A model) capable of delivering 30 volts and 3 amperes. A magnetic stirrer (IKA RH basic 2) was used to stir the mixture at 200 rpm. For the EC test, the batch approach was used. The experiments were carried out using 1 Ampere, 5 Volt, 20 min working time and 200 rpm mixing speed at 20 ºC. Sample conductivity and pH were measured both initially and finally using a portable Hach-Lange HQ40d multi-metering equipment. COD was analysed by the Standard Methods for the Investigation of Water and Wastewater Treatment, 23rd edition, 2017.

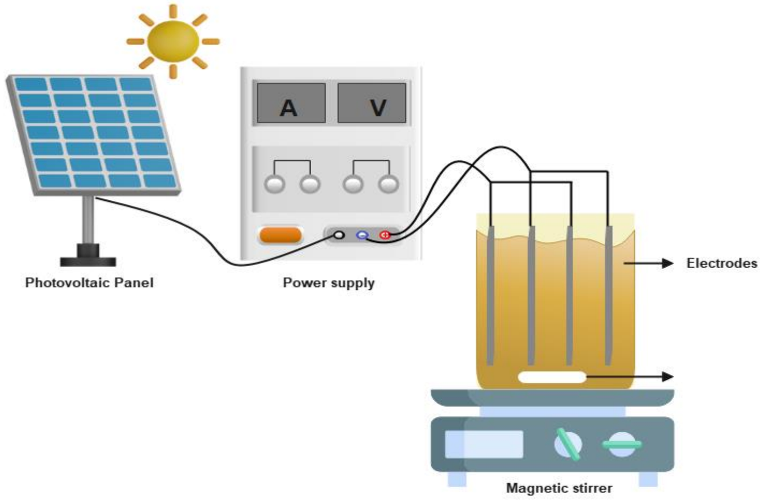

Fig. 1. An illustration of the EC configuration.

A sample was taken every minute and passed through 0.45 µm filter of syringes and necessary analyses were performed. Laboratory scale removal studies have been performed with real wastewater samples taken from the effluent of a textile company. This study is important in terms of showing that the wastewater does not have a structure that will prevent floc formation and that the pollutants it contains have affinity for metal flocs.

2.2 PV System Installation

PV panels are set up to supply all of the energy required for the EC process. The installation process includes determining the energy needs, assessing the solar potential and organising the panels according to safety standards. Optimal sites and orientation are determined, and sensors and meters are installed to monitor energy efficiency. The solar EC system generally consists of equipment such as PV panels, charge controller and battery. PV panels generate the electricity required for the EC system by converting sunlight into electrical energy. The charge controller controls the battery that stores the energy from the solar panels and prevents overcharging. The battery is an energy storage unit where the energy from the solar panel is stored and made available for use [18].

2.3 Monte Carlo Simulation and Sensitivity Analysis

The MCS was chosen for 20,000 runs because a larger number of runs can improve the coherence of results. Oracle Crystal Ball (version 11.1.2.4.850) was used in the study.

Sensitivity analysis quantifies the potential impact of varying independent variable values on the dependent variable. Additionally, it analyses how modifications to input data may affect an MCS's output. Sensitivity analysis revealed that COD removal efficiency and energy consumption based on diverse factors of the EC process. MCS was used in SA to predict the electrochemical process's future performance [19, 20]. The SA of these findings can direct further investigation and advancement in the electrochemical treatment of sludge and wastewater.

By selecting parameter values from their appropriate distributions, the exposure risk and point value are calculated using this technique. The US Environmental Protection Agency calculates SA and MCS employ probability distribution functions.

2.4 Energy Consumption

Energy consumption in EC process was calculated by Eq. (7):

$$Energy\ Consumption\ \left(\frac{kWh}{m^3}\right) = \frac{voltage \times current \times run\ time}{working\ volume\ of\ reactor} \qquad (7)$$

3 Results and Discussion

3.1 Optimization Using Monte Carlo Simulation and Sensitivity Analysis

In MCS 20,000 data were generated in statistical distributions. In Fig. 2, the MCS for Al electrodes shows an average value of 97.57 in the electrocoagulation process. The standard deviation of these simulations is the variance around the mean, while the normal probability distribution merely characterizes the mean or expected value. Values close to the centre have the highest probability of occurring. The specified optimized conditions are the initial COD concentration of 1114 mg/L, voltage of 5 V, average pH of 8.71, ampere of 1, TDS of 2440 mg/L, time of 180 min, and current density of about 10 mA/cm^2.

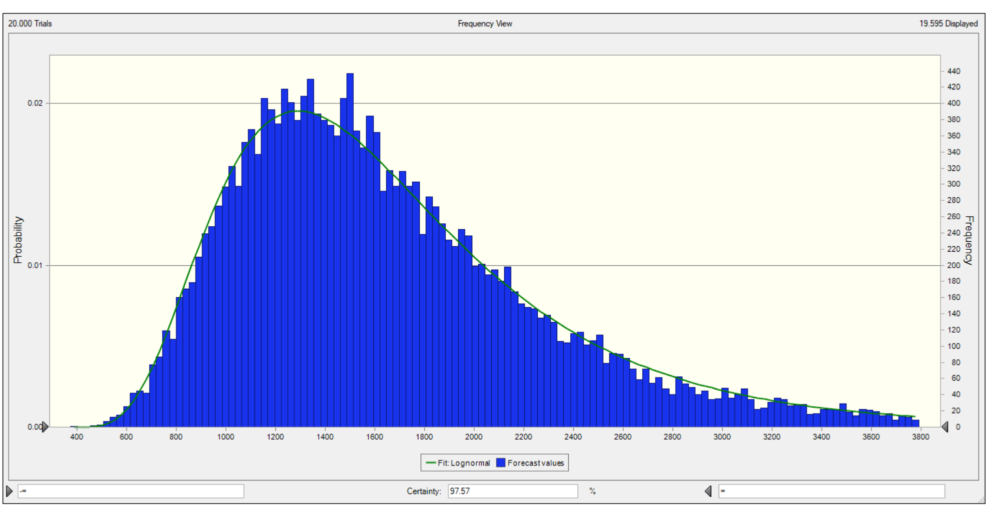

Fig. 2. Monte Carlo simulation for the electrocoagulation process using Al electrode.

In Fig. 3, the Monte Carlo simulation for Fe electrodes shows an average value of 94.45 in the electrocoagulation process. The standard deviation of these simulations is the variance around the mean, while the normal probability distribution merely characterizes the mean or expected value. Values close to the centre have the highest probability of occurring. The specified optimized conditions are the initial COD concentration of 1021 mg/L, voltage of 5 V, average pH of 8.67, ampere of 1, TDS of 2310 mg/L, time of 180 min, and current density of about 10 mA/cm^2.

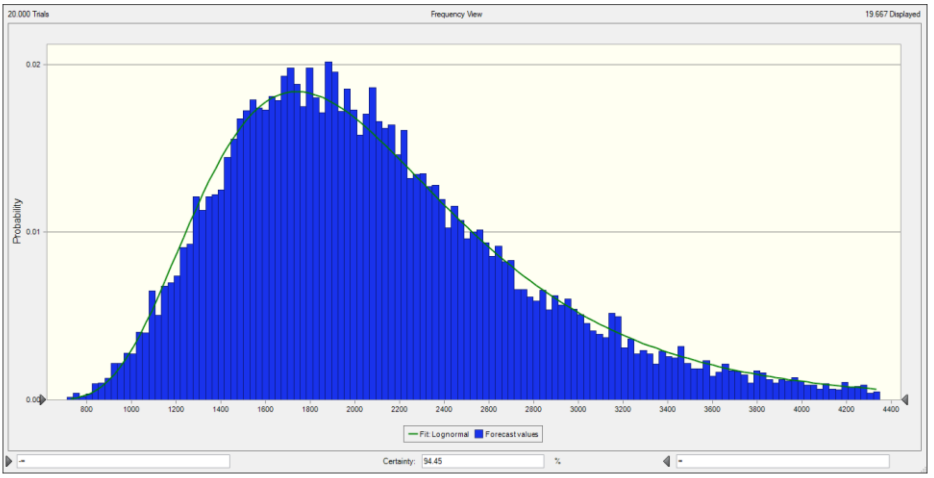

Fig. 3. Monte Carlo simulation for the electrocoagulation process using Fe electrode.

Subsequently, spearman's rank correlation was used in sensitivity analysis along with the MCS methodology. The most crucial factors for COD removal are TDS > color > COD concentration > color removal > COD removal as illustrated in Fig. 4 for Al electrode. TDS has been identified in earlier studies as a critical component of EC performance [21, 22].

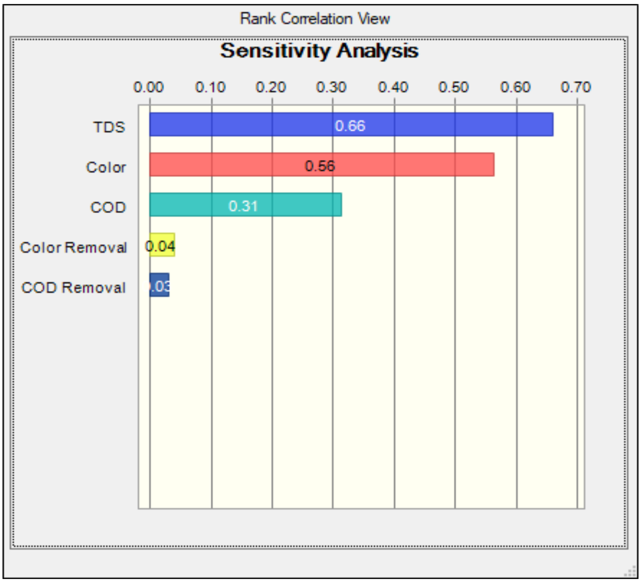

Fig. 4. Sensitivity analysis using Spearman's rank correlation and the MCS approach for Al electrode.

The most crucial factors for COD removal are TDS > color > COD concentration > COD removal > color removal > pH as illustrated in Fig. 5 for Fe electrode.

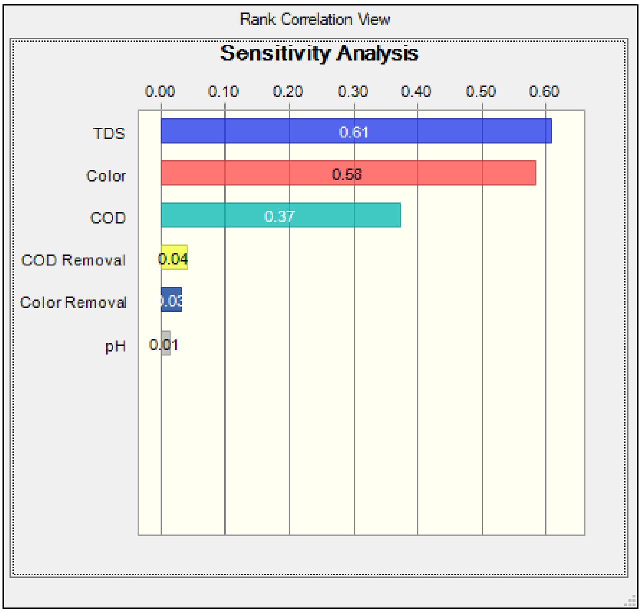

Fig. 5. Sensitivity analysis using Spearman's rank correlation and the MCS approach for Fe electrode.

3.2 Energy Consumption and Cost Analysis

Energy consumption and current efficiency metrics are used to compare the performance of the electrocoagulation process. Current efficiency is defined as the electric current ratio used to the total energy used. Mass transfer and the system's surface reactions are both included in the term "current efficiency". Here, current efficiency and energy consumption are used to depict the electrochemical reactor's removal performance in its ideal location [23]. These parameters were computed using the formulas provided in the literature [24]. The least amount of energy needed to react with the Al and Fe electrodes for 180 minutes calculated using Eq. 7. was 1.2 kWh/m^3 at a current density of 10 A/m^2. While calculating the electricity consumption EC process's cost under optimum conditions, the industrial electricity price of 0.12 \$/kWh (Türkiye, 1\$ = 32.38 TL as of 30 March 2024) was considered. This results in a total electricity consumption of 0.144 \$/m^3.

4 Conclusion

This study investigates the Monte Carlo optimization and cost analysis of a solar-powered EC process for COD removal from textile wastewater. The relationship between electrocoagulation process efficiency and surface area, distance between electrodes and anode type, initial concentration, reaction time and current density was determined. COD removal and energy consumption in the current process were analysed by Monte Carlo simulation and uncertainty and precision were measured. It showed a mean value of 97.57 for Al electrode and 94.45 for Fe electrode. Furthermore, the cost analysis shows that this method is economically competitive. These equations can be used to predict the efficiency of pilot or full-scale processes when all design parameters are proportional and appropriately scaled.

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