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Muhammad Saleem
Department Civil Engineering, Jubail Industrial College, Royal Commission for Jubail & Yanbu, Jubail Industrial City, Saudi Arabia, saleemm@rcjy.edu.sa

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RESEARCH ARTICLE

Mitigating the Challenges of Textile Wastewater Treatment in Saudi Arabia Utilizing Electrocoagulation Process: Optimization of Operating Parameters

Muhammad Saleem

Department Civil Engineering, Jubail Industrial College, Royal Commission for Jubail & Yanbu, Jubail Industrial City, Saudi Arabia

ABSTRACT

The increasing importance of treating industrial effluents for environmental and public health protection has necessitated reliable and economical treatment methods capable of meeting stringent effluent quality standards. This study aimed to evaluate the effectiveness of the electrocoagulation (EC) process using iron electrodes for treating real textile wastewater by removing total solids (TS), COD, colour, and turbidity. Various operating parameters, including treatment time, initial pH, current density, stirring speed, and inter-electrode spacing (IES), were investigated to optimize removal efficiency. The results demonstrated that the optimal conditions for maximum pollutant removal were achieved at a treatment time of 60 minutes, a current density of 6.2 mA/cm^2, a solution pH of 8–8.5, a stirring speed of 150 rpm, and an IES of 5 cm. Under these conditions, the removal efficiencies reached 79.2% for TS, 92.7% for COD, 88.9% for turbidity, and 98.7% for colour. The findings of this research indicate that the EC process is a simple, quick, and economically viable method for effectively removing pollutants from textile wastewater. Additionally, it is recommended that a coupled treatment unit, such as filtration or adsorption, be employed following the EC process to enhance pollutant removal. Saudi Arabia's Vision 2030 aims to address environmental pollution from industrial wastewater, including textile wastewater, highlighting the importance of balancing industrial growth with environmental stewardship. Present study offers the first thorough analysis of textile wastewater treatment utilizing EC process in the region, enhancing understanding of effective strategies for sustainability and compliance with effluent quality standards.

Keywords: Electrocoagulation, Textile wastewater, Iron electrodes, Removal efficiency, Optimum parameters

1. Introduction

Effluents from various industries, particularly the textile sector, are significant sources of pollution in receiving water bodies, leading to severe environmental challenges [18]. This pollution has serious repercussions for aquatic ecosystems and is a major source of environmental contaminants [14]. The wastewater generated by the textile industry contains numerous harmful substances, including toxic chemicals that pose risks to living organisms [21]. The composition of textile effluent varies greatly across different operations, influenced by factors such as the equipment used, production processes, types of fabrics manufactured, chemicals involved, and even seasonal and fashion trends. Typically, textile wastewater is characterized by its color, elevated pH levels, high biochemical oxygen demand (BOD), suspended solids (SS), chemical oxygen demand (COD), salts, and elevated temperatures [5].

The textile industry is notable for its high water usage, surpassing that of any other industrial sector, which inevitably leads to significant environmental repercussions. It has been noted that an

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E-mail address: saleemm@rcjy.edu.sa, i_am_saleem@yahoo.com (M. Saleem).

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average textile facility consumes approximately 200 liters of water for every kilogram of fabric processed [31]. Textile industries utilize large volumes of water, which in turn generates large volumes of wastewater [20]. The coloring dyes used in textile wastewater can adversely affect the photosynthesis process in plants. Recently, there has been a shift towards the utilization of aromatic and heterocyclic dyes in textile manufacturing. These dyes are structurally complex and stable, making them particularly challenging to degrade.

In Saudi Arabia, as the nation diversifies its economy through initiatives like Vision 2030, the textile and fashion sector is experiencing rapid growth. However, this expansion comes at a cost, particularly concerning the generation of textile wastewater. Estimates regarding the actual quantity of textile wastewater produced in Saudi Arabia vary, but reports indicate that as the textile industry continues to grow, the volume of wastewater is escalating dramatically. It is estimated that the textile sector can generate anywhere from 15,000 to 20,000 cubic meters of wastewater per day in larger factories alone [32].

Given the depletion of freshwater resources and the rising levels of pollution in existing water resources, the reuse of wastewater has become essential. This necessitates the urgent development of cost-effective methods for wastewater treatment. While various conventional treatment strategies have been implemented such as, adsorption [19], ion exchange [36], advanced oxidation processes [43], reverse osmosis, biological methods [12], membrane separation, ultrafiltration [24], chemical precipitation, chemical coagulation [30], and electrocoagulation [35]. Many of these methods are effective but costly, often exhibiting several limitations and drawbacks. Electrocoagulation (EC) emerges as an attractive process for pollutant removal from wastewater, offering operational simplicity, cost-effectiveness, and environmentally friendly features. In the electrocoagulation process, coagulants are generated through electrical means, and the wastewater undergoes purification within an electrochemical cell. By connecting the system to a direct current (DC) power supply, sacrificial anodes dissolve and function as coagulants in the treatment process. Previous studies have indicated that the EC process can effectively address the limitations of conventional treatment methods. Research has revealed the efficacy of EC process in treating various contaminants present in textile wastewater [9].

Electrocoagulation's effectiveness relies on several factors, including the applied current density, treatment time, electrode materials, pH levels of the wastewater, and the inter electrodes spacing (IES), which is the centre to centre distance between parallal electrodes [28]. Hashim and colleagues noted that the color removal efficiency of wastewater is significantly influenced by pH. Coagulation is most effective at neutral pH, where iron hydroxides form, while in acidic environment, iron species are generally more soluble [16]. Bayramoglu et al. conducted a study on the treatment of textile wastewater using aluminum and iron electrodes, emphasizing how the characteristics of the wastewater affect treatment efficiencies. Their findings revealed that the cost of electrocoagulation (EC) under optimal conditions is roughly 3.2 times lower than that of conventional coagulation and flocculation processes [8].

In the electrocoagulation (EC) process, when electrical current is passed through water containing contaminants, leading to coagulation of suspended particles and the removal of impurities. Following are the electrocoagulation reaction equations that occur when using iron electrodes [34].

(a) Mechanism 1:

$$\begin{aligned}
&\textbf{Anode: } Fe(s) \longrightarrow \quad Fe^{2+}(aq) + 2e^- \\
&Fe^{2+}(aq) + 2OH^-(aq) \longrightarrow Fe(OH)_2(s) \\
&\textbf{Cathode: } 2H_2O(l) + 2e^- \longrightarrow H_2(g) + 2OH^-(aq) \\
&\textbf{Overall: } Fe(s) + 2H_2O(l) \longrightarrow Fe(OH)_2(s) + H_2(g)
\end{aligned} \tag{1}$$

(b) Mechanism 2:

$$\begin{aligned}
&\textbf{Anode: } 4Fe(s) \longrightarrow 4Fe^{2+}(aq) + 8e^- \\
&4Fe^{2+}(aq) + 10H_2O(l) + O_2(g) \longrightarrow \\
&\qquad 4Fe(OH)_3(s) + 8H^+(aq) \\
&\textbf{Cathode: } 8H^+(aq) + 8e^- \longrightarrow 4H_2(g) \\
&\textbf{Overall: } 4Fe(s) + 10H_2O(l) + O_2(g) \longrightarrow \\
&\qquad\qquad 4Fe(OH)_3(s) + 4H_2(g)
\end{aligned} \tag{2}$$

When iron electrodes are employed, an electric current through the water causes the oxidation of iron at the anode, resulting in the formation of ferric ions (Fe^{3+}). These ions hydrolyze in the presence of water to produce ferric hydroxide ($Fe(OH)_3$), a flocculent precipitate that can capture suspended solids, heavy metals, and organic pollutants. As the EC process continues, the generated flocs agglomerate and settle, facilitating their removal from the water. The specific form of iron hydroxide (either $Fe(OH)_2$ or $Fe(OH)_3$) that predominates will depend on available conditions (e.g., pH, liberation of oxygen and carbon dioxide, etc.) during the electrocoagulation process.

However, the mechanisms of EC process needs to be certainly understood and there was little or no attention on the influence of operating parameters

that have an effect on the powerful elimination of pollutants including ionic species, organic materials, polymeric wastes, phenolic wastes, priority pollutants, from textile wastewater utilizing electrocoagulation process [37].

The scientific hypothesis of this work is that the electrocoagulation (EC) process using iron electrodes is an effective and economical method for treating real textile wastewater, capable of achieving significant removal efficiencies for total solids (TS), chemical oxygen demand (COD), colour, and turbidity when optimized under specific operating parameters.

This study presents a novel investigation into the treatment of real textile wastewater using the electrocoagulation (EC) process, marking a significant departure from previous research predominantly focused on synthetic wastewater in controlled conditions. By systematically evaluating critical operating parameters such as treatment time, initial pH, stirring speed, applied voltage, current density, and inter-electrode spacing this research not only enhances understanding of the EC process in the context of complex real wastewater but also establishes optimized conditions tailored specifically for local textile effluent. Furthermore, this work addresses an important gap in the literature by providing the first comprehensive analysis of real textile wastewater treatment in this region, thereby contributing valuable insights into effective strategies for meeting stringent effluent quality standards and promoting sustainable textile industry practices. The outcomes of this study pave the way for further exploration of EC technology, emphasizing its potential as a viable solution for real-world wastewater challenges.

2. Materials and method

The subsequent subsections outline the comprehensive experimental program designed to gather the necessary information. This includes the utilization of various chemicals, materials, and instruments essential for conducting the study.

2.1. Wastewater samples

The wastewater samples were collected from a local textile industry in the eastern province, which primarily produces products including bedsheets, curtains, rugs, and textile uniforms. Samples were collected and transported to the laboratory in iceboxes within two hours, while maintaining strictly sterile conditions throughout the collection and conveyance process.

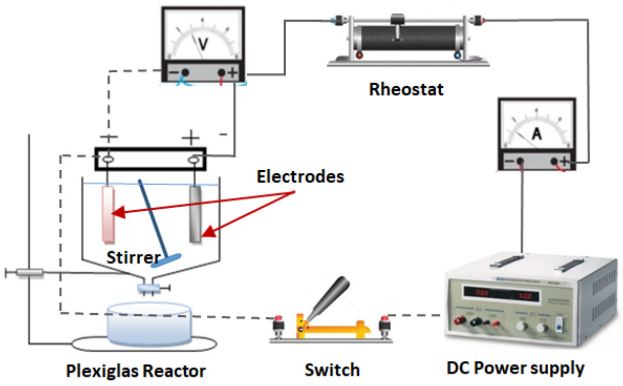

Fig. 1. Schematics of electrocoagulation experimental setup.

2.2. Chemicals & other materials

All chemicals used were of analytical grade and supplied by Merck. The pH of the solution was adjusted by adding either 0.1 mol/L solution of NaOH or H_2SO_4 (95% purity). Standard LCK 114 COD cuvettes from HACH were used to determine the chemical oxygen demand (COD) of the samples.

2.3. Experimental setup

An electrochemical reactor was established in the water and wastewater engineering lab at JIC. The setup consists of a cylindrical cell, electrodes, a DC power supply, an ammeter, a voltmeter, and other necessary accessories, as illustrated in Fig. 1. The electrocoagulation cell has an internal diameter of 35 cm and a height of 47 cm, providing an effective volume of 4.5 liters. For each test, 3.5 liters of wastewater were treated using the electrocoagulation (EC) process. Two iron electrodes, each with a surface area of 35 cm^2, were employed in the EC cell, as referenced in previous studies [33]. Ironn electrodes were selected based on previous studies reporting that bbesides being cheaper, iron electrode treatment demonstrating better removal efficiencies for studied pollutants [27].

The distance between the cathode and anode was maintained at 5 cm during all runs, following the methodology outlined in prior research [34], except for investigations into the effects of electrode spacing. Temperature control was achieved using a thermostatic water bath (LEMC-A20, LAB TRON, UK). The solution within the reactor was stirred using a plate stirrer at a rotational speed of 150 rpm (HEIDOLPH 036110460). DC current was provided by a regulated DC power supply (Model RPS-6030, China). Throughout the experimental runs, constant current was provided using a rheostat (Model: Sliding

Table 1. Summary of testing parameters along with the selected variables and constant parameters in various runs.

Testing Parameter/Units	Selected range of variable parameter	Selected constant variables
Time of treatment (min)	10, 20, 30, 50, 60	Current density: 6.2 mA/cm^2, Stirring speed: 150 rpm, Initial pH: 8.5, Operating temperature: 25°C, IES: 5 cm.
Operating temperature (°C)	20, 25, 30, 35, 40	Current density: 6.2 mA/cm^2, Stirring speed: 150 rpm, Initial pH: 8.5, IES: 5 cm.
Initial pH	3, 5, 7, 7.5, 8, 8.5, 9, 11	Current density: 6.2 mA/cm^2, Stirring speed: 150 rpm, IES: 5 cm, Operating temperature: 25°C
Stirring speed (rpm)	50, 100, 150, 250, 350	Current density: 6.2 mA/cm^2, Initial pH: 8.5, Operating temperature: 25°C, IES: 5 cm.
Applied Current Density (mA/cm^2)	1.2, 4.2, 5.1, 6.2, 6.6, 7.3	Stirring speed: 150 rpm, Initial pH: 8.5, Operating temperature: 25°C, IES: 5 cm.
IES (cm)	2, 3, 4, 5, 6, 7, 8	Current density: 6.2 mA/cm^2, Stirring speed: 150 rpm, Initial pH: 8.5, Operating temperature: 25°C

rheostat 2A20) and was monitored with a multimeter (MS8050 Bench Type, MASTECH).

Following a thorough characterization of the raw wastewater, multiple experimental runs involving electrocoagulation (EC) were conducted in the lab. First, the textile wastewater was vigorously stirred for a few minutes using a stirrer to ensure the sample was homogenized. During EC experimental runs current density of 1.2 mA/cm^2 was applied up to 60 minutes of treatment time. Samples of treated textile wastewater were collected at specific time intervals in order to analyze the impact of treatment duration on the removal efficiency of total solids (TS), COD, turbidity, and color. All sampling and analysis procedures were carried out according to the Standard Methods for the Examination of Water and Wastewater [29].

Table 1 presents a summary of the testing parameters, including selected variables and constant parameters across various trials. To assess the impact of treatment time, samples were collected at intervals of 10, 20, 30, 50, and 60 minutes, which were then analyzed for the reduction of the studied parameters. The influence of solution temperature was examined at temperatures of 20, 25, 30, 35, and 40 °C. To evaluate the effect of the initial pH of the solution, the pH of textile wastewater was adjusted to levels of 3, 5, 7, 7.5, 8, 8.5, 9, and 11. The range of pH selected in order to cover the wider range of acidic and alkline zone of solution pH. Additionally, the effects of stirring speed and Interelectrode Spacing (IES) were investigated with stirring speeds of 50, 100, 150, 250, and 350 rpm, and IES values of 2, 3, 4, 5, 6, 7, and 8 cm. The range of IES was selected based on the EC study conducted in past with iron electrodes [34]. Regarding current density, currents of 42, 147, 179, 215, 231, and 256 mA were applied, resulting in current densities of 1.2, 4.2, 5.1, 6.2, 6.6, and 7.3 mA/cm^2, respectively. After each trial, the samples were allowed to settle for 30 to 40 minutes to ensure that the flocs formed during the electrocoagulation (EC) process had adequately settled.

3. Results and discussion

The following subsections present a detailed discussion of the laboratory analysis and experimental findings, concentrating on the characteristics of textile wastewater before and after electrocoagulation (EC) treatment. Additionally, this section outlines the testing parameters, as well as the chosen variables and constant parameters used in various experimental trials.

3.1. Characterization of raw wastewater

Textile wastewater analyzed in the study (Table 2) showed significantly elevated levels of total solids (TS), color, chemical oxygen demand (COD), and turbidity compared to typical domestic wastewater [23]. The average pH was near neutral (6.8±0.5), while electrical conductivity was high (4830±15 μS/cm), facilitating the EC treatment process without additional electrolytes. Additionally, chloride concentrations were also elevated (2473±6 mg/l), promoting chlorine production during electrochemical treatment. Chlorine serves as an oxidizing agent, converting soluble ferrous ions to insoluble ferric ions, as supported by Larue and Vorobiev [22].

Wang et al. [41], reviewed characteristics of various textile wastewater samples and found, the major contaminants present in textile wastewater are high suspended substances, COD, acidity, heat, colour, and other soluble substances and the concentration of these pollutants is quite variable due to different methods utilized during production process [41]. In a past study researchers collected wastewater samples from various textile industries having operation, from the washing of fibers to bleaching, mercerizing,

Table 2. Characteristics of textile wastewater and Instruments/ method used in the study.

Parameters*	Units	Characteristic Value of Textile Wastewater	Instruments/ Method Used
Total Solids (TS)	mg/l	2874±16	POLYSCIENCE WBE05L11B Water Bath, Lab Muffle Furnace Model BR-14S /Gravimetric
Total Dissolved Solids (TDS)	mg/l	936±8	POLYSCIENCE WBE05L11B Water Bath, Lab Muffle Furnace Model BR-14S /Gravimetric
Total Suspended Solids (TS)	mg/l	1938±9	POLYSCIENCE WBE05L11B Water Bath, Lab Muffle Furnace Model BR-14S /Gravimetric
Colour	Pt-Co Units	1840±12	LaMotte 1910 Smart 3 Colorimeter/Pt-Co Standard Method
pH	–	6.8±0.5	pH meter Mi-151, Italy/ Electrometric
Chemical Oxygen Demand (COD)	mg/l	1932±8	Closed Reflex, Titrimetric Method/APHA
Conductivity	μS/cm	4830±15	HACH/ 51800-10/APHA
Turbidity	NTU	995±5	Orion™ AQUAfast AQ3010 Turbidity Meter Thermo Scientific/APHA
Chlorides	mg/l	2473±6	METTLER TOLEDO's 3000CS/ Microfluidic capillary electrophoresis
Sulfate	mg/l	529.4±3	METTLER TOLEDO's 3000CS/ Microfluidic capillary electrophoresis

dyeing, printing and washing of finished products and reported that the characteristics of textile wastewater is strongly related to the dominant process being used in the textile industry [17]. Therefore, probably the characteristics of wastewater used in the present study has similar characteristics than reported in literature obtained from similar textile industries producing cotton, rayon and linen [42].

Subsequently, experiments on electrochemical processes were conducted to assess the impact of different operating parameters on the efficiency of the process. The findings from each trial are discussed below.

3.2. Determination of optimum operating parameters

Following section discusses the results obtained during EC runs and the analysis of obtained results.

3.2.1. Effect of treatment time

The duration of electrocoagulation (EC) treatment is crucial for controlling costs and enhancing efficiency in wastewater management, particularly in continuous flow systems where detention time matters. Initially, the effluent treated with iron electrodes displayed a brownish hue, which later changed to a yellow, turbid appearance. This coloration stems from Fe^{2+} and Fe^{3+} ions generated during the electrocoagulation process. Fe^{2+}, primarily formed during electrolysis, is more soluble in acidic or neutral conditions and can be oxidized to Fe^{3+} by dissolved oxygen [38]. An examination of EC treatment duration at a constant current density of 6.2 mA/cm^2 for 70 minutes revealed a significant impact on the removal of total solids (TS), chemical oxygen demand (COD), turbidity, and color.

As illustrated in Fig. 2, the removal efficiency of the electrocoagulation (EC) process was notably rapid during the first 20 minutes, achieving rates of 38.6%, 52.7%, 41.3%, and 68.4% for total solids (TS), chemical oxygen demand (COD), turbidity, and color, respectively. However, when the treatment time was extended from 20 to 40 minutes, the increases in removal efficiency were considerably slower. By the end of this period, the TS, COD, turbidity, and color removal rates reached 47.3%, 67.9%, 53.4%, and 81.2%, respectively. After 60 minutes of treatment, the removal efficiencies for total solids (TS), chemical oxygen demand (COD), turbidity, and color reached 79.2%, 92.7%, 88.9%, and 98.7%, respectively. However, no significant improvement in removal efficiency was observed beyond this duration.

The color removal was quite fast, with more than 98% of the color being removed within 50 minutes. In this study, it was observed that the electrocoagulation (EC) process involves three stages: destabilization, aggregation, and settling. During the first 20 minutes, the EC process was rapid, and all studied pollutants were removed quickly, which may be attributed to the initial destabilization and agglomeration of pollutants with the formed Fe^{2+} and Fe^{3+} ions. However, the process slowed down between 20 and 40 minutes due to the formation of excess sludge between the electrodes, and the removal efficiency did not improve significantly during this period. Furthermore, from 40 minutes to 60 minutes, secondary aggregation enhanced the removal efficiency, with almost all parameters reaching their maximum removal efficiency. Naje et al. [26], utilized Al-Fe electrodes, demonstrated the treatment time for maximum efficiency of their textile wastewater around 80 min. The findings of the current study indicate that optimal efficiency in the electrocoagulation (EC) process

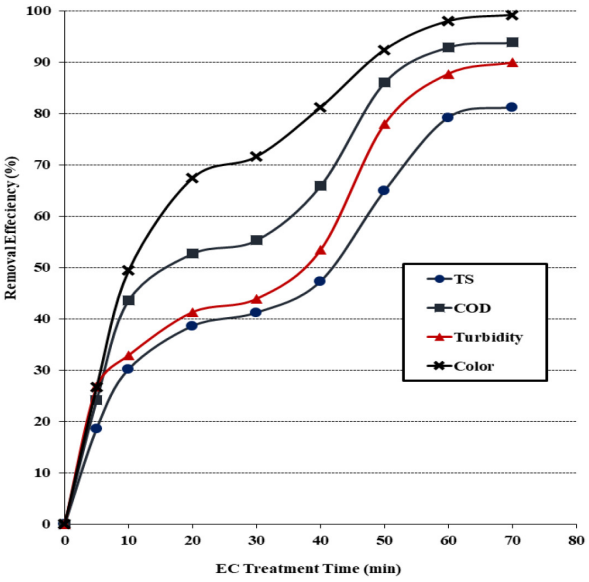

Fig. 2. Temporal variation in removal efficiency of studied parameters EC process.

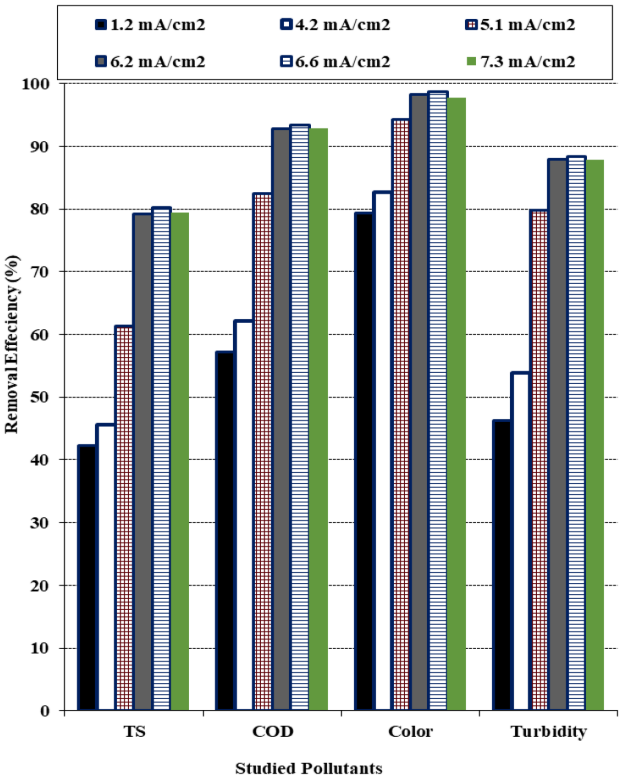

Fig. 3. Removal efficiency of studied parameters at various current densities utilizing EC process.

is reached after 60 minutes of treatment. Extending the treatment time beyond this duration results in only slight improvements in removal efficiency for the parameters examined. This is probably due to the reduced number of remaining pollutants available for interaction with the iron coagulant, which leads to decreased flock formation. Consequently, these results suggest that incorporating a supplementary treatment unit, such as filtration and/or adsorption, following the EC process would be more effective for further pollutant removal.

To investigate the effect of operating parameters on the removal efficiency of the studied pollutants, we thoroughly examined current density, initial pH, stirring speed, and IES. The effects of these parameters are discussed in detail in the following sections.

3.2.2. Effect of applied current density

The influence of applied current density on pollutant removal efficiency in the electrocoagulation (EC) process was investigated. The DC current was meticulously regulated to achieve current densities ranging from 1.2 to 7.3 mA/cm^2 over six experimental trials, with a treatment duration of 60 minutes for each current density. Results, illustrated in Fig. 3, indicated that removal efficiency significantly increased with higher current densities for the same duration. Conversely, a decrease in current density required more time to achieve similar removal efficiency, aligning with previous findings that linked treatment efficiency primarily to charge loading [13]. However, Can et al. [10] reported lower removal efficiency at elevated current densities, attributing this to excessive sludge formation that hindered the even distribution of coagulant iron particles within the reactor, leading to reduced effectiveness at high current levels.

Current density is a key factor in the electrocoagulation (EC) process, as it regulates the reaction rate in the reactor. Some researchers have recognized that current density affects the coagulant dosage rate, the size of the flocs, and their growth, all of which can affect the efficiency of the electrocoagulation process [11]. As a result, the overall cost of the process is influenced by the use of a soluble electrode and the consumption of electrical energy, which economically reflects the benefits of this method. Since higher current densities can lead to increased treatment costs, it is advisable to determine an optimal current density that balances effective treatment with minimal expenses. Galvão and colleagues studied the rate of coagulant generation at high applied current. They reported best removal efficiencies were obtained by applying current density of 128 A/m^2 for 90 min of electrolysis, removing 82%, 82%, and 40% of colour, turbidity, and COD from landfill leachate. Requirement of such high current density may be attributed to the nature of concentrated leachate which

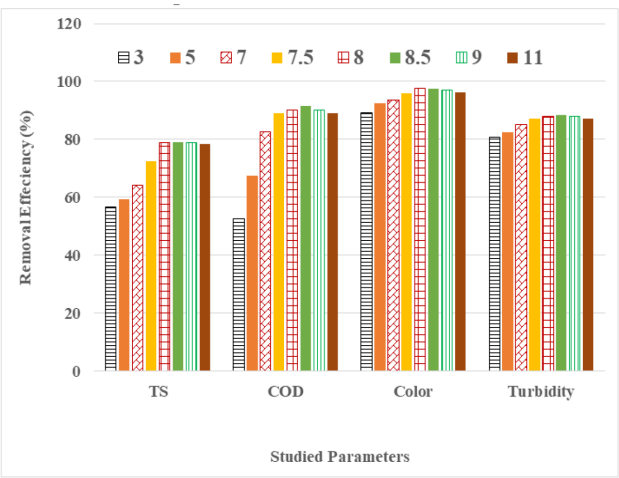

Fig. 4. Removal efficiency of studied parameters at pH values of 3, 5, 7, 7.5, 8, 8.5, 9 and 11 utilizing EC process.

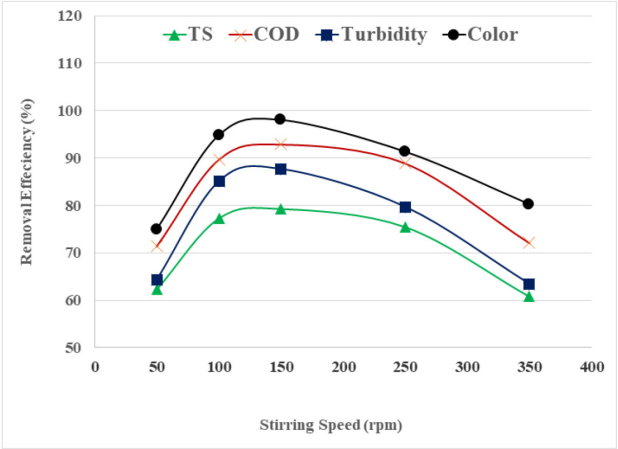

Fig. 5. Removal efficiency of studied parameters at various stirring speed utilizing EC process.

making EC process more expensive [15]. The data presented in Fig. 3 suggests that a current density of 6.2 mA/cm^2 is an appropriate value, as any increase beyond this point yields only marginal improvements in removal efficiency.

3.2.3. Effect of initial pH

As the initial pH is one of the key factors affecting the performance of the electrocoagulation (EC) process, it was examined in this part of the research. To explore this parameter, a series of experiments were conducted at initial pH values of 3, 5, 7, 7.5, 8, 8.5, 9, and 11, with a current density of 6.2 mA/cm^2, a stirring speed of 150 rpm, and an inter-electrode spacing (IES) of 5 cm (as shown in Table 1). The results presented in Fig. 4 indicate that the COD removal efficiencies were 52.7%, 67.4%, 82.6%, 89.2%, 90.3%, 91.6%, 90%, and 89.2%, respectively, at the end of 60 minutes for the corresponding studied pH values. However, at all initial pH values, the COD removal efficiency reached between 96% and 98% by the end of the 60-minute period.

The solubility of iron hydroxide species is significantly influenced by the chemical conditions of the aqueous environment. The efficiency of chemical oxygen demand (COD) removal through electrocoagulation is particularly affected by the solution's pH during the first 30 to 40 minutes of the process. Both the initial pH and any subsequent increases in pH during electrocoagulation are crucial in determining the solubility of pollutants and, as a result, their removal. As the electrocoagulation process continues, the pH rises due to the accumulation of hydroxide ions (OH^-) in the solution. Previous studies have shown that different forms of iron hydroxide, especially Fe(OH), can aggregate, promoting flock formation and enhancing pollutant adsorption. In present study optimal removal efficiency was achieved at a pH of 8.0 to 8.5, where $Fe(OH)_3$ exhibits maximum stability. This study attributes the notable increase in Chemical Oxygen Demand (COD) removal to the aggregation of Fe(OH) flocks during the electrolysis process.

3.2.4. Effect of stirring speed

To examine the effect of stirring speed, a series of experimental runs were performed at speeds of 50, 100, 150, 250, and 350 rpm (see Table 1). It was observed that stirring speeds below 100 rpm resulted in low COD removal efficiency (Fig. 5). This may be attributed to the fact that at lower speeds, a homogeneous mixture of the pollutant and coagulant is not formed in the reactor, leading to inefficient COD removal. The results displayed in Fig. 5, along with observations from the experimental runs, indicate that the floc was dispersed unevenly between the electrodes. This uneven dispersion occurred due to the coagulant not being mixed uniformly, resulting in floc deposition in suspension between the electrodes. Consequently, the cell resistance increased at lower stirring speeds. An increase in cell resistance leads to a rise in potential value in the reactor, where a constant current density results in greater energy consumption per unit volume [26]. Furthermore, at high rpm, the formation of flocs reverses, causing the destruction of previously formed flocs. This, in turn, also decreases the removal efficiency of the electrocoagulation process as can be seen from the results presented in Fig. 5.

3.2.5. Effect of inter-electrode spacing (IES)

Electrode arrangement, such as Interelectrode Spacing (IES), is critical in the electrocoagulation

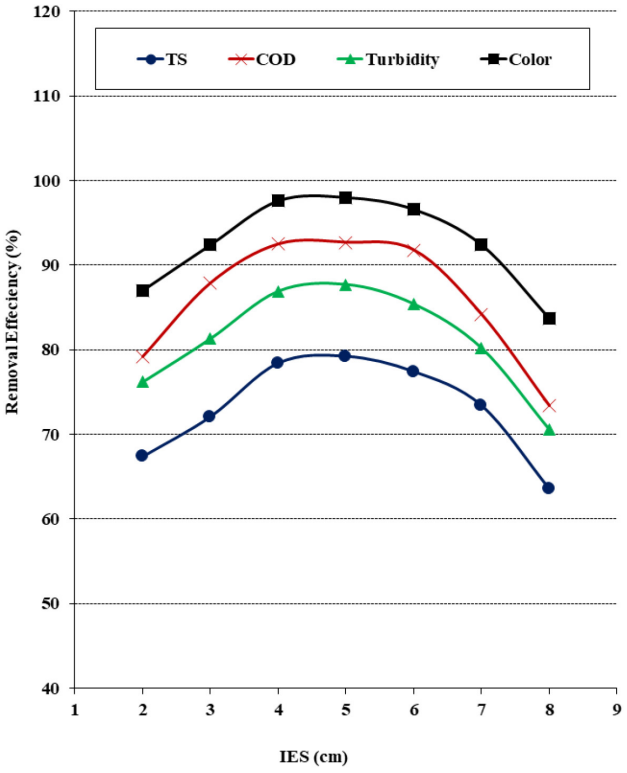

Fig. 6. Removal efficiency of studied parameters at various IES utilizing EC process.

(EC) process for wastewater treatment [2]. Earlier research has highlighted the significance of electrode configuration in pollutant removal [3]. A recent study emphasized the importance of optimizing the electrode gap, noting that while a smaller gap risks short circuits, a larger gap improves process efficiency and minimizes contamination on the electrode surfaces. Adjustments to the IES should be tailored to specific applications and desired outcomes [2]. Increased Internal Electrical Resistance in an EC cell elevates the resistance between electrodes, necessitating a higher applied potential, which raises treatment costs. Furthermore, a larger IES can diminish the interaction between ions and hydroxide complexes, potentially affecting overall treatment efficacy [4].

The removal of the studied pollutants at inter-electrode spacing (IES) values of 2, 3, 4, 5, 6, 7, and 8 cm was examined in this part of the study. During each electrocoagulation (EC) run, the treatment duration was consistently maintained at 60 minutes. The change in pollutant removal efficiency with varying IES is shown in Fig. 6. Analysis of Fig. 6 revealed that the removal efficiency of the EC process for COD was 91.8% at an IES of 6 cm, which increased to 92.7% as the IES decreased from 6 cm to 5 cm and remained almost the same until the IES was reduced to 4 cm. However, a further decrease in IES from 4 to 2 cm led to a decrease in COD removal efficiency to 73.4%. The maximum removal efficiency of COD observed was 92.7% at an IES of 5 cm. Furthermore, when the IES increased from 6 to 7 and 8 cm, a significant decrease in COD removal efficiency was observed, dropping from 91.8% to 84.2% and then to 73.4%, respectively. A similar pattern was observed for total solids (TS), color, and turbidity removal (Fig. 6).

This observation aligns with the notion that a smaller gap would promote the reduction of the potential drop, resulting in an increased current density. However, beyond an optimal IES, the surface charge double layer becomes predominant and hinders the treatment efficiency. Some researchers have also pointed out this phenomenon. Additionally, researchers have indicated that the development of scale on the surface of cathode may also lead to passivation of the electrode [6]. In a study, Sun and collegues mentioned that tthicker passivation layers were observed at edges of electrodes at higher electrode potential at shorter distance between parallel plate electrodes [39]. At the other hand increase in the IES cause the increase in the cell potential. In turn, it will increase the internal resistance between the electrodes and adversely affect the EC process efficiency [25]. The drop in the internal resistance between the electrodes is the potential drop mainly due to the solution resistance. This study shows that the molecular interactions with the coagulant are weaker when IES is increased from 5 cm, which causes a reduction in the removal efficiency [10]. It may be concluded that, under the examined operational conditions, an IES of 5 cm is viable for the removal of the analyzed pollutants from textile wastewater.

4. Conclusions and recommendations

The present investigation evaluated the electrocoagulation (EC) process for treating real textile wastewater, aiming to achieve environmental conservation and public health safety while assessing its feasibility as an efficient and economical treatment method. The findings of the study demonstrate the technical viability of the EC process, highlighting it as a rapid, cost-effective, and efficient method for removing pollutants from textile wastewater.

This research explores the effectiveness of the EC process in removing total solids (TS), chemical oxygen demand (COD), color, and turbidity from actual textile wastewater using iron electrodes. The effects

of treatment time, current density, initial solution pH, stirring speed, and inter-electrode spacing (IES) on the removal of these pollutants was examined. The optimal conditions identified were a treatment time of 60 minutes, a current density of 6.2 mA/cm^2, a pH range of 8 to 8.5, a stirring speed of 150 rpm, and an IES of 5 cm. Under these optimal parameters, the EC process proved to be highly effective, achieving removal efficiencies of 79.2% for TS, 92.7% for COD, 88.9% for turbidity, and 98.7% for color. Compared to previous studies by Naje et al. [26] and Can et al. [10], which reported lower removal efficiencies, the parameters identified in this study demonstrate improved performance.

By focusing on the treatment of real textile wastewater, this study diverges from past research that primarily dealt with synthetic samples. Optimizing key parameters offers insights into effective effluent treatment strategies, addressing a critical regional gap and showcasing the potential of EC technology for sustainable practices in the textile industry.

However, while the EC process shows promising results for treating textile wastewater, several challenges may arise when scaling up for industrial applications. These hurdles include managing energy consumption at larger scales, ensuring consistent and effective electrode performance over extended operational periods, and handling potential increases in sludge production. Furthermore, variations in wastewater composition across different textile manufacturing operations could impact the efficacy of the EC process, necessitating adjustments in operational parameters.

Future research should focus on testing the EC process under diverse industrial conditions, including variations in wastewater characteristics and flow rates, to establish a comprehensive understanding of its adaptability. Additionally, as reported by some researchers [7], exploring hybrid treatment systems that integrate EC with other technologies, such as biological treatments or advanced oxidation processes, could enhance pollutant removal efficiency and promote sustainable practices within the textile industry. Conducting long-term studies to assess the operational stability and cost-effectiveness of EC in real-world settings will further contribute to its viability for widespread implementation in textile wastewater management.

As part of its Vision 2030 initiative, Saudi Arabia aims to mitigate the adverse effects of environmental pollution, including textile wastewater. Balancing industrial growth with environmental stewardship is essential for ensuring a sustainable future for both the textile industry and the nation as a whole. The findings of this study will serve as a foundation for establishing environmental protection goals in the country.

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Conflict of interest

The authors declare no conflict of interest.

Author contribution

MS: Sole author of the paper involved in Conceptualization, Methodology, Formal analysis, Investigation, Writing-Original draft, Editing, Visualization, & Submission.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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