# The Application of Electrocoagulation in Textile Wastewater Treatment- A Scoping Review of Recent Trends (2021-2025)

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## ABSTRACT

Nowadays, electrochemical wastewater treatment methods are receiving increasing interest among researchers to overcome the limitations of conventional chemical and biological treatment methods. Electrocoagulation (EC) is one of the methods that generates in-situ coagulants via electrically oxidizing a sacrificial anode. Through a scoping review, this study aims to identify and analyse the state-of-the-art in EC application for the treatment of synthetic textile dye effluents. This study was conducted following the PRISMA protocol on the Scopus database from 2021 to 2025. This work mapped the research trend on EC, its application mechanism, and advancements for improved efficiency. It further investigated the modelling techniques and hybrid technologies integrated with electrocoagulation and identifies the research gap from the literature. The results show a steep increase in publications over the years, with most originating in Asia, demonstrating to be effective in treating a wide range of dyes. Several factors directly controls the electrochemical reactions and some indirectly affects the performance. Overall, while EC treatment demonstrates strong performance at lab scale, most literature reviewed in this study were conducted under controlled conditions with limited evidence for industrial scale feasibility for long-term and continuous flow management. For optimization, RSM, with Central Composite, and Box-Behnken Designs, is the most widely used modelling technique, and integration of advanced techniques such as ozonation, the Fenton process, catalyst addition, and sonication shows the potential to achieve enhanced wastewater treatment efficiency. Further integration of AI shows future direction towards enhance process control in EC.

**Keywords**: Electrocoagulation; Scoping review; Textile dyes; Textile wastewater; Wastewater treatment

## INTRODUCTION

The textile industry is a major global manufacturing sector and is the largest consumer of water. Production processes like sizing, de-sizing, scouring, bleaching, mercerizing, dyeing, printing, and finishing use large amounts of water, producing wastewater that contains salts, minerals, oils, metals, chemicals, and dyes. According to the United States Environmental Protection Agency (US EPA) reports, dyeing 1 kg of fabric requires at least 40 L of freshwater. It also notes that 830 billion liters of freshwater are consumed annually, generating 640 billion liters of wastewater (Basak, S; Pandit, P; Samanta, KK; Samanta, 2019; Thombre et al., 2025). According to the European Parliamentary Research Service (EPRS), producing a single cotton T-shirt requires 2700 L of fresh water (Van Woensel & Lipp, 2020).

Among the various operations in textile manufacturing, dyeing is considered one of the most harmful units, generating coloured wastewater that can cause severe damage to nearby waterbodies when released untreated

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(Navin & Mathur, 2018). According to the European Environmental Agency, the dyeing and finishing process alone accounts for approximately 20% of global clean water pollution (European Parliament, 2021). Therefore, proper treatment of effluent before releasing it into the environment is essential to protect the environment, aquatic life, the natural balance, and human health.

Wastewater treatment refers to removing impurities, such as pollutants, coarse particles, toxicants, and potential pathogens (Silva, 2023), from wastewater/sewage before releasing it into natural waterbodies (Archis Ambulkar & Nathanson, 2025). Wastewater treatment is typically classified into several levels, including preliminary screening (Silva, 2023), primary sedimentation, secondary biological treatment, and tertiary effluent polishing (Archis Ambulkar & Nathanson, 2025; Senthil Kumar & Saravanan, 2017). In general, several methods are employed in textile wastewater treatment. Adsorption, coagulation, membrane separation, flotation, ozonation, ion exchange, evaporation, and crystallization are the commonly employed conventional treatment methods (Senthil Kumar & Saravanan, 2017) which are not always effective (Ghasem et al., 2016) in removing textile dyes, which often contain organic compounds and heavy metals.

Among these techniques, coagulation/flocculation is one of the most widely used treatment units in the water industry (Jiang, 2015; Jo et al., 2024). However, there are several drawbacks in chemical coagulation as well, including the generation of secondary pollutants and the production of large amounts of sludge (Sajath et al., 2022). Moreover, in recent years, researchers have shown growing interest in electrochemical treatment methods, including EF-electro flotation, ER-electrokinetic remediation, EC-electrocoagulation, and EO-electrooxidation (Boinpally et al., 2023).

In addition to these, microbial fuel cells have also emerged as an electrochemical approach with electrochemically active bacteria (Lepage et al., 2014). Since the conventional chemical coagulation method has potential drawbacks, this review focuses on the electrocoagulation method, which provides a similar effect to chemical coagulation but operates through multiple mechanisms, such as electrochemical kinetics, charge transport, thermodynamics, and adsorption isotherms, all occurring simultaneously in the system (Gholami Shirkoohi et al., 2022).

**Electrocoagulation (EC)**

The theory of EC has been explained by several authors (Bener et al., 2019; Mollah et al., 2001). Coagulation is the core mechanism behind the EC phenomena. EC is an electrochemical process that involves an in-situ coagulant generation mechanism via an electrically oxidizing metal anode, such as the commonly used Fe or Al.

Like chemical coagulation, metal hydroxides serve as coagulants in EC to efficiently adsorb and remove dissolved pollutants from water and mineralizes and decomposes the suspended particles in the wastewater effluent (Gasmi et al., 2022; Tanveer et al., 2022).

**Initial application of electrocoagulation**

The history of electrocoagulation, reported by Bharti et al. (Bharti et al., 2023), shows that EC was first implemented in the United States in 1946. Then it was introduced in Russia, Europe, South America, and elsewhere. **Table 1** summarizes key developments in EC.

Table 1: Milestones of EC technology innovation, application, and global spread

| **Year** | **Country/ Region** | **Application** |
|---|---|---|
| 1946 | United States | Colour removal from drinking water |
| 1970 | Russia, Europe, and South America | Removal of inorganic compounds in industrial wastewater |

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| | | |
|---|---|---|
| 1980 | North America | Implementation in the mining and metal processing industries |
| 1984 | London | Introduction of EC |
| 1988 | London | Construction of a household wastewater treatment facility |

Even with the increasing literature, there is a lack of a comprehensive scoping review mapping the research trends showing recent patterns on EC study, used modelling approaches, and integrated hybrid methods applicable with EC for textile wastewater treatment. This study fills that gap by a scoping review of publications retrieved from the Scopus database over 2021 to 2025

**Research Design**

This study adopted the scoping review method described by Barahmand & Eikeland (2022) to gather existing knowledge from recent studies relevant to EC in textile wastewater treatment. A procedure scheme was planned, as illustrated in **Figure 1**, outlining the key steps for systematically carrying out the review.

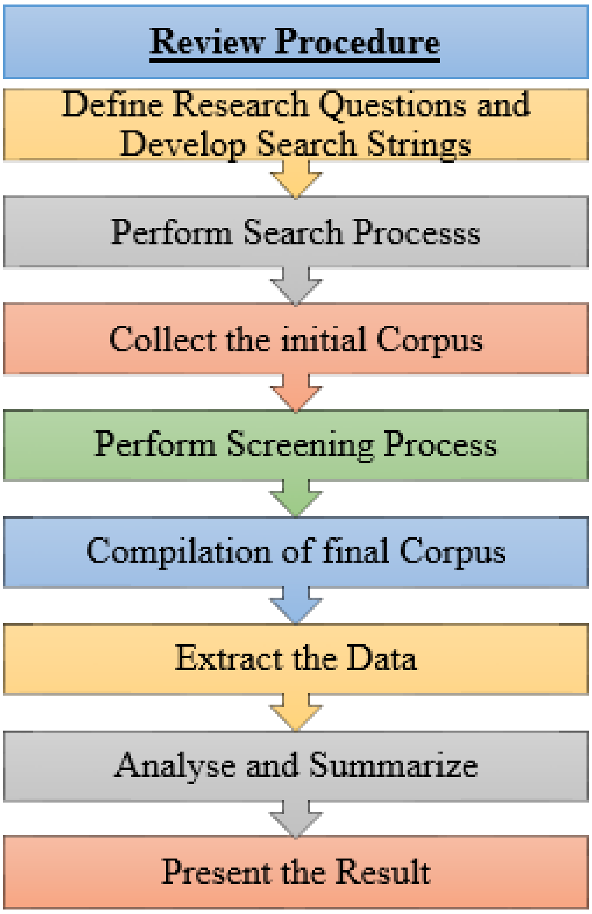


Fig. 1. Flowchart of literature review procedure detailing the key steps followed to gather and analyze the recent studies on EC.

Initially, a keyword search was conducted in the Scopus database to identify all the relevant papers on EC. The initial keywords were refined with multiple trials to enhance the search string and to capture the most relevant papers. With the collection of a wide range of relevant studies, screening and sorting processes were performed to clean and filter the corpus according to the PRISMA protocol. **Table 2** presents the detailed paper selection and screening process, including the number of papers retrieved at each step.

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**Developing Search String:**

1. The initial search was performed in the Scopus database using the relevant keywords, electrocoagulation and textile, as initially defined. This search was conducted across article titles, abstracts and keywords, yielding a total of 459 papers.

2. Next, the keyword tailoring was performed by altering the term “ electrocoagulation ” to “ (“electro coagulation” OR electro-coagulation OR electrocoagulation) ”, yielding a few more documents and resulting in 482 papers.

**Table 2**: Search string development and screening criteria for review on EC in textile wastewater treatment.

| **Title: Electrocoagulation in Textile Wastewater Treatment** | | | | |
|---|---|---|---|---|
| Database: Scopus | | Date last accessed: 29.04.2025 | | Scope: Electrocoagulation |
| | Process | Description | No of papers | Search String |
| Searching | Identifying and developing search string | Initial search results within article title, abstract, and keywords | 459 | electrocoagulation AND textile |
| | | Tailoring the term electrocoagulation | 482 | ( "electro coagulation" OR electro-coagulation OR electrocoagulation ) AND textile |
| | | Adding another strong key word, wastewater | 410 | ( "electro coagulation" OR electro-coagulation OR electrocoagulation ) AND textile AND wastewater |
| | | Refining the keyword, wastewater | 420 | ( "electro coagulation" OR electro-coagulation OR electrocoagulation ) AND textile AND ( wastewater OR "waste water" ) |
| | | Adding more terms denoting dye/colour removal | 474 | ( electrocoagulation OR electro-coagulation OR "electro coagulation" ) AND textile AND ( ( wastewater OR "waste water" ) OR ( dye* OR colour OR color OR decolour* OR decolor* ) ) |
| Screening | Screening the search field | Limiting the search within title only | 167 | |
| | Screening the recent studies | Limiting the papers to last 5 years (2021 - 2025) | 67 | |
| | Screening the document type | Limiting the search to article only | 51 | |
| | Manual screening | Limitng the papers of irrelevency | 49 | |
| | | Removing duplicate studies | 48 | |
| | | reliminating the papers with no access | 46 | |
| | | Added relenvent papers manually | 47 | |

3. Then, another keyword, wastewater, was added to the search to strongly represent wastewater treatment, reducing the number of papers by filtering out them containing this keyword, resulting in 410 documents.

4. The keyword “ wastewater ” was then refined to “ (wastewater OR “waste water”) ” due to usage variation, adding 10 more documents to the results, bringing the total to 420.

5. Some papers were found without the term wastewater in their title, but with the terms dye removal, colour removal, or decolouring, with variations in spelling due to American and British English, such as colour, color, decolour, and decolor. Thus, all these terms were added with the keyword wastewater, using the OR Boolean operator. This has captured 54 additional papers, bringing the total to 474 documents.

Once the search string was finalized, the screening process was started to sort and filter the papers.

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### Screening Process

1. The search type was limited to the article titles, filtering out 167 documents.
2. Next, the most recent documents from the past 5 years were sorted, resulting in 67 total documents.
3. The document type was then screened to select only articles, eliminating conference papers and book chapters from the collected documents published over the last five years, resulting in 51 papers.
4. Then, each paper underwent manual cleaning, and 2 non-relevant papers, 2 papers with no access, and a duplicate paper were eliminated, bringing the number of papers to 46.
5. Additionally, 1 paper was added to the final corpus, bringing the total to 47.

This final corpus was used for reviewing the EC treatment process.

## RESULTS

In this section, the selected latest papers on EC are categorized with available descriptive information.

### Analysis by year

This analysis gives the status of available papers by year under the final refined search string development. No studies on this topic were found on the Scopus database before 2002. In 2002, there was one publication. Starting from 2002, the number of publications has increased each year. **Figure 2** shows that the trend of publications has increased over time in Scopus using the final search string applied only to the article title, disregarding the abstracts and keywords that contain the same search string.

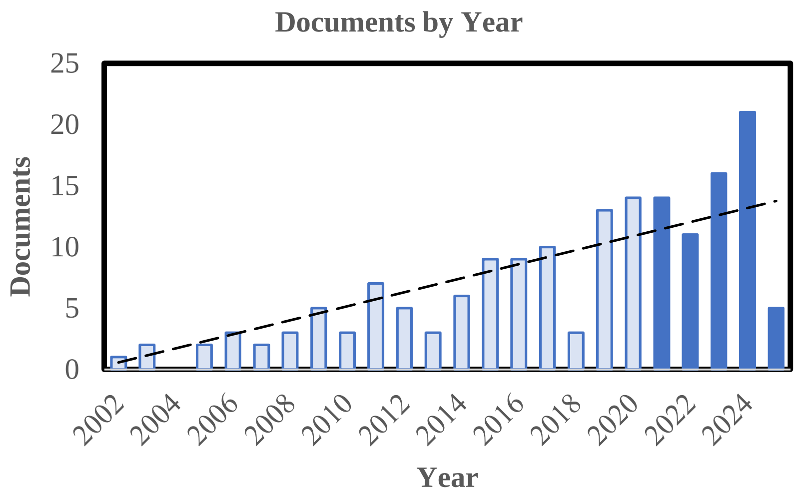


Fig. 2. Annual publication trend on electrocoagulation (EC) in Scopus from 2002 to 2025, showing increasing research interest over time.

The data reveals a gradual increase in research interest in EC over time, as reflected in the growing number of available publications. This rise in recent years is significantly higher than in the early years from 2002 to 2014 (1 to 7 papers) rising to 13 in 2019, and 14 in both 2020 and 2021. The year, 2024, shows the highest number of publications (21 papers) with 5 paper until Feb, 2025. Occasional fluctuations was observed in 2018 (3 papers) and 2022 (11 papers) reflecting a variability in research output. The overall analysis suggests that the research interest will keep increasing in the coming years. From all these publications, the papers published in the last five years (2021-2025) were selected for the review purpose of this study.

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**Country-wise analysis**

The publications between 2021 and 2025 were categorized based on the country-wise publication to see the trend of global research interest. A total of 34 countries have been involved in this field of research. Among them, India is the leading contributor with16 papers, followed by Brazil with 8 papers. All other countries contributed even fewer. Moreover, the continent-wise summary shows significant research interest from all the continents, while Asia has the highest level of research (51 publications), followed by Africa (13), South America (11), North America (6), Europe (5), and Australia (3), reflecting a strong concentration in developing regions where textile production is prominent.

**Figure 3** illustrates a continent-wise summary of publications over the last five years, and **Figure 4** shows the publication trend of the top 10 countries that contributed to those publications in Scopus.

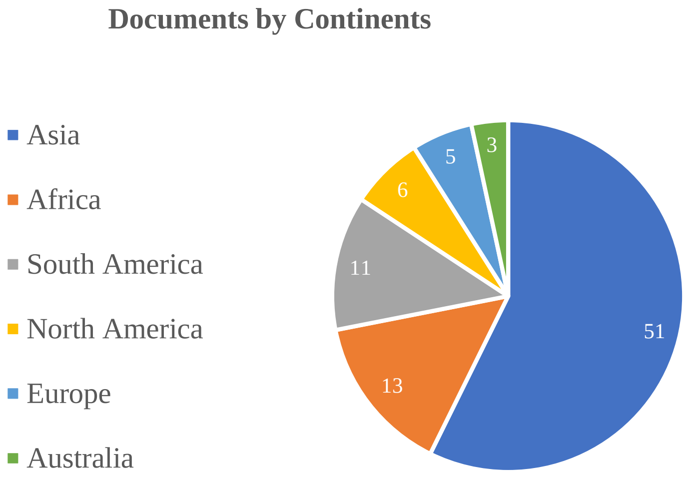


Fig. 3. Continent-wise distribution of studies (2021-2025) on electrocoagulation (EC) available on the Scopus database.

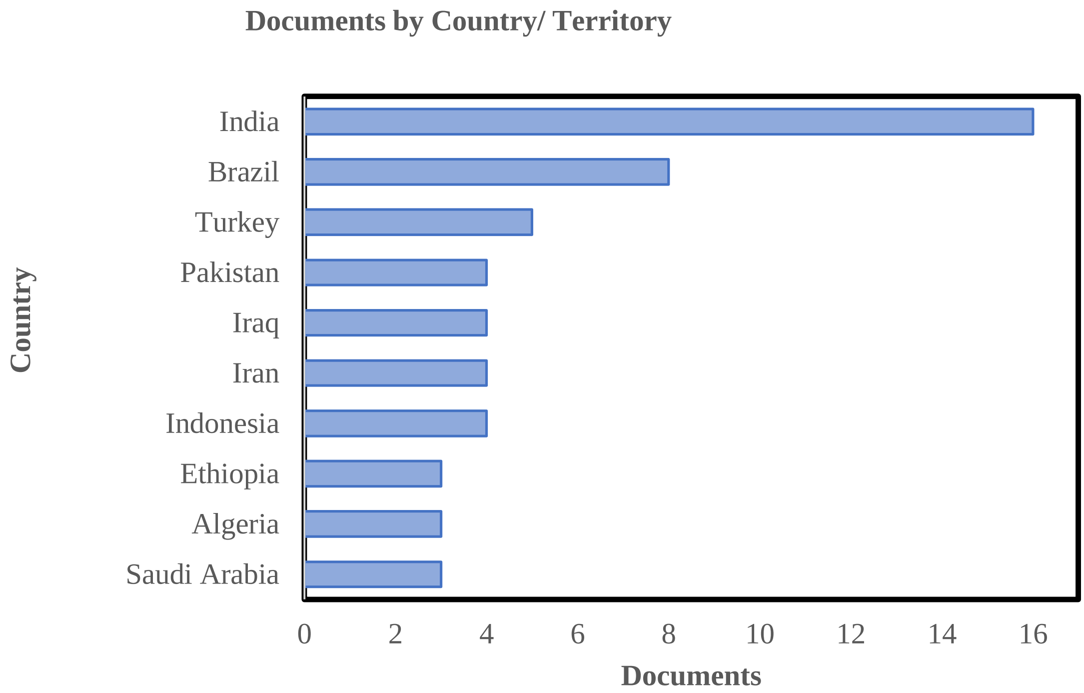

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Fig. 4. Top 10 countries contributing to publications on electrocoagulation (EC) during 2021-2025

### Classification based on document types

In this section, the publications of the last 5 years were further analyzed based on the type of literature.

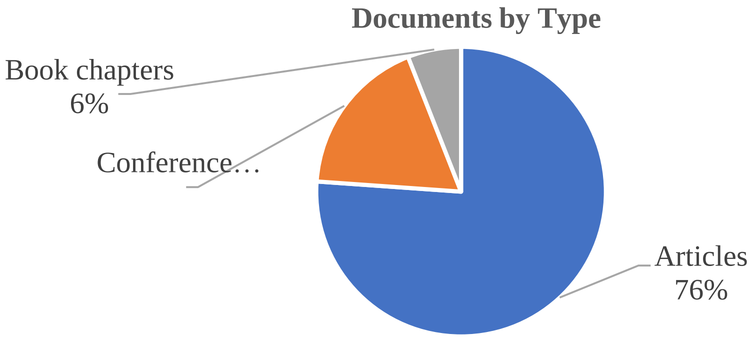


Fig. 5. Types of available literature on electrocoagulation (EC) in Scopus from 2021 to 2025

There are 3 types of literature available in the form of articles, conference papers, and book chapters, which is given and **Figure 5**, representing their percentages. The type of document selected for the reviewing purpose of this study was only articles.

### Classification based on subject area

Additionally, the final classification was done on the selected papers in search of identifying the subject areas involved in this research, and the following **Figure 6** illustrates the key area of the selected papers under the categories of different subject areas.

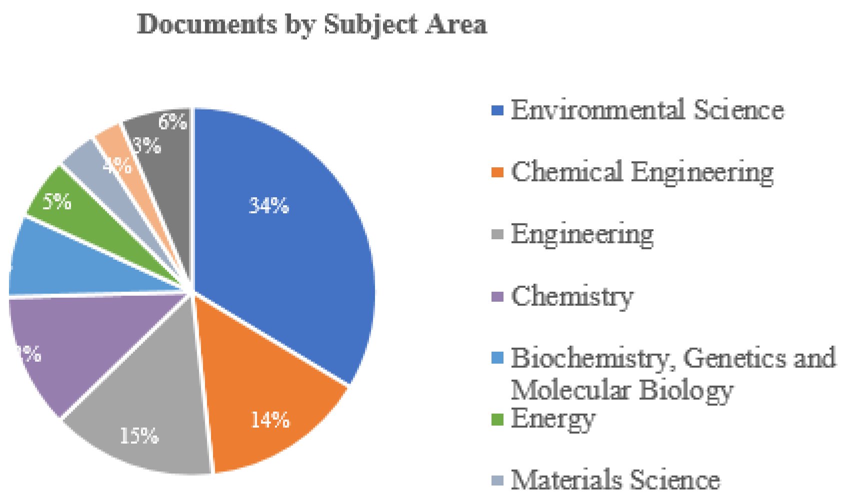


Fig. 6. Classification of publications on electrocoagulation (EC) based on subject areas such as chemistry, engineering and environmental science.

## DISCUSSION

### Types of dyes treated with EC

The literature demonstrates that EC has been widely applied to treat a wide range of dyes in textile wastewater. Studies have been carried out on both synthetic single dye as well as real textile effluents. (Refer to the summary at **Appendix-A**). Studies on synthetic dyes include reactive dyes, acidic dyes, basic dyes, vat dyes, direct dyes, disperse dyes, and indicators. From the final corpus, the most available studies are on reactive dyes suggesting their extensive use in the textile industry. Vat dyes are another widely used class used for denim colouring,

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highlighting the relevance of EC for treating denim effluent. On the other hand, disperse dyes are reported relatively less in the literature, suggesting they are less widely used in the industry compared to reactive dyes whereas succesful to treat through EC. Likewise, acid dyes and basic dyes are also available in the literature under EC studies. Meanwhile some researchers have also studied EC to treat indicator dyes as well. Most of these dye classes including reactive, direct, acid, and disperse dyes belong to the Azo dye group which contain N=N linkage producing vibrant range in colours. These dyes are used to colour different fabrics, and each dye has its own specific chemical structure, functional groups, molecular complexity, and reactivity. The effectiveness of EC and optimal operational conditions can vary depending on the specific characteristics of each dye. A study by Omwene & Keyikoğlu (2023) demonstrates how the treatment efficiency differs among different dyes under the same operational condition.

Moreover, a number of studies focused on synthetically prepared wastewater containing a single dye to identify operational conditions and EC-based dye removal efficiency. However, a significant number of studies have examined real textile wastewater which contains a mix of dyes and chemical effluents. Thus, studying each dye type is important for evaluating EC performance on that dye. In contrast, studying real textile wastewater is essential for assessing EC performance in practical industrial applications.

### Factors affecting EC performance

EC mechanism is controlled by several factors. The primary factors including type of electrode material, applied voltage/ current density, electrolysis time, concentration of the added electrolyte causing initial conductivity of the effluent, inter-electrode distance, and initial pH of the effluent, are the main dominant parameters that directly effect the electrochemical reaction process. On the other hand, there are some secondary factors such as volume of the effluent, flow rate of the effluent, electrode configuration, and mixing speed that do not directly control the EC performance but indirectly influences the impacts of the primary factors, depending on system design. The secondary factors are crucial when scaling-up the treatment unit for practical application from lab-scale treatment. As in the literature, researchers have studied, varying the primary factors to identify the optimal conditions to achieve the maximum dye removal efficiency.

In EC, the main material that generates coagulant agent that treats the pollutant is the sacrificial anode metal. The literature shows that Aluminium (Asfaha, 2022; Bünyamin, 2023; Gasmi et al., 2022; Guillermo et al., 2022; Houssini et al., 2021; Hussain et al., 2023; Lach et al., 2022; Lamhar et al., 2024, 2025) and Iron (Bünyamin, 2023; Guillermo et al., 2022; Houssini et al., 2021; Hussain et al., 2023) are the mostly used electrode materials since the widely used conventional coagulants in wastewater treatment are Aluminium and Iron Chloride salts. Moreover, the metal ions with higher valence charges are most preferred in EC to effectively compress the electrical double layer to improve the pollutant coagulation. Thus, Al and Fe metals are commonly accepted as standard metal anodes for their good coagulant properties, their multivalent ions and also their high availability at low cost (Garcia-segura et al., 2017). In this regard, some researchers have studied, waste iron slag (Maman, Conrado, et al., 2022) and scrap iron (Maman, Behling, et al., 2022) from foundries, as well as recycled and non-recycled waste aluminium cans (Elhadeuf, Bougdah, Balaska, et al., 2023) as cost effective electrodes. Nevertheless, some studies investigated, alternative electrode materials including copper (Hussain et al., 2023), mild steel (Jegathambal et al., 2024), and titanium-coated aluminium (Jegathambal et al., 2024). However, the optimal conditional values of the operating parameters differ based on the material used as the electrode.

The applied voltage/current density is one of the most influential parameters directly affecting the dissolution rate of the sacrificial anode, and thereby controlling coagulant generation and dye removal efficiency. An increase in applied voltage can result in higher current density leading better coagulation performance at the same time leading to higher power consumption (Abdulhadi et al., 2019). Researchers have found a varied optimal current density value such that 0.83 $mA/cm^2$ was applied by Omwene et al. (Omwene & Keyikoğlu, 2023) while 50 $mA/cm^2$ by Guillermo et. Al. (Guillermo et al., 2022), each based on the specific treatment setup with different other parameter values. Therefore, investigating optimal current density is important considering dye removal efficiency meanwhile investigating the other parameters to reduce energy consumption.

The treatment time has the effect in achieving the higher efficiency because with time the formation of cations from the electrode (anode) increase and hence the hydroxide species increase. As a result the efficiency increases

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(Gonçalves et al., 2016). However, some studies (Hussain et al., 2023; Sinna Lebbe et al., 2026) show a decline in treatment efficiency with prolonged electrolysis time after a certain point, which will also affect negatively with operating cost. Therefore, optimizing the electrolysis time is an important parameter to achieve the maximum EC efficiency.

Adding various types of salts as supporting electrolytes (e.g., NaCl (Elhadeuf, Bougdah, Balaska, et al., 2023; Lach et al., 2022; Maman, Behling, et al., 2022; Maman, Conrado, et al., 2022) KCL (Lamhar et al., 2024, 2025), and $Na_2SO_4$ (Hussain et al., 2023)) has a passive effect on dye removal efficiency. In general, an electrolyte is usually used to increase the solution conductivity in EC because of the ion concentration, which will reduce the electrical resistance and enhance the current flow. However, excessive electrolyte addition may lead to secondary pollution and operational cost. Therefore, this need to be optimised to ensure the EC efficiency.

The inter electrode distance directly effects the solution resistance and the energy consumption of EC due to its influence in the electric field strength. smaller electrode gap is generally considered to give stronger electric field, and lower resistance affecting the rate of electrode dissolution and coagulant generation. However, considering the short-circuiting and clogging concerns, optimization of this factor is very important.

Initial pH is another factor that determines which kind of coagulant agents are produced from the anode based on the pH level of the solution. A study by Guillermo *et al.* (Guillermo et al., 2022) shows higher removal efficiency at pH 10 with Fe electrodes and at pH 4 with Al electrodes. Therefore, it is crucial to investigate the effect of the initial pH based on the specific conditions of the studies.

**Performance indicators to assess electrocoagulation efficiency**

To identify the effectiveness of the EC treatment, researchers have used several performance metrics such as dye removal efficiency, COD removal, turbidity removal, TOC removal, TSS removal, phenol removal, electricity consumption, energy consumption, electrode consumption, operating cost, and sludge formation. These matrices can be classified into categories such as pollutant removal-based performance indicators, operational performance indicators, as well as economic performance indicators.

Dye removal efficiency is one of the most widely reported pollutant removal indicators that shows how clear the coloured wastewater gets after the treatment process, since the primary objective of the EC treatment in textile wastewater is stabilizing the dye pollutants to trap them and getting colourless water as a result.

However, the real textile effluent consists of complex types of pollutants, sizing agents, detergents, finishing chemicals, etc. Therefore, the colour removal alone doesn’t indicate the complete water purification, as the colourless effluent still may contain dissolved organic matter and suspended impurities. In this case, some other common parameters are important to evaluate the treatment efficiency. Those are chemical oxygen demand (COD) which measures the total amount of oxygen required to chemically oxidize the organic and inorganic substances in the wastewater, total organic carbon (TOC) which measures the total amount of carbon present in the organic compounds, turbidity which measures the cloudiness of the effluent due to the fine colloids present in the water, and total suspended solids (TSS) which measures the total mass of the solid particles suspended in the wastewater. In addition, some studies by Maman, Behling, et al. (2022) and Maman, Conrado, et al. (2022) have reported phenol removal through EC treatment, specifically in real textile denim effluents, as phenol is one of the finishing chemicals and its removal is another indicator for the detoxification of the treated effluent.

In addition to the pollutant removal, the operational and economic performance indicators evaluate the technical and economic feasibility of the EC process. Electricity/energy consumption evaluates the amount of electrical energy consumed to treat a unit volume of wastewater or to treat a unit volume of pollutant. This is directly influenced by applied current density, treatment time, and the electrode material. Although a higher applied potential enhances pollutant removal efficiency (Sinna Lebbe et al., 2026), it will result in increased energy consumption leading to higher operating costs. Electrode consumption indicates how much the sacrificial anode dissolves during the EC process. When the electrode consumption is excessive, the sludge formation will be higher, as well as the operating costs.

Overall, the efficiency of EC requires optimization among all these performance metrics, to attain the maximum effectiveness in practical applications.

**Types of Modelling techniques Integrated with EC**

From the selected literature, some studies were identified where researchers have integrated modelling techniques along with EC for process optimization. The statistical modelling techniques found were RSM (Houssini et al., 2021) with Central Composite Design (Gasmi et al., 2022; Tanyol et al., 2021), Box Behnken Design (Asfaha, 2022; Guillermo et al., 2022), and Factorial Experiment Design (Lach et al., 2022). These models were fitted to a second-order polynomial regression to capture the relationship between the operational factors influencing the EC mechanism.

The common independent variables studied were pH, current density, electrolysis time, dye concentration, and electrolyte concentration, in order to draw the response for colour removal, COD, turbidity and energy consumption. Several software applications, such as Design-Expert, Minitab, Statistica, Statgraphics Centurion, and JMP.11, are used for model building and for model validation, ANOVA, $R^2$, adjusted $R^2$, predicted $R^2$, adequate precision, Spearman correlation, Tukey's test, lack of fit tests, coefficient of variation, normal percentage probability plot, and experimental vs. predicted values comparison were used.

These modelling approaches were used to optimize operating parameters, maximize removal efficiency, minimize operational cost and energy consumption, and to understand the interactions among the operational parameters.

**Hybrid approaches integrated with electrocoagulation**

Publications from the selected corpus indicate that researchers are increasingly focusing on several advancements for an effective and efficient water treatment method through the application of EC integrated with some advanced technologies and with some hybrid approaches for enhanced treatment results. From the selected studies, 57% of the publications demonstrate a combination of EC with other technologies.

Several studies are exploring EC integrated with advanced oxidation processes. Tanveer et al. (2022) investigated the treatment efficiency of EC combined with AOPs such as ozonation, Fenton, and photo-Fenton processes in textile dye removal. Similarly, the same treatment for EC with Photo electro-Fenton Processes was studied by Moazeni et al. (2023), and EC with electro-Fenton was also studied by Agarwal (2024). There was another study by Domínguez et al. (2022), which explores EC combined with oxidation through oxygen and ozone, and Javed et al. (Javed et al., 2025) also studied hybrid ZIF-67 catalyzed ozonation coupled with EC. Martínez et al. (2024) further investigated the effect of high-rate aeration in EC; meanwhile, Asfaha et al. (2022) investigated hybrid electrocoagulation and electrooxidation processes. Then, EC and anodic oxidation were studied by Sugha et al. (2025). Ángeles et al. (2025) analyzed the sequence of textile washing treatment with ozonolysis, EC, and electrooxidation. In terms of enhancing the floatation in EC, Abdulrazzaq et al. (2021) applied air microbubbles for enhanced treatment. Isawi et al. (2024) demonstrate a combined EC/Flotation technique with membrane desalination.

Moreover, Agarwal et al. (2024) integrated EC and electrooxidation to treat textile wastewater to fit for biological remediation, and Ghosh et al. (2024) approached a hybrid treatment method comprising anaerobic digestion and EC. Bulca et al. (2021) investigated the hybrid wastewater treatment method by evaluating the performance of absorption after EC and the performance of catalytic wet air oxidation (CWAO) after EC. Similarly, the integrated EC and adsorption treatment method was studied by Somasundaram et al. (2024) and Jegathambal & Gafoor (2021) as well. In another study, Selvaraj & Arivazhagan (2024) examined the integration of EC and adsorption by algal-activated carbon.

Pacheco et al. (2023) proposed the addition of a bio-coagulant from Pithaya peel, and Yazdandoust et al. (2024) proposed the addition of Moringa oleifera seed extract for EC enhancement. Ahmed et al. (2024) evaluated the impact of seawater integration on EC. Other novel approaches by Kalia et al. (2023) explored hybrid electrocoagulation and laccase-mediated treatment. Conversely, Góes et al. (2021) studied EC combined with conventional flocculation by adding Pectin and SDS as flocculants. Another study by Arshad et al. (2023) explored the combination of chemical coagulation with EC. While Abdelshafi & Sadik (2021) examined EC integrated with granular activated carbon filtration, and another similar study was conducted by Elhadeuf et al. (2023), who combined micro-filtration with EC.

Moreover, an EC combined sonication process called sono-EC was optimized by Manikandan & Saraswathi (2023) and Karthikeyan & Vijayachitra (2021) developed an IoT monitoring system with sensors for the EC reactor. These advanced technological innovations were explored to further improve the efficient control of EC.

### Research gaps and future directions

This study reveals that the lack of large-scale study for industrial application as most of the studies were conducted at lab-scale. Also, the literatures lack the long-term and continuous flow performance report. The majority of the studies were conducted in batch reactor where the operating cost and efficiency will differ from the large scale set up with continuous flow. Therefore, future studies should focus on for assisting practical implementation. Moreover, most of the studies lack sludge characterization, this should be analysed as in EC a significant amount of metallic sludge will be generated. Also, electrode passivation is rarely assessed and it should be assessed through long term and continuous flow treatment system. The integration of IoT by Manikandan & Saraswathi (2023) and Karthikeyan & Vijayachitra (2021) represents the promising direction towards AI-enhanced system control. However, this sector needs to be studies further.

## CONCLUSION

The scoping review has comprehensively explored the recent trend in the application of electrocoagulation to treat dye pollutants from textile wastewater from 2021 to 2025. The reviewed literature demonstrates that electrocoagulation is effective in treating a wide range of textile dyes. However, the optimal condition varies depending on the type of dye being treated and the electrode material used. Therefore, each study with a new dye or with a new electrode material requires specific optimisation to find the optimal working condition with maximum efficiency. The selection of performance indicators whether pollutant removal, economic performance, or operational performance was found to depend on the nature of the wastewater selected for study, such as a synthetic single dye wastewater and a real textile effluent. However, for real industrial applications, a combination of all the performance indicators should be considered for practical implementation. Modelling approaches mostly RSM have been applied to effectively interpret the outcomes of the experiments. Moreover, a growing number of studies report the integration of electrocoagulation with some other advanced water treatment techniques to achieve an improved treatment performance. Despite the available studies on both synthetic and real industrial effluent, most studies were carried out at lab-scale and larger-scale continuous flow performance assessment remains unexplored to support industrial application. The future works should priorities long run and performance reporting frameworks. Further integration of AI-based process control system and sustainable electrode materials has the potential for advanced and viable industrial application.

### Conflict of Interest

The authors declare no conflict of interest.

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**Appendix-A**: Summary of selected studies on EC for textile dye removal.

| **Treated dye** | **Operating condition (at optimum)** | **Type of electrode** | **Performance metrics** | Ref. |
|---|---|---|---|---|
| Real Textile wastewter, India | Applied current = 1.5 A<br>Flow rate = 150 mL.min$^{-1}$ | Ti coated Al | Colour removal efficiency= 92.1%<br>COD removal = 70% | (Jegathambal et al., 2024) |
| | Flow rate = 50 mL.min$^{-1}$<br>Applied current = 1.5 A | Mild steel | Colour removal efficiency = 95.11%<br>COD removal = 70% | |
| Remazol Ultra Red RGB (reactive red 239) | pH = 3<br>Current density = 50 A/m$^2$<br>Conductivity = 250 μS/cm<br>Mixing speed = 250 rpm | Al | Color = 95.49<br>COD = 89.34<br>Turbidity = 92.18%<br>Electricity consumption = 11.48 kWh/m$^3$<br>Energy consumption = 0.56 kg/m$^3$ | (Bünyamin, 2023) |
| | pH = 5<br>Current density = 75 A/m$^2$<br>Conductivity = 500 μS/cm<br>Mixing speed = 250 rpm | Fe | Color = 99.94%<br>COD = 66.83%<br>Turbidity = 83.15%<br>Electricity consumption = 6.60 kWh/m$^3$<br>Energy consumption = 0.46 kg/m$^3$ | |
| Denim textile wastewater, Monastir City, Tunisia | pH = 9<br>Electrolysis time = 36.26 min<br>voltage = 4 V<br>Operational cost = 0.47 USD/m$^3$<br>No. of electrodes = 2<br>Electrode size = 90×35 mm$^2$ ×1mm<br>Submerged depth of electrode = 5 cm<br>Reactor volume = 400 ml | Al | Color = 99.07%<br>COD = 63.05%<br>Turbidity = 96.31% | (Gasmi et al., 2022) |
| Reactive Red 231 (RR231) azo dye | Current intensity = 4 A<br>Electrolyte = 2.0 g/L NaCl<br>Mixing speed = 600 rpm<br>Electrode size = 100×40×1 mm$^3$<br>Submerge depth of electrode = 78 mm<br>Reactor volume = 1 L | Al | Color removal = 96.5%<br>TOC removal = 93.5%<br>COD removal = 85.0% | (Lach et al., 2022) |

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| | | | | |
|---|---|---|---|---|
| Vivizol Red 3BS reactive dye (VR 3BS 150%) | Current density = 32.95 $mA.cm^{-2}$<br>Initial pH = 3<br>Dye concentration = 600 mg/L<br>Electrolysis time = 25 min<br>No. of electrodes = 4 (2 anode & 2 cathode)<br>Electrode size = 6.5x 2.5$cm^2$ x 0.1 cm (effective surface of 65 $cm^2$ )<br>Mixing speed = 150 r.p.m<br>Reactor volume = 600 mL | Al | Color removal = 89%<br>TOC removal = 47%<br>COD removal = 76%<br>Operating cost > 5.80 US$/$m^3$ | (Asfaha, 2022) |
| Commercial indigo blue dye | pH = 7.5-8.7 (unadjusted)<br>Electrolysis time = 25 min<br>Electrolyte = 1 g/L NaCl<br>Reactor volume = 3 L<br>At room temperature (20-25 °C) | Iron slag | Color removal = 85%<br>Phenol removal = 100% | (Maman, Conrado, et al., 2022) |
| Real textile denim effluent, Erechim-RS, Brazil | pH = 7.5-8.7 (unadjusted)<br>Electric current = 0.3 A<br>Electrolysis time = 60 min<br>Electrolyte = 1 g/L NaCl<br>Reactor volume = 3 L<br>At room temperature (20-25 °C) | | Color removal = 80%<br>Turbidity removal = 91%<br>Phenol removal = 100%<br>COD removal = 55%<br>TOC removal = 73% | |
| Commercial indigo blue dye | Electric current = 9.0 A<br>Electrolysis time = 120 min<br>Electrode size = 12×9 cm<br>Reactor volume = 3 L<br>Electrode spacing = 10 cm<br>Electrolyte = 1 g/L NaCl | Scrap Iron | Color removal = 95%<br>Phenol removal = 96% | (Maman, Behling, et al., 2022) |
| Real textile denim effluent, , Brazil | Electric current = 0.6 A<br>Electrolysis time = 90 min<br>Electrode size = 12×9 cm<br>Reactor volume = 3 L<br>Electrode spacing = 10 cm<br>Electrolyte = 1 g/L NaCl | | Color removal = 92%<br>Turbidity removal = 97%<br>Phenol removal = 100%<br>COD removal = 55%<br>TOC removal = 65% | |
| Real textile wastewater, Arequipa-Peru city | pH = 4<br>Current density = 50 mA/$cm^2$<br>Electrode size = 10 × 5 cm<br>Interelectrode distance = 3 cm<br>Reactor volume = 0.7 L<br>Mixing speed = 400 rpm | Al | COD removal = 89.92 %<br>Turbidity removal = 99.75% | (Guillermo et al., 2022) |
| | pH = 10<br>Current density = 50 mA/$cm^2$<br>Electrode size = 10 × 5 cm<br>Interelectrode distance = 3 cm<br>Reactor volume = 0.7 L<br>Mixing speed = 400 rpm | Fe | COD removal = 86.38%<br>Turbidity removal = 97.67% | |

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| Reactive blue and disperse red 74 dye | Current density = 17.08 mA/cm$^2$<br>Operating time = 20 min<br>pH = 9<br>electrolyte concentration = 2 g/L<br>Mixing speed = 100 rpm<br>(6 cm propeller stirrer)<br>Electrode area = 70 cm$^2$<br>Interelectrode distance = 1 cm<br>Dye concentration = 40 g/L | Fe | Colour removal = 95%<br>Energy consumption = 5.45 kWh/kg<br>Operating cost = 83.879 \$/m$^3$ | (Houssini et al., 2021) |
| | Current density = 25 mA/cm$^2$<br>Operating time = 60 min<br>pH = 4<br>electrolyte concentration = 2.5 g/L<br>Mixing speed = 100 rpm<br>(6 cm propeller stirrer)<br>Electrode area = 70 cm$^2$<br>Interelectrode distance = 1 cm<br>Dye concentration = 40 g/L | Al | Colour removal = 93%<br>Energy consumption = 5 kWh/kg<br>Operating cost = 126.23 \$/m$^3$ | |
| Indigo carmine dye | pH = 5.86<br>Current density = 13.31 mA/cm$^2$<br>Electrolysis time = 115.80 min<br>Electrode size = 50 mm × 80 mm<br>Interelectrode distance = 4 cm<br>Reactor volume = 500 mL<br>Temperature = 20 °C<br>Mixing speed = 200 rpm<br>Dye concentration = 20.01 mg/L<br>Electrolyte = 1.46 g/L NaCl | Fe | Colour removal = 82.55%<br>Sludge formation = 0.928 kg/m$^3$<br>Electrode consumption = 0.0305 kg/m$^3$<br>Energy consumption = 7.461 kWh/m$^3$<br>Operating cost = 0.79 US\$/ m$^3$ | (Tanyol et al., 2021) |
| Reactive Orange 16 | pH = 4<br>Current density = 0.025 A/cm$^2$<br>Dye concentration = 5 ppm<br>Electrolysis time = 15 min<br>Electrolyte = 1 g/L $Na_2SO_4$ | Fe | Colour removal = 93%<br>COD removal = 91% | (Hussain et al., 2023) |
| | | Al | Colour removal = 82%<br>COD removal = 51% | |
| | | Cu | Colour removal = 70%<br>COD removal = 56% | |
| Disperse Orange 30 | Dye concentration = 50 mg/L<br>Electrolyte = 1 g/L NaCl<br>Initial conductivity = 2015.8 µs/cm<br>Electrolysis time = 15 mins<br>Current density = 0.83 mA/cm$^2$<br>Mixing speed = 100 rpm<br>No of electrodes = 5 (3 anode & 2 cathode)<br>Electrode size = 20 x 6 (cm x cm)<br>Interelectrode distance = 1 cm<br>Reactor volume = 500 ml | Al | Colour removal = 98.13%<br>Operating cost = 0.25 \$/kg dye at 0.0502mA/cm$^2$ | (Omwene & Keyikoğlu, 2023) |
| Acid Blue 324 | | | Colour removal = 91.98%<br>Operating cost = 0.647 \$/kg dye at 0.0502mA/cm$^2$ | |
| Basic Yellow 28 | | | Colour removal = 47.46 %<br>Operating cost = 0.764 \$/kg dye at 0.0502mA/cm$^2$ | |
| Reactive Black 5 | | | Colour removal = 82.60%<br>Operating cost = 0.55 \$/kg dye at 0.0502mA/cm$^2$ | |
| Vat Brown 1 | | | Colour removal = 92.55%<br>Operating cost = 0.274 \$/kg dye at 0.0502mA/cm$^2$ | |

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| Real textile effluent, Bangladesh | Electrode size = 16cm x 0.95cm dia<br>(surface area = 42 $cm^2$)<br>Electrode spacing = 10 cm<br>At room temperature (25 ◦C)<br>Reactor volume = 1L<br>Electrolyte = 1g/L of table salt<br>Voltage supply = 20V<br>Initial current = 0.9 A<br>Initial current density = 15.0 $A/m^2$<br>Electrolysis time = 60 min | Al, Zn, C, Cu, Mild steel (ms), stainless steel (ss) | COD = 92.09% (Al–C pair)<br>TSS = 99.66% (Al–Cu pair)<br>Turbidity = 99.17% (Al-MS pair)<br>TOC = 70.99% (SS-SS pair)<br>Al–Zn is efficient overall:<br>TSS = 99.32%<br>Turbidity = 98.88%<br>COD = 68.62%<br>TOC = 57.96% | (Ahmed, Ahsan, et al., 2024) |
| Reactive Black 5 | Recirculation flowrate = 70 $Lh^{-1}$<br>Current intensity = 100 mA<br>Electrolysis time = 34.6 min<br>No. of electrodes = 10 pairs<br>Active electrode area = 621 $cm^2$<br>Electrolyte = KCl<br>Initial conductivity = 2400 µS/cm<br>Dye concentration = 10 mg/L<br>Electrode size = 50cm x 2cm x 0.2cm<br>Reactor volume = 9.445 L<br>Electrode spacing = 14 mm | Al | Dye removal= 70.9%<br>Energy consumption= 4.6 $Wh.m^{-3}$ | (Lamhar et al., 2024) |
| Azucryl red (AR) | Initial pH = 8<br>Electrode spacing = 1 cm<br>Electrolysis time = 35 min<br>Current intensity = 0.25 A<br>Electrolyte = 1 g/L NaCl | Al from recycled cans | Dye removal= 99.76%<br>Treatment cost = $2.4x10^{-5}$ $ /L | (Elhadeuf, Bougdah, Balaska, et al., 2023) |
| | Initial pH = 8<br>Electrode spacing = 1 cm<br>Electrolysis time = 60 min<br>Current intensity = 0.25 A<br>Electrolyte = 1 g/L NaCl | Al from non-recycled cans | Dye removal= 94.16%<br>Treatment cost = $4.4x10^{-6}$ $ /L | |
| Reactive Black 5 | Current intensity = 1 A<br>Electrolysis time = 32.5 min<br>Flowrate = 65.5 L/h<br>No. of electrodes = 9 pairs (surface area of 621 $cm^2$)<br>Electrolyte = 1.85 g/L KCl<br>Initial conductivity = 2400 µS/cm<br>Dye concentration = 100 mg/L<br>pH = 7 | Al | Decolorization = 42.72%<br>Energy consumption = 26 $Wh/m^3$<br>Total foam volume = 166.92 $cm^3$<br>Foam in last compartment = 5.24 $cm^3$ | (Lamhar et al., 2025) |
| Real textile wastewater, East China | Initial pH = 3.0<br>Current density = 32.43 $A/m^2$<br>Electrolyte = 8.0 g/L NaCl<br>Reaction time = 20 minutes<br>Reactor volume = 500 ml<br>Effective electrode area = 30.84 $cm^2$<br>Interelectrode distance = 1cm | Fe anode, Al cathode | Energy consumption = 0.187 kWh/m3<br>Removal efficiencies:<br>P = 100%<br>Cr(VI) = 89.97 %<br>Sb(V) =66.90%<br>Energy consumption = 0.187 $kWh/m^3$<br>Operating cost = 0.815 $USD/m^3$ | (Huang et al., 2025) |

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| Real textile wastewater, Brazil | Electrolysis Time = 45 mins<br>Mixing speed = 400 rpm<br>Reactor volume = 800 ml<br>Electrode size = 100 x 50 x 2 $mm^3$ | Stainless steel 304 L | Color removal = 100%<br>DOC removal = 92%<br>Turbidity removal = 99.53%<br>$H_2$ production = up to 89.87% v/v<br>Energy consumption = 19.02–55.74 $kWh/m^3$ $H_2$ | (Thiago et al., 2024) |
| Navy blue dye (AM-16) | Electrode size = 3 cm × 5 cm × 2 mm<br>Electrode distance = 8 cm<br>Electrolyte = 1 g/L NaCl<br>Electrolysis time = 10 mins | | COD removal = 29.32% | (Bressan et al., 2024) |