

Treatment of Textile Industry Wastewater using Coagulation and Flocculation Process to Meet the Discharge Standards


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Abstract

The textile industry produces vast quantities of wastewater characterized by high concentrations of organic pollutants, intense coloration, turbidity, and toxic substances, posing significant environmental and public health hazards. This study explores an integrated treatment strategy that combines chitosan-based coagulation–flocculation with electrocoagulation to enhance the removal of contaminants from synthetic textile wastewater. Initially, chitosan—a biodegradable and eco-friendly natural polymer—was applied as a coagulant to destabilize suspended solids, reduce turbidity, and partially remove organic matter, thereby minimizing the need for chemical additives and lowering sludge toxicity. Subsequently, electrocoagulation employing aluminum and iron electrodes was conducted to target residual pollutants, including chemical oxygen demand (COD), biochemical oxygen demand (BOD), color, and total suspended solids (TSS). The electrocoagulation process was evaluated under both aerated and non-aerated conditions, with aeration proving to significantly enhance treatment efficiency by facilitating oxidation and flotation mechanisms. The hybrid system achieved removal efficiencies up to 86% for BOD and near-complete elimination of TSS, demonstrating synergistic effects between the coagulation and electrochemical stages. This combined approach offers operational advantages such as reduced chemical consumption, lower sludge generation, and economic feasibility, making it particularly suitable for decentralized applications in small-scale textile processing units. The findings highlight the potential of this sustainable and cost-effective method to meet stringent discharge standards while mitigating the environmental footprint of textile wastewater.

Keywords: Textile industry wastewater, sustainable treatment, small-scale industries.

1. Introduction.

The textile industry is one of the most water-intensive industries in the world, using massive amounts of freshwater for processes including sizing, bleaching, dyeing, printing, washing, and finishing both natural and synthetic fibers. The explosive expansion of the textile industry has led to the production of large amounts of highly contaminated effluent containing dyes, surfactants, suspended particles, salts, organic debris, and hazardous compounds. The dyeing and finishing of textiles are thought to be the source of 17–20% of the world's industrial water pollution. The treatment of textile effluents is a major environmental problem because of their bright color, high chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS), and the existence of resistant organic compounds (Azanaw et al., 2022; Catarino et al., 2025; Thombre et al., 2025).

Untreated or inadequately treated textile effluents pose major risks to human health and seriously degrade aquatic habitats. Textile effluents contain residual dyes and auxiliary compounds that limit light penetration into water bodies, inhibiting photosynthetic activity and lowering the concentration of dissolved oxygen. Furthermore, many synthetic dyes can accumulate in the food chain and are poisonous, mutagenic, and carcinogenic. Several textile compounds are resistant to biodegradation because of their intricate aromatic molecular structures, which reduces the efficacy of traditional biological treatment techniques (Azanaw et al., 2022; M. Kumar et al., 2025; Liu et al., 2024). Untreated or inadequately treated textile

effluents pose major risks to human health and seriously degrade aquatic habitats (M. Kumar et al., 2025). Textile effluents contain residual dyes and auxiliary compounds that limit light penetration into water bodies, inhibiting photosynthetic activity and lowering the concentration of dissolved oxygen (Azanaw et al., 2022). Typically, these effluents exhibit high salinity, strong coloration, fluctuating pH, elevated turbidity, and substantial organic loading (Nabwey & Tony, 2026). Therefore, the treatment of textile wastewater requires efficient and sustainable technologies that can remove both suspended and dissolved contaminants. Various physical, chemical, biological, and electrochemical treatment methods have been investigated for textile wastewater remediation, including adsorption, membrane filtration, coagulation–flocculation, advanced oxidation processes, biological degradation, and electrochemical techniques. However, individual treatment methods often suffer from limitations such as incomplete pollutant removal, sludge generation, high operational costs, and poor treatment efficiency for recalcitrant pollutants.

Among the available treatment technologies, coagulation–flocculation is considered one of the most effective and economical physicochemical methods for the removal of suspended solids, colloidal particles, color, and organic matter from textile wastewater. Conventional coagulants, such as alum, ferric chloride, and polyaluminum chloride, are widely used; however, their application may result in excessive sludge generation and secondary environmental pollution (El Mouhri et al., 2024). Consequently, increasing attention has been directed toward the use of natural and biodegradable coagulants, such as chitosan. Chitosan, a natural biopolymer derived from chitin, possesses excellent coagulating and flocculating properties due to the presence of amino and hydroxyl functional groups that facilitate charge neutralization and adsorption of pollutants (Renault et al., 2009). Additionally, chitosan is biodegradable, non-toxic, eco-friendly, and capable of producing comparatively lower sludge volumes than conventional chemical coagulants. Several studies have reported significant removal efficiencies of color, turbidity, COD, and suspended solids from textile wastewater using chitosan-based coagulation–flocculation processes (Issahaku et al., 2023).

Electrocoagulation (EC) has emerged as a promising advanced treatment technology for industrial wastewater owing to its simplicity, high efficiency, low chemical requirement, and environmental compatibility. In the electrocoagulation process, sacrificial metal electrodes, such as iron or aluminum, generate coagulant species in situ through electrochemical dissolution, resulting in the destabilization and aggregation of pollutants. Simultaneously, the hydrogen gas bubbles generated at the cathode aided in pollutant flotation and separation. Electrocoagulation has demonstrated excellent capability for removing dyes, organic compounds, heavy metals, turbidity, and suspended solids from textile wastewater (Khandegar & Saroha, 2013). Compared to conventional coagulation methods, electrocoagulation generally produces less sludge, requires fewer chemical additives, and exhibits higher pollutant removal efficiency.

Recently, integrated treatment systems combining coagulation–flocculation and electrocoagulation have attracted considerable interest because of their synergistic effects and enhanced treatment performance. The integration of chitosan-based coagulation–flocculation with electrocoagulation can significantly improve pollutant removal efficiency by reducing colloidal stability, enhancing floc formation, and facilitating subsequent electrochemical removal processes. The coagulation–flocculation step is an effective pretreatment process that reduces suspended solids, color, and organic load, thereby improving the operational efficiency and reducing the energy consumption of the electrocoagulation unit (Chik et al., 2026). Furthermore, hybrid treatment approaches have been reported to achieve superior removal efficiencies for COD, color, turbidity, and recalcitrant compounds compared to standalone treatment systems (Feng et al., 2025).

Given the increasingly stringent environmental regulations and the growing need for sustainable wastewater management practices, the development of efficient hybrid treatment technologies for textile wastewater has become essential. Therefore, this study aimed to investigate the treatment of synthetic textile wastewater using an integrated treatment system combining chitosan-based coagulation–flocculation and electrocoagulation processes. This study focused on evaluating the efficiency of the integrated process for the removal of color, COD, turbidity, and other physicochemical contaminants, while also assessing the operational feasibility and environmental sustainability of the proposed treatment approach.

2. Literature Review

The textile industry is one of the most significant global economic sectors and a major contributor to industrial water pollution (Nabwey & Tony, 2026). Textile activities are estimated to account for approximately 20% of global drinking water contamination, consuming between 50 and 240 liters of water per kilogram of fabric (Espinosa et al., 2026). The resulting textile wastewater (TWW) is a complex matrix characterized by intense coloration, high chemical oxygen demand (COD), fluctuating pH, and high salinity (Nabwey & Tony, 2026). Many synthetic dyes, particularly azo dyes, are

engineered for chemical stability, making them resistant to conventional biological degradation. They pose severe risks to aquatic life by reducing light penetration and oxygen levels. (Navin et al., 2018).

2.1. Environmental and Health Impacts

The discharge of untreated TWW has dire consequences for human health and ecosystems. Research on textile clusters has linked heavy metal contamination (Pb, Cd, Ni, Zn) to gastrointestinal disorders, ulcers, and increased cancer risks in local populations. These toxins enter the human body via the food chain through the consumption of contaminated agricultural products and fish. Furthermore, suspended particles in TWW can choke fish gills, while the dyes themselves inhibit the photosynthetic functions of aquatic plants and algae (Navin et al., 2018).

2.2. Conventional and Advanced Treatment Technologies

2.2.1. Physical and Chemical Methods

Physical treatments such as adsorption (using activated carbon, silica gel, or peat) and membrane filtration (MF, UF, NF, RO) are widely used for dye removal. Although effective, adsorption faces challenges in adsorbent regeneration, and membrane processes are limited by severe fouling and high operational costs (Espinosa et al., 2026; Khandegar & Saroha, 2013).

Chemical methods, particularly Advanced Oxidation Processes (AOPs), use highly reactive oxygen species (ROS), such as hydroxyl radicals (OH), to mineralize organic pollutants. Electrooxidation (EO) is a versatile AOP that utilizes "clean" electrons to degrade recalcitrant compounds without the addition of chemicals. Similarly, electrocoagulation (EC) has gained attention for its environmental compatibility and low sludge production compared to chemical coagulation (Attia et al., 2026)

2.2.2. Innovative Catalytic Systems

Recent research has reimagined TWW treatment through Metal-Organic Frameworks (MOFs). These tunable porous platforms integrate adsorption and oxidation, enhancing pollutant concentration near active sites. Additionally, the bicarbonate-activated peroxide (BAP) system, often catalyzed by cobalt ions (Co^{2+}), has proven efficient for degrading metal-complex dyes like Acid Black 194 at near-neutral pH (Ariza-Pineda et al., 2023)

2.3. Biological Technologies

Biological treatments are favored for their sustainability and low cost.

- **Bacteria:** Bacterial consortia are often more effective than single strains, using enzymes like azo reductases to break down complex dye structures.
- **Fungi:** White-rot fungi secrete extracellular enzymes (laccase, lignin peroxidase) capable of complete mineralization of synthetic dyes.
- **Algae:** Algae remove pollutants through biosorption on their large surface areas and bioaccumulation, while simultaneously sequestering carbon (Liu et al., 2024).

2.4. Integrated and Hybrid Systems

Because no single method is universally effective, hybrid systems are increasingly prioritized. Integrated and hybrid systems represent a strategic evolution in textile wastewater remediation, utilizing the complementary mechanisms of multiple technologies to achieve superior removal efficiencies compared to standalone methods (Khandegar & Saroha, 2013). A particularly effective synergy involves the integration of electrocoagulation (EC) with coagulation using chitosan, a natural cationic biopolymer (Momeni et al., 2018). While EC generates coagulating metal ions in-situ through electrolytic dissolution thereby eliminating the need for traditional chemical additions the incorporation of chitosan enhances the process through its unique ability to facilitate charge neutralization and inter-particle bridging. This hybrid approach allows for the rapid destabilization of colloidal dyes and organic matter by electrical fields, while the long-chain protein structure of chitosan aggregates these destabilized particles into larger, more stable flocs that contain less bound water and are more easily removed. By combining these processes in a unified "one-pot" configuration or sequential train, treatment systems can achieve near-complete color removal and significant COD reduction while simultaneously minimizing the volume of toxic sludge, offering a sustainable and cost-effective pathway for treating complex industrial effluents (Khandegar & Saroha, 2013). Summary of various studies on treatment of textile industry are summarised in table 3 discussing the various treatment technology used and their limitation to understand the significance of the treatment technique adopted in the current study.

Table 1: Summary of various studies on treatment of textile wastewater treatment.

Author(s) & Year	Technology/Focus	Key Findings & Methodology	Limitations & Challenges
(Momeni et al., 2018)	Modified Chitosan Coagulation	Natural chitosan was modified with CHPTAC to boost its cationic content. The removal of complicated Melanoidin dyes was optimized using Response Surface Methodology (RSM).	The effectiveness is very pH dependant; overdose might cause colloid instability.
(Ma et al., 2016)	Chitosan & Aluminum Salts	A combination of natural chitosan and AlCl ₃ . When compared to employing Al alone, the sludge volume was significantly reduced by 80%, and residual Al levels were reduced.	Standalone chitosan removal is sometimes insufficient for further sand filtering.
(Ariza-Pineda et al., 2023)	Bicarbonate-Activated Peroxide (BAP)	Cobalt ions (Co ²⁺) catalyze an AOP at slightly alkaline pH levels. Complete decolorization (>99.4%) and reduced acute toxicity in guppy fish.	Mineralization rates are low (32.2%) when compared to decolorization; cobalt must be removed after oxidation.
(Gupta & Mukhopadhyay, 2025)	Heavy Metal Impact (Case Study)	West Bengal was investigated for lead, cadmium, and nickel contamination. Untreated TWW has been linked to cancer, ulcers, and gastrointestinal diseases through the food chain.	Highlights the failure of current public policy and the need for eco-planning of industrial clusters.
(Nabwey & Tony, 2026)	Metal-Organic Frameworks (MOFs)	MOFs act as tunable porous substrates for adsorption and oxidation. Hybridization (for example, with carbon) boosts the charge of transport.	Hydrolytic robustness (water instability), high synthesis costs, and metal leaching are some of the challenges.
(Espinosa et al., 2026)	Membrane & Electrooxidation (EO)	Integration of EO with membranes (NF/RO). EO is used as a pretreatment to decrease fouling or a post-treatment for concentrates.	Large volumes require a lot of energy, and few long-term studies on membrane durability under electrical exposure.
(Liu et al., 2024)	Biological Technologies	A comprehensive review of bacteria, fungus, and algae. White-rot fungi produce enzymes (laccase) that mineralize azo dyes.	Biological mechanisms are frequently slow and inefficient if dealing with very toxic or salty effluents.
(Zurita et al., 2024)	Natural Coagulants & Wetlands	Moringa oleifera seeds were integrated into newly created wetlands. Achieved excellent elimination of perceived color and total suspended solids (TSS).	Moringa had no effect on raw, high-strength vinasses and required a first biological treatment to be successful.

3. Materials and Methods

3.1. Wastewater Sources and Reagents

Research typically utilizes both real industrial effluents and synthetic dye solutions.

• **Real Samples:** Wastewater is often sourced from textile plants (containing Acid Black 194), yeast factories (containing Melanoidin), or distillery processes such as tequila vinasse. Preliminary analysis of sample collected from industry were analysed and reported in Table 2.

Table 2: Characteristics of real textile wastewater.

Parameter	Reported Value
pH	9.5
COD	3,200 mg/L
BOD	850 mg/L
TSS	780 mg/L
Color	Dark blue

• **Synthetic sample:** synthetic wastewater sample is prepared in lab by adopting the composition mentioned in Table 3 adopted from Dos Santos et al., (2022).

Table 3: Composition of real synthetic textile wastewater.

Chemical	Concentration
Reactive Black 5	100 mg/L
Glucose	1000 mg/L
NaCl	2000 mg/L
Na ₂ SO ₄	1000 mg/L
Starch	300 mg/L
NH ₄ Cl	100 mg/L
KH ₂ PO ₄	30 mg/L
Surfactant	50 mg/L

• **Reagents:** High-purity chemicals such as chitosan (for coagulation), and metal salts like aluminum chloride (AlCl₃) or aluminum sulfate are standard. For oxidation processes, reagents include hydrogen peroxide (H₂O₂), sodium bicarbonate (NaHCO₃), and cobalt chloride hexahydrate catalysts.

3.2. Preparation of Treatment Agents

• **Modified Chitosan Coagulant:** Dried chitosan is mixed with distilled water and NaOH, then heated to 50 °C. The cationic monomer (CHPTAC) is added dropwise, and the reaction proceeds for 24 hours before being neutralized with HCl, washed with ethanol, and vacuum-dried.

• **Electrodes for Electrocoagulation:** Common electrode materials include aluminum, and iron. These are often arranged in monopolar or bipolar configurations in serial connections, with spacing of 2.5 cm from electrode to electrode.

3.3. Experimental Configurations

• **Coagulation/Flocculation (Jar Test):** Experiments are conducted in batch systems using a jar test apparatus. A typical sequence involves rapid mixing (e.g., 100–200 RPM for 3 minutes) followed by slow mixing (e.g., 30 RPM for 20–30 minutes) and a final sedimentation period of 30–60 minutes.

• **Electrocoagulation (EC) Setup:** The EC cell is connected to an external DC power supply. Studies explore the effects of current density, electrolysis time, and electrode spacing on pollutant removal in both batch and continuous modes. Experimental conditions such as Applied voltage 12 V, initial pH 7, inner electrode spacing 2.5 cm.

3.4. Analytical Procedures

Standardized methods are used to characterize wastewater before and after treatment. Parameters include **pH**, **Chemical Oxygen Demand (COD)**, and **Biochemical Oxygen Demand (BOD)** were analysed as per APHA guideline. **Color removal** is determined via UV–Vis spectrophotometry at the dye's maximum absorption wavelength (λ_{max}).

3.5. Experimental Design and Optimization

In this study we have employed Response Surface Methodology (RSM) based on a Central Composite Design (CCD). Which allows to model the simple and interactive effects of variables like pH, coagulant dose, current density, and reaction time. The results are validated using Analysis of Variance (ANOVA) to ensure the statistical significance of the optimized treatment parameters. The methodology for whole treatment process are shown in

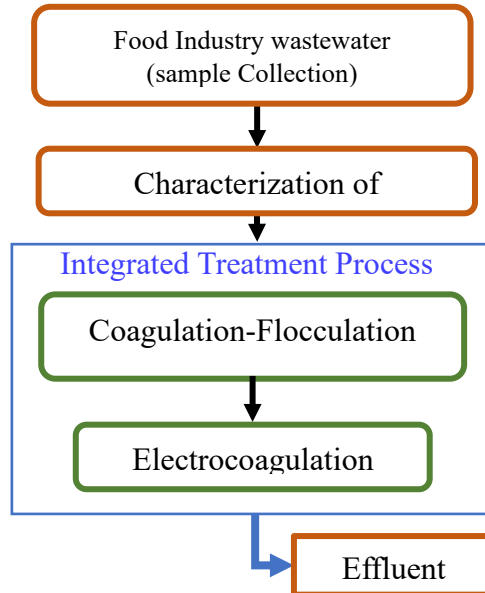


Figure 1: Methodology flow chart of textile wastewater treatment.

4. Results and Discussion

4.1. Coagulation flocculation by using natural coagulant chitosan

A laboratory jar test apparatus (VELP Scientifica JLT4 Flocculation tester, Europe) was used for coagulation-flocculation studies. The jar test apparatus has four paddles with rectangular blades to mix leachate sample and coagulant. Five hundred milliliters of raw leachate sample were transferred to 1L beakers for each run. At a time, four experiments could be run. The initial pH of each sample was adjusted using 5M HCl or 5M NaOH and various dosages of natural coagulant depending on the experimental design for each coagulant. The beakers were then placed in a jar test set up to initiate the coagulation-flocculation process. In this study, mixing was conducted in two stages- rapid mixing followed by slow mixing. Accordingly, for this study, the operating parameters were adopted as rapid mixing speed of 250 rpm with a rapid mixing time of 3 min, slow mixing speed of 30 rpm and settling time of 60 min. Post settling of floc particles, the supernatant liquid sample was collected without disturbing the settled floc particles, and the supernatant was analysed for the extent of COD, TSS and turbidity removal. The effluent pH was also noted down. The percentage removal for the parameters of COD, TSS and turbidity were calculated using the Eq. (1). given below:

$$\text{Removal Efficiency (\%)} = ((C_i - C_f) / C_i) \times 100 \quad (1)$$

where C_i and C_f are the initial and final concentrations of leachate pollutant, respectively. For the supernatant of each sample, experiments were performed in duplicates and then the average of the two readings was taken to obtain the final values of the COD, TSS and turbidity. After calculation of the final readings for each sample, the removal percentage of COD, TSS and turbidity was calculated using the Eq. (1), mentioned above.

Table 4: Turbidity removal efficiency of different pH and coagulant doses.

Expt. No.	pH	Coagulant Dose mg/L	Turbidity Removal (%)
1	7.41	2.595	70.635
2	6	1.625	64.947
3	6	0.25	0

4	7.41	0.655	44.974
5	4.59	0.655	82.13
6	4.59	2.595	73.478
7	4	1.625	53.696

Table 5: Suspended solids removal efficiency of different pH and coagulant doses.

Expt. No.	pH	Coagulant Dose mg/L	Suspended Solid Removal (%)
1	7.41	2.595	65.278
2	6	1.625	25
3	6	0.25	2.778
4	7.41	0.655	1.389
5	4.59	0.655	30.882
6	4.59	2.595	0
7	4	1.625	0

Table 6: Turbidity removal efficiency of different pH and coagulant doses.

Expt. No.	pH	Coagulant Dose mg/L	COD Removal (%)
1	7.41	2.595	1.818
2	6	1.625	10.909
3	6	0.25	13.636
4	7.41	0.655	31.818
5	4.59	0.655	0
6	4.59	2.595	0
7	4	1.625	7.143

Textile wastewater was initially treated by using natural coagulant chitosan at different pH range from 4 to 7.41 with varying dose of coagulant. The removal efficiency of turbidity, suspended solids and COD were analysed and reported in above tables. The turbidity removal was reported in Table 4 and highest removal of 82.13% at pH 4.59 with coagulant dose of 0.665 mg/L, while the lowest removal was reported at pH 6 with coagulant dose of 0.25mg/L. Which shows the higher pH and lower dose is ineffective to removal rate. In case suspended solid removal of 65.278% at pH 7.4 with highest coagulant doses, removal efficiency at varying dose and pH are mentioned in Table 5. While the Table 6 represent the COD removal efficiency the neutral pH offers highest removal. Overall coagulation -flocculation by using natural coagulant offer significant removal of turbidity and suspended solids while very less are negligible removal of COD were reported. To remove remaining COD and various other pollutant such as BOD, COD, Color and solids were removed during the electrocoagulation of wastewater.

4.2. Electrocoagulation

Various combinations of aluminum and iron electrodes, such as Al-Al, Fe-Fe, Al-Fe, and Fe-Al, were used to examine the efficacy of the electrocoagulation (EC) process for wastewater treatment under aerated and non-aerated circumstances. The treatment performance was measured in terms of COD, BOD, color, and TSS removal efficiency at various electrolysis times.

4.2.1. COD removal efficiency.

The COD removal from different electrode combinations are presented in Fig. 2. During electrocoagulation process (without aeration), COD reduction increased with electrolysis time for all electrode configurations. At 120 minutes, COD removal efficiencies for Al-Al, Fe-Fe, Al-Fe, and Fe-Al were 60%, 56%, 72%, and 74%, respectively. Among the electrodes examined, the Fe-Al combination reduced COD the most under non-aerated circumstances.

The inclusion of constant air supply resulted in a considerable increase in COD removal efficiency. Following 120 minutes of treatment, the removal efficiency climbed to 62%, 74%, 86%, and 79% for Al-Al + Air, Fe-Fe + Air, Al-Fe + Air, and Fe-Al + Air, respectively. Under aerated circumstances, the Al-Fe electrode combination provided the best COD removal

results. The improved pollutant removal in aerated electrocoagulation could be due to improved electro-flotation and oxidation processes. Aeration increases dissolved oxygen availability, facilitating the oxidation of Fe^{2+} ions into Fe^{3+} ions. This leads to the development of ferric hydroxide flocs with higher adsorption properties (A. Kumar et al., 2018). Furthermore, external aeration produces fine bubbles that aid in the flotation of suspended and colloidal pollutants to the liquid surface (Aswathy et al., 2016). (Parga et al., 2005) showed a similar increase in pollutant clearance following oxygen infusion.

Higher elimination efficiency found with Al-Fe and Fe-Al combinations may also be attributed to the synergistic coagulation actions of aluminum and iron hydroxides. Aluminium hydroxides have a high adsorption capability, whereas iron hydroxides help to oxidize and destabilize contaminants. The combined action enhances organic matter elimination substantially (Katal & Pahlavanzadeh, 2011).

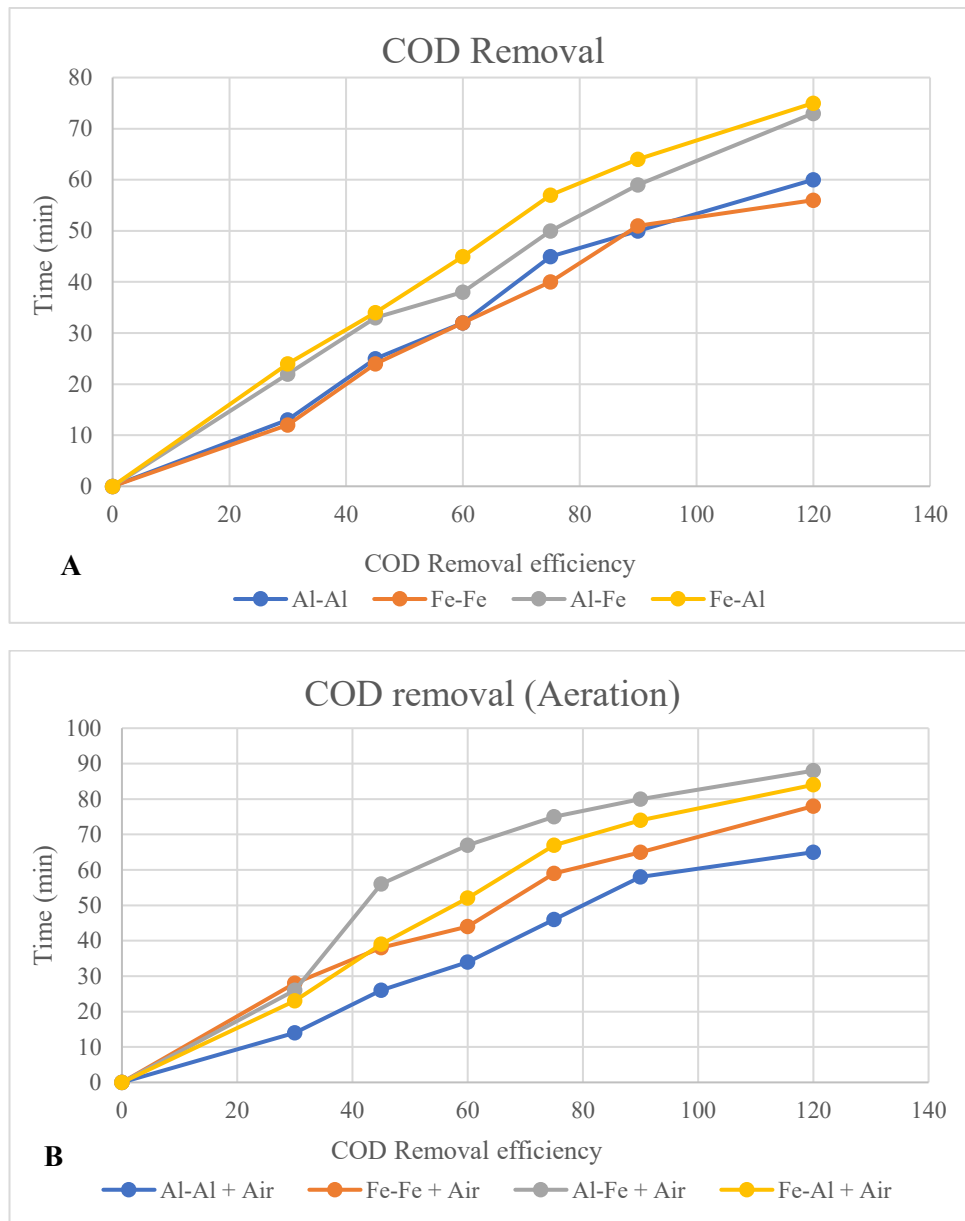


Fig. 2. COD removal efficiency for different electrode combinations with (A) and without aeration (B).

4.2.2. BOD removal efficiency.

The BOD removal efficiency for various electrode combinations followed similar trends to COD removal shown in Fig. 3. Under non-aerated conditions, BOD removal efficiencies after 120 minutes were 55%, 56%, 72%, and 74% for Al-Al, Fe-Fe, Al-Fe, and Fe-Al combinations, respectively.

Following aeration, efficiency increased significantly, reaching 62%, 74%, 86%, and 79% for Al-Al + Air, Fe-Fe + Air, Al-Fe + Air, and Fe-Al + Air, respectively. The maximum BOD removal effectiveness of 86% was achieved with the Al-Fe electrode combination in the presence of an air supply.

Improved BOD removal under aerated conditions is mostly due to increased oxidation and flotation of biodegradable organic materials. Increased dissolved oxygen availability enhances the breakdown of biodegradable organics and promotes the production of larger and denser hydroxide flocs capable of efficiently entrapping organic pollutants. Aeration also improves mixing conditions and mass transport within the reactor, which increases overall treatment efficiency.

The enhanced performance of the Al-Fe combination could be attributed to higher current density and increased coagulant species formation during electrolysis. Increased bubble density and decreased bubble size at increased current density contribute to enhanced upward flux and electro-flotation efficiency (Katal & Pahlavanzadeh, 2011).

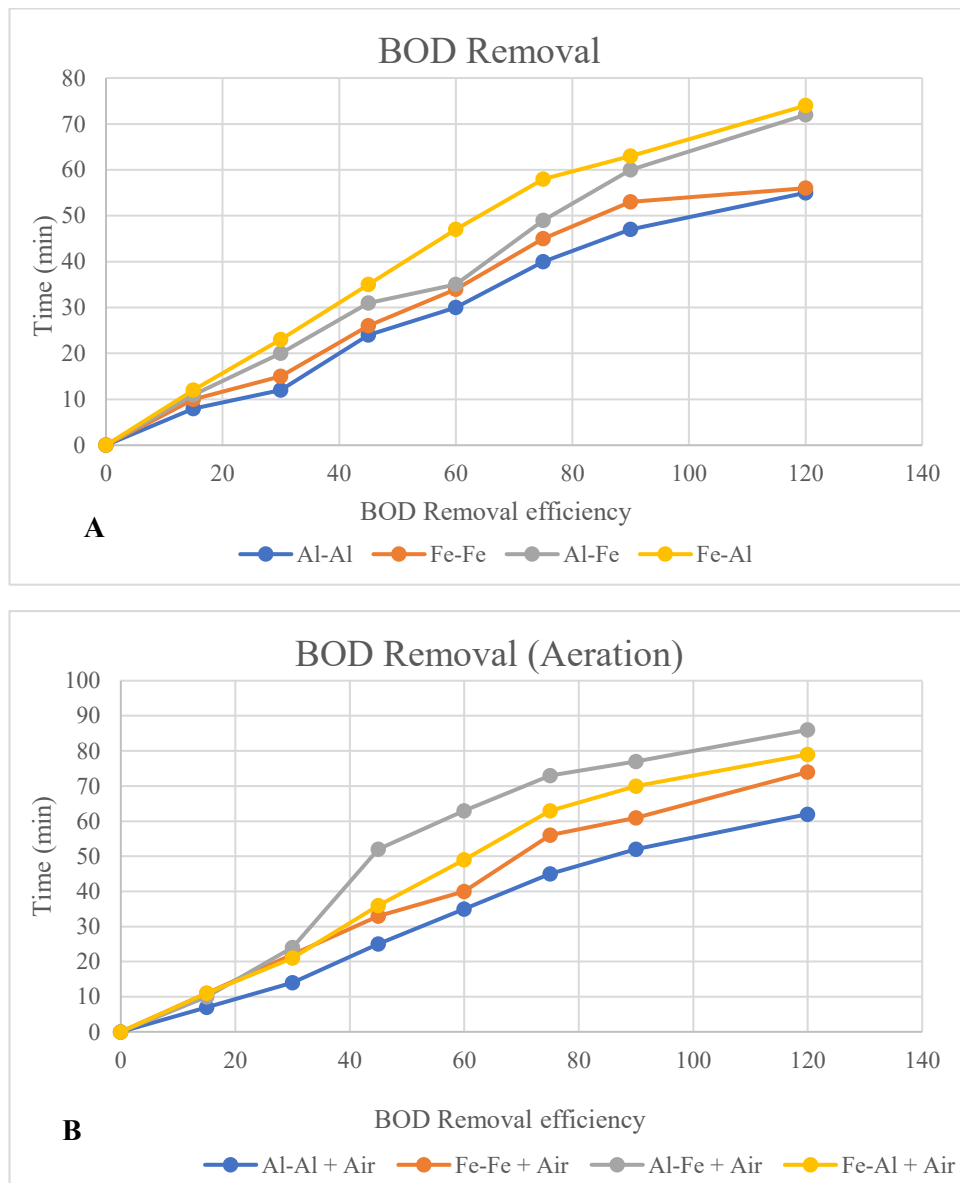


Fig. 3. BOD removal efficiency for different electrode combinations with (A) and without aeration (B).

4.2.3. Color & TSS Removal

Color removal efficiency increased over time with treatment time throughout the electrocoagulation procedure. Color removal efficiencies were determined to be 10%, 13%, 18%, 16%, 22%, 26%, and 31% after 15, 30, 45, 60, 75, 90, and 120 minutes, respectively.

The moderate color reduction observed throughout the treatment procedure could be attributed to the adsorption and coagulation of color-causing chemicals onto aluminum and iron hydroxide flocs formed during electrolysis. Destabilization of dissolved colored organic compounds, followed by floatation by hydrogen gas bubbles, also helped to reduce color. Although color removal was significantly lower than COD and BOD removal, continual improvement with electrolysis duration suggests progressive degradation and separation of dissolved chromophoric chemicals from the effluent.

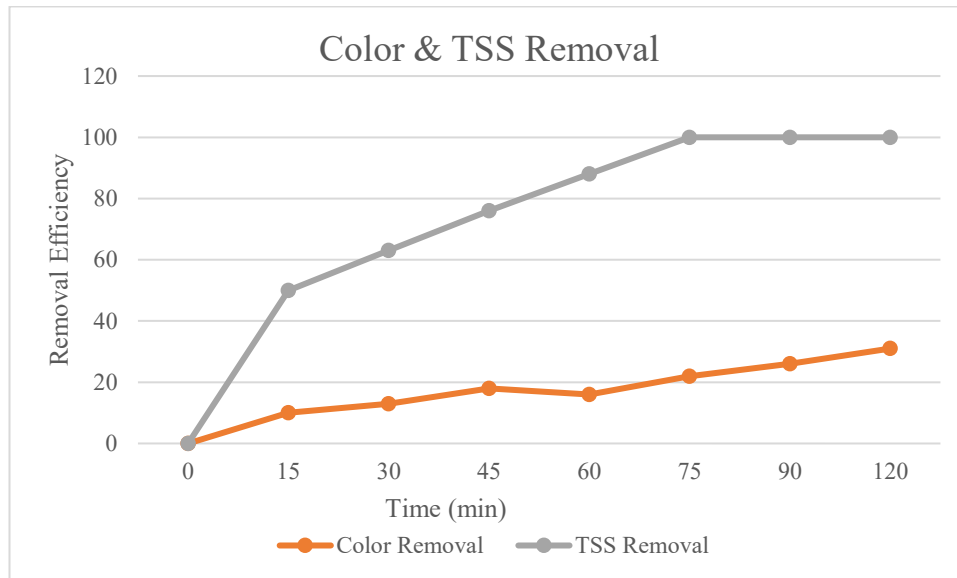


Fig. 4. Color & TSS removal efficiency for different electrode combinations.

The electrocoagulation technique had a high TSS elimination efficiency. TSS elimination rose dramatically with electrolysis duration, reaching 100% removal after 75 minutes of treatment. TSS elimination efficiencies were found to be 50%, 63%, 76%, 88%, 100%, and 100% after 15, 30, 45, 60, 75, 90, and 120 minutes.

The quick removal of suspended particles is due to the effective destabilization and agglomeration of particulate matter by metal hydroxide flocs produced during electrolysis. The created hydrogen bubbles aided in the floatation of suspended particles to the surface, while heavier flocs sunk at the bottom due to coagulation mechanisms.

The total elimination of TSS after 75 minutes demonstrates high electrocoagulation capabilities for solid-liquid separation. Similar findings have been reported in prior research where electrocoagulation effectively cleared suspended particles due to the generation of metallic hydroxides and electro-flotation mechanisms (Aswathy et al., 2016; Avsar et al., 2007; A. Kumar et al., 2018).

5. Conclusion

The integrated treatment approach combining chitosan-based coagulation–flocculation followed by electrocoagulation effectively addresses the complex pollutant profile of textile industry wastewater. Chitosan demonstrated high efficacy in removing turbidity and suspended solids, especially at acidic pH levels, by promoting floc formation and charge neutralization with minimal chemical use and sludge production. Subsequent electrocoagulation using aluminum and iron electrodes significantly enhanced the removal of residual organic pollutants, including COD, BOD, and color, with the Al-Fe electrode pair under aerated conditions delivering the highest treatment performance. Aeration contributed to improved oxidation of iron species and increased generation of fine hydrogen bubbles, which enhanced pollutant floatation and overall removal efficiency. The hybrid system benefits from the complementary mechanisms of natural coagulation and electrochemical destabilization, resulting in superior contaminant reduction, operational simplicity, and economic viability. This approach reduces chemical dependency and sludge volume compared to conventional methods, aligning with environmental sustainability goals. The system’s scalability and ease of operation make it well-suited for implementation in small-scale and decentralized textile wastewater treatment scenarios. Future research should focus on optimizing process parameters, assessing long-term operational stability, and scaling up to pilot and industrial levels to fully validate the technology’s applicability and environmental benefits. This study contributes valuable insights toward developing

sustainable wastewater treatment technologies that comply with regulatory standards and safeguard aquatic ecosystems and public health.

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