

Evaluation of electrocatalytic activity Ti and Al as anodes for the remediation of textile dyeing effluent

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One of the industries that uses huge volumes of water is the textile sector, which generates a lot of wastewaters. Electrocoagulation (EC), an environmentally friendly method, has been utilized to remediate textile dyeing effluent. The goal of this work is to compare the catalytic activity of Ti with Al using two sets of experiments (Al-Ti, Ti-Al), one of which contains Al as an anode and in the other Ti as an anode to treat textile dyeing effluent to reduce operating costs of the process as Ti electrode undergoes uniform dissolution with less energy consumption compared to Al. The maximum color removal efficiency (CRE) of 97.13% and 96.8% was obtained while using Al-Ti and Ti-Al electrodes. The removal efficiency of Total Dissolved Solids (TDS), Total Suspended Solids (TSS), and Chemical Oxygen Demand (COD) were also found to be comparable with both electrodes. The FTIR analysis of treated water demonstrated that the pollutant removal was similar in both electrodes. The generation of hydroxides during the EC process is demonstrated by XPS examination of sludge, with Al appearing as Al2p in the +3-oxidation state and Ti appearing as Ti2p_{1/2} and Ti2p_{3/2} in the +4-oxidation state. The operating cost calculated for Al-Ti and Ti-Al electrodes was found to be 2.90 US and 0.87 US. The difference in operating cost between these two electrodes was found to be 70%. The energy, electrode consumption, and operating cost for the Al-Ti electrode were found to be high due to its high dissolution.

Keywords: Aluminium; Cost; Electrocatalyst; Textile effluent; Titanium

1. Introduction

Organic-colored wastewater is common in a wide range of industries, including textile, paper, plastic, leather, food, and mineral manufacturing [1]. The textile industry consumes a lot of water during dyeing and finishing processes [2]. Before the middle of the 19th century, dyes were made from natural materials like beetroot, indigo, marigold, turmeric, beetle nut, etc. [3]. Natural colorants are obtained from plants (flowers, fruits, seeds, leaves, barks, and trunks) and animal/insect (dried bodies of insects) [4]. Nowadays, only 1% of natural dyes are being consumed in comparison to total synthetic dye consumption due to the high production cost of natural dye as plant materials [5]. Synthetic dyes have advantages over natural dyes, but their use causes en-

vironmental and health issues. Many synthetic dyes are poisonous and carcinogenic, endangering the health of living organisms [6–9]. Textile dyes are classified as azo, nitro, indigo, anthraquinone, phthalein, triphenyl methyl, and nitrated dyes according to their chemical structure [10]. Different organic dyes are used in textiles to color different products [11]. Water pollution occurs in dyeing and printing due to the use of a huge amount of water in their processes; it has been found that 45% of effluent is produced in preparatory, 33% in dyeing, and 22% in finishing processes [12]. Annually, around 700,000 tons of approximately 10,000 different types of colorants are generated worldwide, with an estimated 20% being released as industrial effluents during textile dyeing processes [13]. The textile sector in India

consumes around 80% of the total production of 1, 30,000 tons of dyestuff [14]. During the dyeing process, not all of the dyes are bonded to the fiber; some dyes remain in the dye bath, which is discharged with effluents [15]. The release of these untreated textile effluents is unacceptable because it leaves a path to various environmental difficulties [16].

The effluent released from the textile dyeing process contains a high pH, color, and suspended particles, as well as organic and inorganic pollutants, which leads to serious environmental disruption [17, 18]. The effluent may also contain significant levels of alkalinity, chromium, heavy metals, and chlorine, all of which are hazardous to human health [19]. Textile dyes impair photosynthesis, inhibit plant growth, enter the food chain, provide recalcitrance and bioaccumulation, and may promote toxicity, mutagenicity, and carcinogenicity, which lowers microbial activity, diversity, and richness of the soil. The carcinogenic, mutagenic, and teratogenic activity of certain dyes also has a negative impact on aquatic life [20–22]. Methylene blue, a triphenylmethane class dye used in the textile industry, can cause high blood pressure and cardiac depression [23]. Environmental damage is determined not only by the amount of dye disposed but also by the dye combination's content, with certain common constituents having dangerous qualities. When these effluents are discharged into surface or ground-water sources, the concentration of dissolved oxygen in the water decreases while the values of physicochemical and biological parameters such as COD increase [24–26]. To avoid the deterioration in surface water and environmental damage caused by textile effluent, it should be treated before discharging. Electrochemical water treatment systems provide opportunities to develop more sustainable water treatment solutions.

The majority of electrochemical water treatment technologies use electricity as the primary reactant [27]. Electrocoagulation (EC) [28], electro flotation (EF) [29], and electrodialysis (ED) [30] are emerging electrochemical methods that show good prerequisites for their use in industrial-scale applications. EC method successfully removes organic and inorganic contaminants with limited usage of chemicals. Compared to other electrochemical techniques, this method is cost-effective and requires comparatively less time for operation [31]. When a current is applied during the electrocoagulation process, the sacrificial anodes dissolve, forming an active coagulant that is responsible for removing contaminants from the wastewater [32]. The EC process depends heavily on metal electrodes and acts as a catalyst to produce the coagulating agents required to remove different contaminants like heavy metals, and organic pollutants. The choice of metal electrodes is an important step in the EC process. The electrode material has a considerable impact on the performance of the electrochemical reactor and the maximum efficiency of the EC process [33]. A variety of electrode materials like Al, Zn, Mg, Fe, SS, Cu [34–39], and a combination of electrodes such as Fe-Al, Mg-SS, Fe-Al-Fe, and Al-SS [40–43] were used successfully in the EC process. These materials should possess desirable properties like strong conductivity, more surface area, resistance to corro-

sion, and longer electrode lifespan. The most often used electrodes for wastewater treatment are iron and aluminum because of their widespread availability, low cost, and superior solubility [44]. The iron electrodes were more effective than aluminum electrodes for the removal of pollutants, but the dissolution of iron at a fast rate disorders the entire treatment process [45]. The need of the hour in the EC process is the choice of electrodes with high catalytic activity to reduce energy consumption which leads to high cell voltage and operating costs [46, 47]. Metal type, homogeneity, and surface properties are the main factors that determine the electrocatalytic activity. Conversely, increased surface area yields high levels of electrocatalytic activity [48].

Novel electrocatalysts have been employed as efficient electrocatalysts, including metal oxides and silver halides. Although Pt and Pt-based catalysts have been employed, the catalytic activity is reduced by the poisoning impact of CO species that are generated during oxidation [49–51]. Oxides such as CeO₂, TiO₂, ZnO₂, and WO₃, has better catalytic activity but cost and maintenance is high [52, 53]. Among the different electrocatalysts, aluminium has gained significant attention due to its abundant availability, low cost, and high theoretical electrochemical activity making them a promising candidate for applications such as sacrificial anode in electrocoagulation. However, the performance of aluminium electrocatalysts is often hindered by passivation phenomena, where an oxide layer forms on the surface, limiting their catalytic efficiency. Also, the difference in pH and electrolyte concentration influences the passivation to a great extent and overcoming these passivation challenges is crucial for unlocking the full potential of aluminium electrocatalysts. Titanium offers several benefits in many electrochemical processes due to its physical and electrochemical properties [54]. Titanium, being a transition metal, can form multiple oxidation states and complexes due to their catalytic activity. Unlike Al, titanium material has been characterized as an ideal choice of anode material due to its unique electronic structure, corrosion resistance, good catalytic activity, and intense physical and chemical stability [55]. Also, due to the uniform dissolution of Ti, passivation compared to Al is very minimal in the case of Ti. The main focus of this study is comparing Al with Ti in the combination of Al-Ti and Ti-Al in treating the effluent to get maximum removal of color and other physical parameters like TDS, TSS, COD, and BOD with low electrode consumption and operating cost. The dye degradation and formation of intermediate compounds were studied by FTIR analysis. The formation of hydroxides during the EC process was studied in the sludge obtained using the XPS analysis.

2. Materials and methods

2.1 Effluent treatment method

The Electrocoagulation (EC) process was carried out in a batch scale. The raw textile effluent was collected from a textile hub near Erode. The effluent was collected in a 5-litre bottle, which was washed and dried before collection. The Characteristics of textile dyeing effluent is given in Table 1. The EC setup consists of a 250 mL glass beaker placed

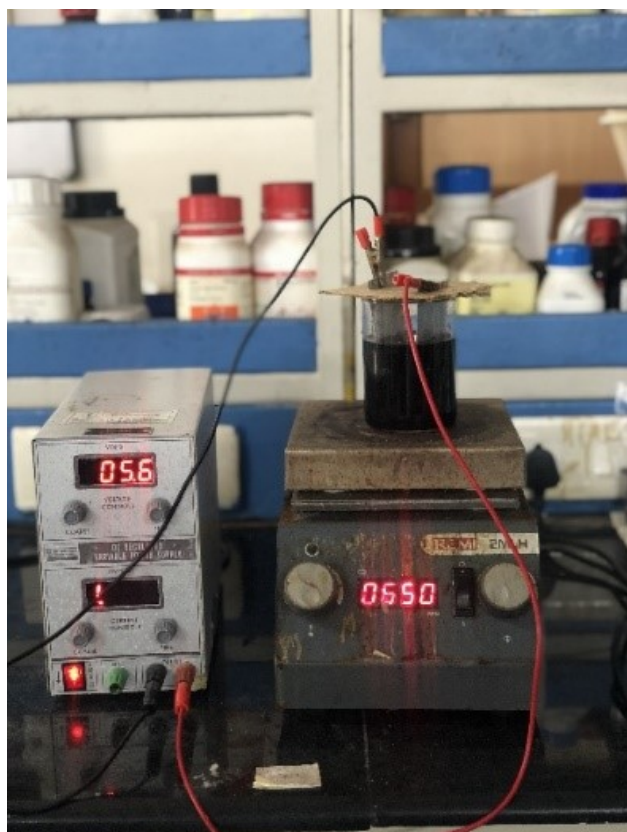


Figure 1. Electrocoagulation setup.

on the magnetic stirrer. The electrodes are placed inside the solution (effluent) with a distance of 4 cm apart and connected to an external power supply (direct current) [56]. Fig. 1 shows the electrocoagulation setup. Two sets of EC processes with Ti-Al and Al-Ti were conducted to optimize operational parameters such as pH, reaction time, voltage, and electrolyte concentration to compare the performance of Ti as anode and cathode. The aluminum and titanium plate used in the EC process is approximately 9 cm × 3.5 cm 0.5 mm in size. In this work, NaCl was utilized as an electrolyte to improve solution conductivity and increase pollutant reduction. The pH of the solution was altered with HCl and NaOH to get the desired pH. The entire procedure was carried out at room temperature with a constant stirring speed of 650 rpm. Before each reaction, the electrodes were washed with HCl, rinsed with distilled water, and dried. The sludge obtained after optimization of operational parameters was dried in the oven overnight and kept for further analysis, and the filtrate collected was used for further analysis.

3. Result and discussion

3.1 Optimization of operational parameters

To achieve the highest level of color removal efficiency, experiments were conducted to optimize operating parameters such as initial pH, reaction time, voltage, and electrolyte concentration.

3.1.1 Optimization of pH

pH is one of the important key parameters as it affects the performance of electrochemical processes like electrode dis-

solution, catalytic activity, and conductivity of the solution [57–60]. To examine this effect, a series of experiments were carried out with initial pH varying from 5 – 12 with a constant reaction time of 15 min, 10 V, and 0.75 g/L electrolyte. NaOH and HCl were used to alter the pH of the effluent. The plot of varying initial pH and CRE% is shown in Fig. 2(a). When the reaction was carried out at pH 5 the CRE after treatment with Al-Ti and Ti-Al electrode was found to be 58.75 and 61%, respectively. The CRE% increased as the pH increased from 5 to 8 for Al-Ti electrodes and there was a fall in CRE% above pH 8. At pH 6, the CRE of Al-Ti and Ti -Al was found to be 66.09 and 72%. The CRE at pH 7 was found to be 72 and 89% for Al-Ti and Ti-Al respectively. The CRE at pH 8 was found to be 89% for the Al-Ti electrode, when the pH was raised to 9 to 12 the CRE% falls from 75.6, 62, 42, to 29% for Al-Ti and 75, 63, 61, to 48% for Ti-Al respectively. The rise in CRE% from 5 to 8 is due to the formation of insoluble aluminum hydroxide Al(OH)₃ [61], when pH increased above 8 the formation of highly soluble weak coagulant Al(OH)₄⁻ takes place resulting in lower CRE% [62, 63]. Using, Ti-Al electrodes the CRE% increased as the pH increased from 5 – 7. When the reaction takes place at acidic conditions the titanium coagulants do not precipitate which automatically lowers the CRE% [64]. The highest removal percentage was observed at pH 7 (89%). Further increase in pH from 8 to 12 reduces the removal efficiency from 84% to 48% due to the formation of negatively charged Ti complexes [65].

3.1.2 Optimization of reaction time

To investigate the effect of reaction time on removal efficiency, reactions were carried out by varying time from 5 to 30 min with constant pH 8 for Al-Ti electrode and pH 7 for Ti-Al electrode, 0.75 g/L electrolyte, and 10 V. The removal efficiency for Al-Ti and Ti-Al electrodes at 5 min of the reaction was found to be 71.4 and 69% respectively. At the reaction time of 10 min the CRE% of Al-Ti and Ti-Al was found to be 84 and 74. When the reaction time was increased to 15 and 20 min the CRE of Al-Ti and Ti-Al increased to 89, 91.5 and 89, 92%, respectively as shown in Fig. 2(b). The efficiency of pollutant removal increases as the electrolysis time increases. However, once the ideal electrolysis time is attained, the effectiveness of pollutant removal remains constant and does not improve as the electrolysis time is increased [66]. The CRE% of Al- Ti and Ti-Al electrode with increased reaction time of 25 and 30 minutes is found to be 92, 92.9 and 93, 93.5 respectively.

Table 1. Characteristics of textile Dyeing effluent.

Parameter	Value
Color	Dark blue
pH	10.28
COD (mg/L)	3436
TSS (mg/L)	723
TDS (mg/L)	2793
EC (μ S/cm)	3311
Absorbance	1.38882 (623.5 nm)

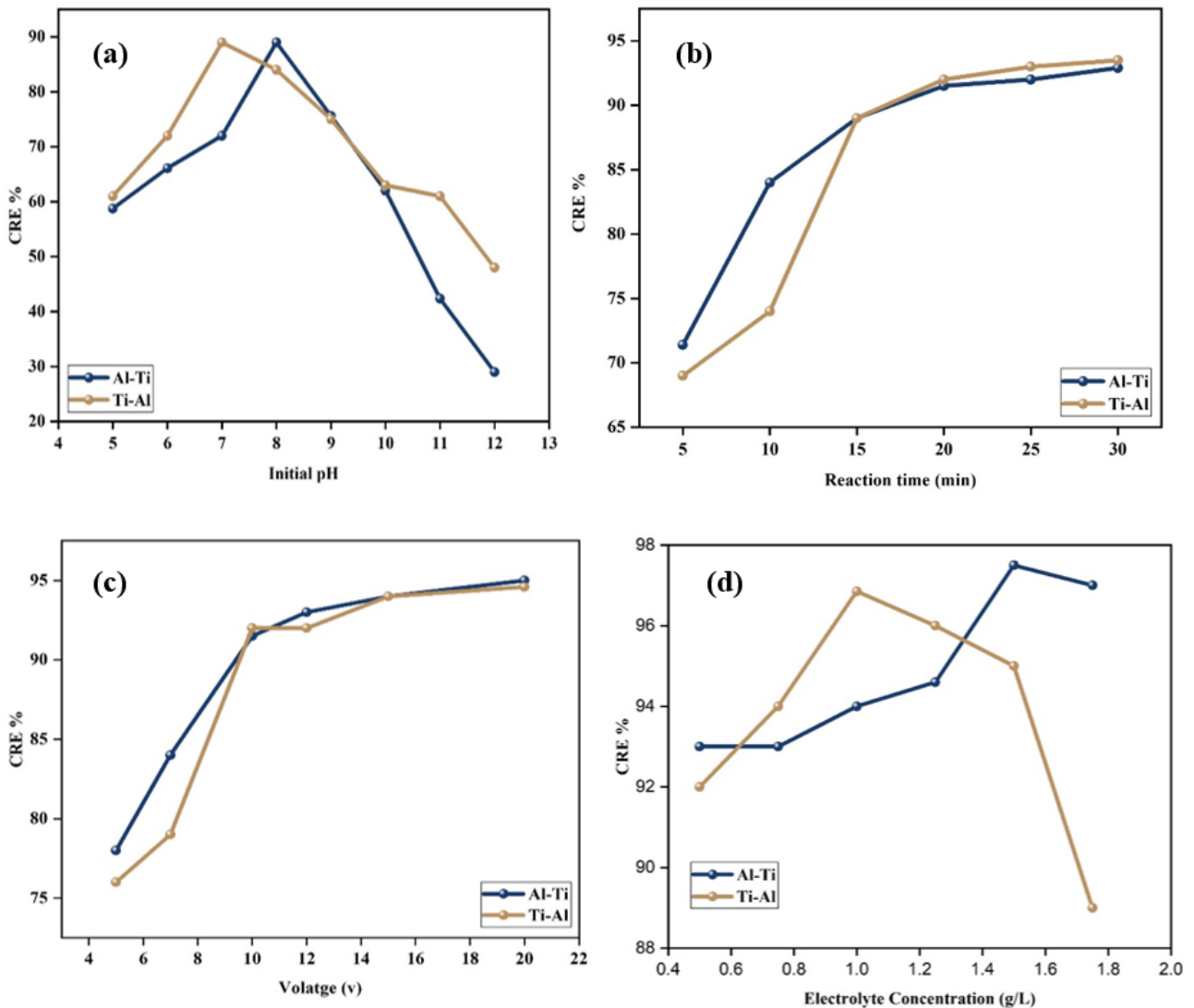


Figure 2. Optimization of (a) pH (b) reaction time (c) applied voltage (d) electrolyte concentration

When the time of reaction is increased to 25 and 30 min for both the electrode sets there is no huge difference in removal efficiency. So, the reaction time of 20 min is optimized for both the set of electrodes.

3.1.3 Optimization of voltage

The effect of applied voltage is an important parameter that determines the floc size and development, eventually affecting EC performance. The applied voltage is expected to have a strong effect on the EC process [67]. To examine the effect of voltage on the EC process, reactions were carried out with varying voltage of 5 V to 20 V with pH 8 for Al-Ti and pH 7 for Ti-Al, reaction time of 20 min for both sets of electrodes, 0.75 g/L electrolyte as shown in Fig. 2(c). For the Al-Ti electrode the removal efficiency with 5 V was 78%. At 7 V the CRE was found to be 84%. When the applied voltage increased to 10 V the removal efficiency of Al-Ti increased to 91.5%. Further increase in voltage from 12, 15 and 20 V the CRE increased from 93%, 94% to 95%. This is because when the supply of applied voltage increases more amount of Al^{3+} ion gets

dissolved in the solution resulting in an increase in the formation of $Al(OH)_3$ [68]. Only a negligible change was found after increasing the voltage from 12 to 20 V. So, the applied voltage of 12 V was optimized for Al-Ti electrodes. When the reaction was carried out with Ti-Al electrodes, the removal efficiency with 5 V was found to be 76% further increase in voltage from 7, 10, 12, 15 and 20 V the removal efficiency increased from 79%, 92%, 92%, 94% to 94.6% respectively. The applied voltage of 10V was optimized for the Ti-Al electrode because the removal efficiency was increased only by 2% after applying 20 V.

3.1.4 Optimization of electrolyte concentration

The conductivity of the solution was increased by adding electrolyte to the solution. The electrolytes type had a substantial impact on electrocoagulation performance. The performance of supporting electrolytes varied greatly depending on the type of electrode material. Electrolytes containing chloride performed better [69]. NaCl was used as an electrolyte in this work. Reactions were carried out with varying electrolyte concentrations (0.5 to 1.75 g/L)

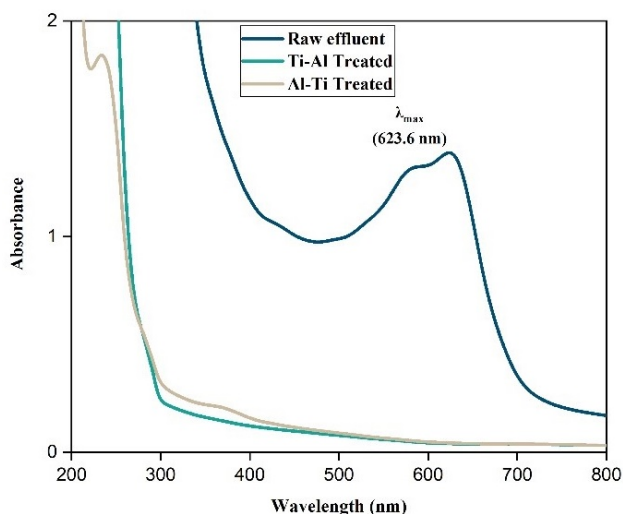


Figure 3. UV-Vis spectrum of the raw effluent and the treated effluent

and other optimized parameters 10 V, 20 min, pH 8 for the Al-Ti electrode and pH 7 for the Ti-Al electrode. The CRE% for reaction with 0.5 g/L NaCl for Al-Ti and Ti-Al was found to be 93 and 92 respectively. Further increase in NaCl concentration increases the CRE% as shown in Fig. 2(d). For the Al-Ti electrode the removal efficiency for 0.75, 1, 1.25, 1.5 and 1.75 g/L NaCl was found to be 93, 93, 94, 94.6, and 97.3, respectively. Further increase in NaCl concentration results in constant CRE%. Using Ti-Al electrode, the CRE% increased from 94, and 96.85 when the NaCl concentration increases from 0.75 to 0.1 g/L. When the NaCl concentration was increased from 1.25, 1.5 to 1.75 the CRE % decreases from 96, and 95 to 89% respectively. There is a fall in CRE% in further addition of NaCl as a result of salt deposition on the metal. The highest removal percentage of 97.13 was observed at 1.5 g/L of NaCl for Al-Ti electrode and 96.8% of CRE% was observed at 1 g/L of NaCl for Ti-Al electrode shown in Fig. 2(d).

3.2 UV-visible spectrum

The UV-visible spectra of effluent were recorded using JASCO V-770 between 200 and 800 nm at room temperature. The absorption spectra were used to calculate the CRE.

The greater the value, the more of a specific wavelength is absorbed. The maximum absorbance (λ_{max}) of raw effluent was observed at 623.6 nm. The absorbance peak obtained before the EC process and after EC with Al-Ti and Ti-Al is given in Fig. 3. The CRE was calculated using the formula (1),

$$CRE\% = \frac{A_0 - A_1}{A_0} \times 100 \quad (1)$$

Where, A_0 and A_1 are the absorbance before and after the EC treatment process.

3.3 FTIR analysis

Dye degradation through the EC process by FTIR analysis is shown in Fig. 4. FTIR (Shimadzu IR prestige 21) was used to analyze the degradation of dye with the KBr pellet method in the range from 4000 to 400 cm^{-1} . The dye

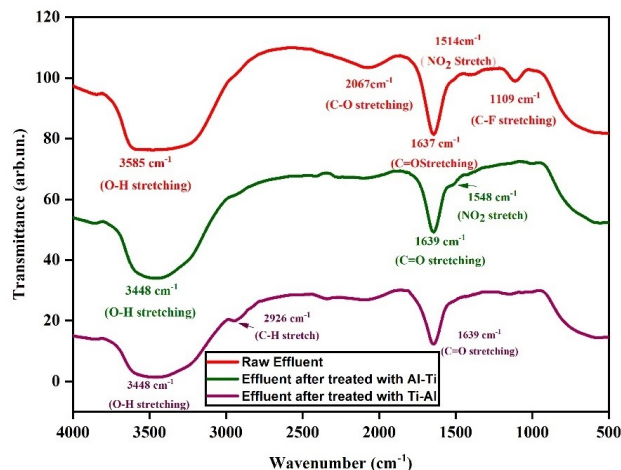


Figure 4. IR spectra of the raw effluent and after treatment

degradation process can be manifested either by the loss of absorbance peaks or by the occurrence of new peaks [70, 71]. The IR analysis of textile effluent shows five different peaks at 3585.67 (O-H, N-H stretching), 2067.69 A (C-O stretching), 1637.56 (C=O stretching) [72], 1514.12 (NO₂ stretch) [73], and 1109.0 (C-F stretch) respectively. The C=O and NO₂ stretch in the textile effluent showed the presence of chromophore group and nitro dye in the textile effluent. A Chromophore is a covalently unsaturated group that absorbs in the ultraviolet or visible range. For example, C=C, C≡C, C=O, C≡N, N=N, NO₂ [74]. The treatment of textile effluent with Al-Ti electrodes shows the disappearance of the C-O and C-F peaks and no new peak was formed of during the process [75]. Disappearance of the NO₂ peak and formation new peak at 2926.01 which corresponds to alkane (C-H stretching) [76] was found after treatment with Ti-Al. This may be due to the formation of an intermediate during the electrocoagulation process. FTIR studies show that both Al-Ti and Ti-Al electrode has similar efficiency in the dye degradation process.

3.4 XPS analysis

High-resolution Al and Ti XPS survey spectra and core line spectra [(Al, O1s, Al2p) and (Ti, O1s, Ti2p)] are provided in Fig. 5 and 6. When a sacrificial metal anode is dissolved in the EC process, metal hydroxides and coagulants are simultaneously formed in situ for the treatment of wastewater. The electro-generated coagulants and OH⁻ are transferred into a bulk solution and go through additional spontaneous hydrolysis reactions to form different monomeric and polymeric species, which are then transferred into soluble hydroxides [77]. The formation of metal hydroxides during electrocoagulation was examined with the sludge obtained using XPS analysis. From the XPS data of the sludge obtained with Al-Ti electrodes, it can be understood that the peak at 532 as shown in Fig. is attributed to O1s binding energy value of Oxygen [78], which is bonded with hydrogen to form hydroxide. The peak at 75 eV is attributed to the bayerite form of Al(OH)₃ [79] which confirms the formation of aluminium hydroxide during the electrocoagulation process. Using Ti-Al electrodes, the pres-

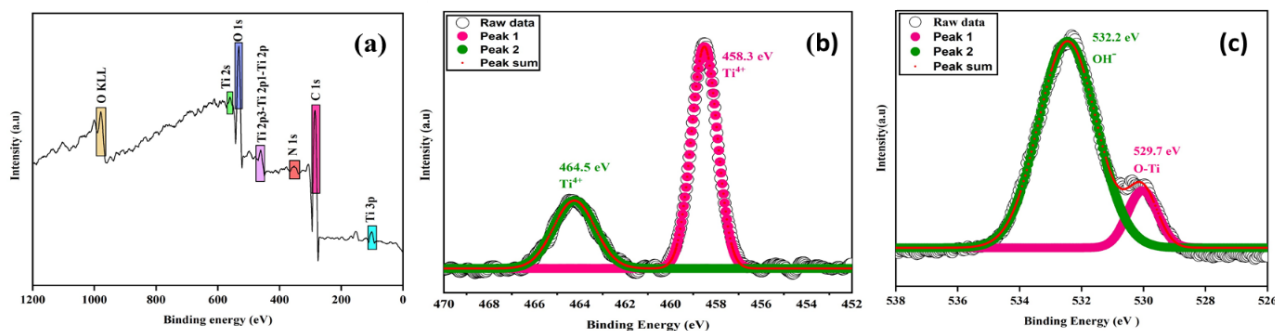
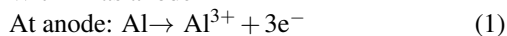


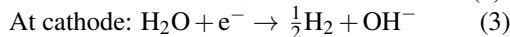
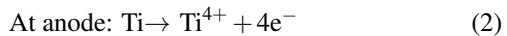
Figure 5. XPS spectra of sludge: Ti-Al (a) Survey spectra (b) Ti2p (c) O1s

ence of 529.7 and 532.2 peaks attributed to the O1s peak demonstrated the existence of oxides and hydroxides [80]. The binding energy of 458.3 and 464.5 eV was attributed to $Ti^{4+}2p_{3/2}$ and $Ti^{4+}2p_{1/2}$ [81] confirms the presence of Ti in its +4 oxidation state and formation of Titanium hydroxide ($Ti(OH)_4$). The possible mechanism occurred during EC process are given in Equations (1), (2) and (3),

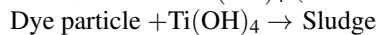
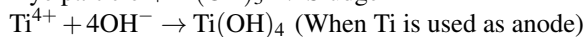
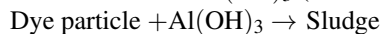
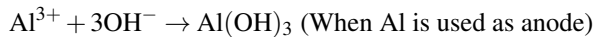
With Al as anode



With Ti as anode



Overall reaction



The hydroxyl ions from the cathode combine with the aluminium and titanium ions to form aluminium hydroxide and titanium hydroxide respectively. The formed metal hydroxides then combine with dye particles, and settle down as sludge during the reaction. Thus, XPS analysis helps to deduce the mechanism of the EC process and to confirm the presence of hydroxides formed during the EC process.

4. Analysis of physical and chemical parameters

The physical and chemical parameters like color, pH, TDS, TSS, EC and COD of the effluent after treatment with Al-Ti and Ti-Al was calculated and compared with that of raw effluent given in Table 2. The removal percentage of all the

parameters was calculated using the formula 2,

$$\text{Removal percentage} = \frac{I_i - I_f}{I_i} \times 100 \quad (2)$$

Where, I_i and I_f are the values obtained before and after EC process.

4.1 pH

pH control is an important factor in textile wet processing. The pH of textile effluent was obtained as 10.12, which is high and shows the alkalinity of the effluent because of the use of alkaline substances like sodium bicarbonate, sodium hydroxide, calcium hydroxide, and so on in textile processing [82]. pH after the EC process with Al-Ti and Ti-Al was calculated and depicted in Table 2.

4.2 (TDS)

The amount of TDS in textile effluent was found to be 2793 mg/L, which is higher than the permissible limit (2100 mg/L) by TN PCB [83] and WHO (2000 mg/L). The amount of solid content in polluted water is classified into two groups based on particle size: colloidal and soluble. The remaining solid is the dissolved solid, which contains soluble metal salts such as calcium, ferrous, sodium, magnesium, potassium, and so on [84, 85]. TDS is primarily used in the study of water quality in streams, rivers, and lakes. It is used to indicate the aesthetic qualities of drinking water as well as the presence of a wide range of chemical pollutants [86]. The highest level of TDS in textile effluent shows that the water is severely polluted and may cause salinity issues if discharged into irrigation water [87]. The TDS value after treatment with Al-Ti and Ti-Al electrodes is shown in Table

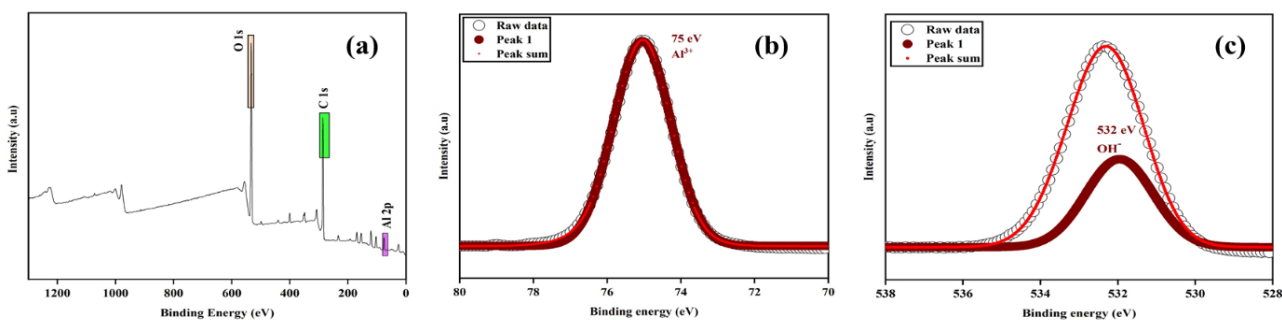


Figure 6. XPS spectra of sludge: Al-Ti (a) Survey spectra (b) Al2p (c) O1s

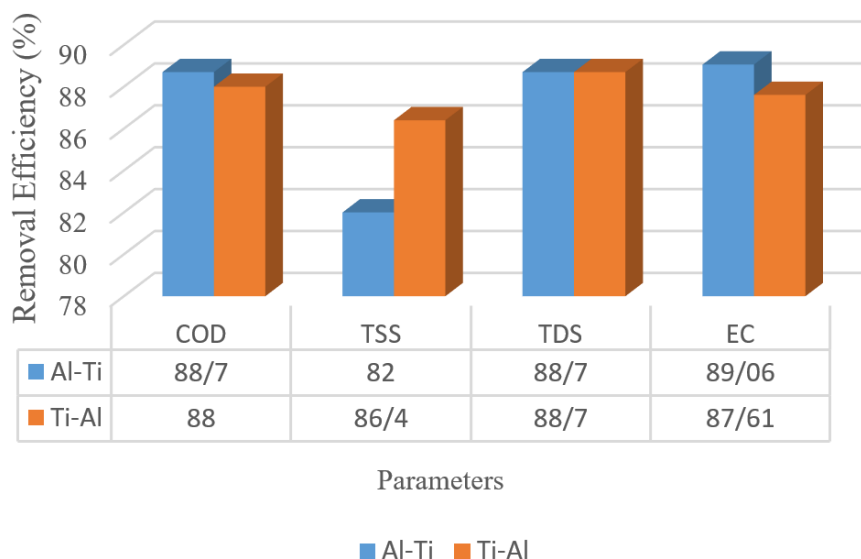


Figure 7. Removal percentage of different water quality parameters

1. The TDS removal percentage using Al-Ti and Ti-Al electrode were found to be 88.7%, respectively as shown in Fig. 7.

4.3 (TSS)

TSS is the dry weight of suspended particles that are not dissolved, in a sample of water. Excessive TSS levels in water bodies can have a substantial negative impact on their physical, chemical, and biological aspects [88]. The TSS value in textile effluent was found to be 723 mg/L higher than the permissible limit (100 mg/L) fixed by TN PCB [83] and WHO (75 mg/L) [15]. The TSS value drastically decreased after the treatment with Al-Ti and Ti-Al electrodes and was found to be 123 and 98 mg/L respectively. The TSS removal percentage using Al-Ti and Ti-Al electrodes was found to be 82 and 86.4% clearly explained in Fig. 7.

4.4 COD

COD is a measurement of the oxygen equivalent of organic matter in a water sample that is oxidizable by a strong chemical oxidant [89]. COD is frequently used as a measurement of contaminants in water, wastewater, and aqueous hazardous waste [90]. The COD value of textile effluent was found to be 3436 mg/L. A high COD value indicates that the

water has a higher concentration of oxidizable organic material. Color reduction may not always signify a decrease in COD values, color reduction may be due to dye degradation [91]. COD reduction is calculated using HACH DRB200 using a standard solution of potassium dichromate (0.25 N), and ferrous ammonium sulphate (0.1 N) [92]. The COD value of textile effluent after the EC process using Al-Ti and Ti-Al electrodes was 385 and 412 mg/L, respectively. COD removal efficiency using Al-Ti and Ti-Al was 88.7 and 88.0%, respectively as depicted in Fig. 7.

4.5 Electrical conductivity (EC)

The total ionized constituents of water are commonly represented via electrical conductivity. The high electrical conductivity indicates the presence of dissolved salts in the effluent. The higher the electrical conductivity, the more pollutants are in the water. [93]. The EC of raw textile effluent was found to be 3311 $\mu\text{S}/\text{cm}$. The removal efficiency of EC after the treatment process is shown in Fig. 7.

5. Analysis of economical parameters

5.1 Consumption of energy

Energy consumption is a significant factor in all electrochemical processes, and it is directly related to the entire

Table 2. Physical and chemical parameters of textile effluent and treated effluent

Parameter	Effluent	Effluent treated with Al-Ti	Effluent treated with Ti-Al
Color	Dark blue	Colorless	Colorless
pH	10.28	8.50	7.70
COD (mg/L)	3436	385	412
TSS (mg/L)	723	123	98
TDS (mg/L)	2793	314	315
EC ($\mu\text{S}/\text{cm}$)	3311	362	410
Absorbance	1.38882 (623.5 nm)		

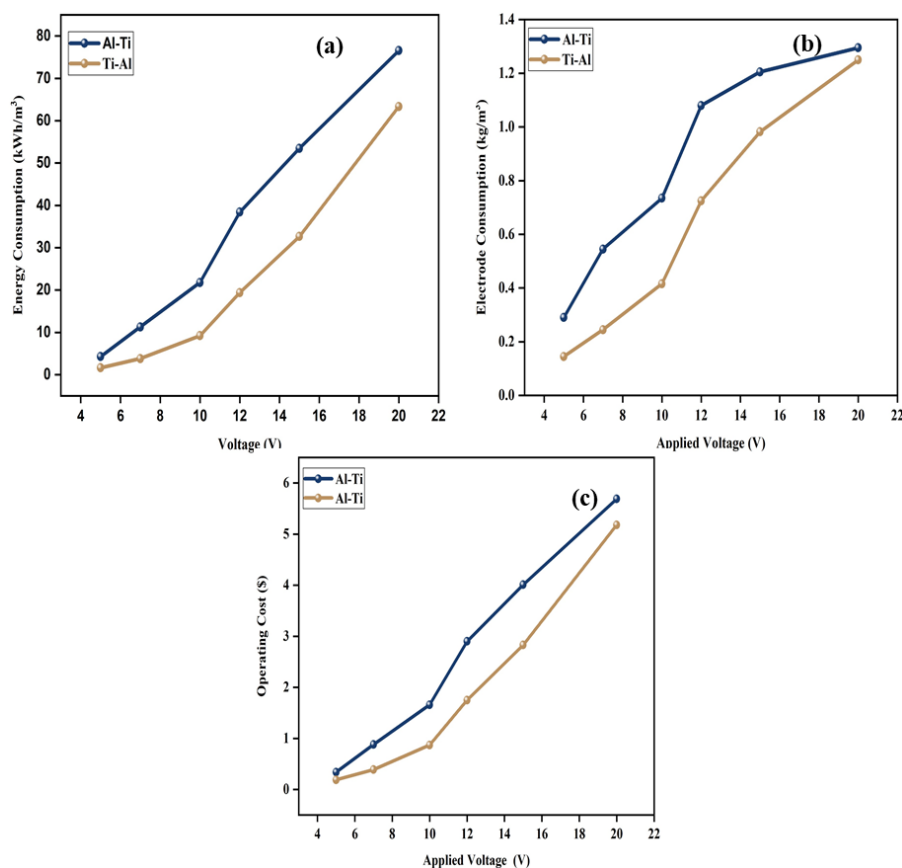


Figure 8. Effect of applied voltage on (a) energy consumption (b) electrode consumption (c) operating cost

operating cost and amount of current supplied during the process [94–96]. The energy consumption increases as the applied voltage increases clearly shown in Fig. 8. The energy consumption was calculated by the formula (3) given below,

$$\text{Consumption of Energy} = \frac{UIt}{v} \quad (3)$$

where U is the voltage applied, I is the applied current, t is the reaction time in hours, and v is the volume of the solution in m^3 . The consumption of electrode for Al-Ti and Ti-Al electrodes was found to be 38.4 kWh/m^3 and 9.24 kWh/m^3 , respectively. Ti as an anode consumed less energy than using Al as anode.

5.2 Consumption of electrode

The consumption of electrode and energy is directly related to the operating cost of the process. When a current is passed through an electrolytic cell, the anode oxidises and the metal dissociates into divalent or trivalent metallic ions, releasing an equivalent number of electrons. The dissolution occurs exclusively at the anode [97]. The electrode consumption during the electrocoagulation process is calculated using the formula 4,

$$\text{Electrode Consumption} = \frac{ItM}{nF} \quad (4)$$

where I is the applied current, t is the reaction time in seconds, M is the molar mass of anode (g/mol), F is the Faraday's constant ($96,485 \text{ C mol}^{-1}$), n is the number of

electrons transferred in the reaction. The consumption of electrode while using Al as anode was found to be 1.08 kg/m^3 which is found to be higher while using Ti as anode (0.416 kWh/m^3).

5.3 Cost calculation

The operational cost is one of the most important factors to consider when selecting a wastewater treatment system. The total operating cost of the EC process includes the electrode material and electrical energy cost [98]. The cost for the EC process can be calculated by given formula 5.

$$C_{\text{op}} = aC_{\text{energy}} + bC_{\text{electrode}} \quad (5)$$

Where a is the energy cost per unit, $C_{\text{electrode}}$ is the energy consumption, b is the cost of the electrode plate, and $C_{\text{electrode}}$ is the electrode consumption. By increasing the applied voltage the cost increases steadily from. The operating cost was calculated as 2.90 US\$ for Al-Ti and 0.87 US\$ for Ti-Al. The results showed that titanium electrode can be used as anode for the effective removal of colour and pollutants due to its low cost. The increase in energy and electrode consumption will lead to an increase in operating cost. The increase in energy, electrode consumption and operating cost with respect to applied voltage is given in Fig. 8.

6. Conclusion

This work investigates the use of two sets of electrodes (Al-Ti and Ti-Al) in the EC method for treating textile

wastewater. The study assessed the impact of various operational parameters, such as pH, applied voltage, reaction time, and electrolyte concentration, on the elimination of pollutants from textile dyeing effluent. The results showed that both sets of electrodes removed colour and pollutants from textile dyeing wastewater in a comparable way. When the Al-Ti electrodes were used at pH 8, 12 V, 1.5 g/L electrolyte concentration, and 20 minutes of reaction time, the maximum colour removal efficiency obtained was 97.13. Using a Ti-Al electrode at pH 7, 10 V, 20 minutes of reaction time, and 1 g/L of electrolyte concentration, 96.8% color removal was reported. The FTIR analysis showed the formation of intermediate compounds and the removal of pollutants. The removal of pollutants in both sets of electrodes are similar. Other parameters such as TSS, TDS, COD and EC were also eliminated effectively in both conditions. However, electrode consumption while using Ti as anode is less than using Al as anode which clearly explains the high dissolution of aluminium. XPS investigations showed that the process was less expensive when using Ti-Al because more hydroxides developed at 10 V voltage as opposed to 12 V for Al-Ti. It was discovered that the two electrodes operating costs differed by 70%. Titanium exhibits improved catalytic activity and lower operating costs, making it a promising electrode material for textile dyeing effluent treatment.

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Ethical Approval

This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

Authors Contributions

Authors have equally contributed in preparing the paper.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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