An Attempt to Reduce the Electrocoagulation Costs and to Ensure the Reuse of Treated Aqueous Dye Solution

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ABSTRACT

In most of the research works, similar metal electrodes were used, resulting in high operating costs, and the reuse of the treated water was not explored. The major goal of this research is to lower the cost of the electrocoagulation (EC) process by employing electrodes made of different metals and to investigate whether it is possible to reuse the water that has been treated by doing so. It was done to optimize the operational parameters such as pH, voltage, time, electrolyte, and dye concentrations. The energy and electrode consumption was calculated as 0.29 kWh.m^{-3} and 3.5×10^{-2} kg.m^{-3}, respectively. The HPLC and LC-MS studies shows the degradation of dye and the formation of intermediary compounds, which were less toxic. The sludge obtained from the EC process was subjected to EDX and XPS analysis to know the composition of metals and the formation of metal hydroxide coagulants. The phytotoxicity of the treated water after EC was examined using *Trigonella foenum-graecum* seeds. The results showed an utmost color removal efficiency (CRE%) and COD removal of 99.78% and 92.86% with an operating cost of US\$ 0.028, which is comparatively 98.12% lower than the other conventional electrodes. The treated toxicity test of water was comparable to the toxicity test of tap water.

INTRODUCTION

All living things primarily depend on water. Nowadays, as the water bodies which are the sources for drinking water and agricultural purposes are getting polluted at a high rate due to the release of contaminants from industries, the scarcity of water has emerged as one of the biggest issues in the world. The wastewater can come from textiles (Kim et al. 2002), food (Sengil & Ozacar 2006), poultry slaughterhouses (Bayramoglu et al. 2006), cosmetic and pharmaceutical (Boroski et al. 2009), paper (Katal & Pahlavanzadeh 2011), paint (Akyol 2012) and various other industries too. But the textile dyeing industry greatly contributes to water pollution (Sharma & Uma 2011). This is because these industries ingest high volumes of water in their fabricating process, such as dyeing and finishing. In the dyeing stage, innumerable dyes are used, eventually giving out a wide range of colors so that the effluent's attributes vary greatly (Gurses et al. 2002).

The most widely used dye in the dyeing units, azo dyes, makes up more than 50% of the commercially available dyes. The next widely used group is the anthraquinone dyes (Holkar et al. 2016). Around 10,000 commercially available dyes are produced annually, and 7×105 tonnes of dye-related materials (Rai et al. 2005). Coraline Rubine GFL, an azo dye, has an annual fabrication rate of about 70%. And 370 thousand metric tons of dyes and pigments are being produced globally (Tony et al. 2009). A mixture of acids, pesticides, salts, pigments, and heavy metals constitutes textile wastewater (Pensupa et al. 2017). Most synthetic dyes and their intermediary compounds may be poisonous, mutagenic, carcinogenic, or teratogenic to the environmental species (Wang et al. 2019, Maron & Ames 1983).

Due to their disorganization, an extensive quantity of dyestuff has been sent out from the industries during the dyeing process. These dyes may easily be distinguished because of their capacity to absorb light in the visible region, even at very low concentrations of around 1 ppm (Holkar et al. 2016). These dye particles avert the sunlight's permeation into the water, constricting the photosynthetic activity of the aquatic plants and decreasing the dissolved oxygen in the water bodies, possibly affecting the marine animals. This is because the dyes easily absorb and reflect

the light (Solis et al. 2012, Mansour et al. 2011). As these dyestuffs undergo biodegradation, many aromatic amines are formed, responsible for the momentous lethal effect on living organisms. Most aromatic amines are found to be suspect cancer factors (Chung 2016). Even before cleaving into aromatic amines, certain azo dyes seem carcinogenic. But this carcinogenicity is due to the other cleaved product known as benzidine, which is a causative agent for plenty of tumors. P-phenylenediamine (p-PDA), another dye constituent, is a contact allergen (Graca et al. 2001). Reports on the negative impact of anthraquinone and triphenylmethane dyes are also seen in the literature (Cui et al. 2016, Sharma et al. 2004, Cheriaa et al. 2012).

Therefore, an urgent need arises to treat these wastewaters by conventional technique. The common methods adopted for the treatment are biological (Wu et al. 2019), chemical oxidation (Azbar et al. 2004), electrocoagulation (EC), electroflotation (Rajeshwar et al. 1994), activated charcoal adsorption, chemical coagulation (Slokar & Le Marechal 1998), photocatalytic degradation (Behera et al. 2008), membrane separation (Van der Bruggen et al. 2001, Joshi et al. 2001), Fenton process (Pan et al. 2020), electrodialysis (Shahi et al. 2001), ultrafiltration and ozonation (Lin & Chen 1997) and aerobic or anaerobic digestion (An et al. 1996). Even though all these methods have been known, each has its drawbacks when treating real-time effluent. When the biological treatment method is used, the microorganisms employed in the treatment process get deceased due to a high amount of dye particles (Vlyssides et al. 1999). Secondary water pollution will occur as other chemicals are added to chemical coagulation and oxidation (Azbar et al. 2004). Adsorption with activated carbon (AC) often removes the dye from an aqueous solution. Still, AC regeneration and efficiency are confined to its equilibrium (Low & Lee 1997, McKay 1984). In the photocatalytic process, a pre-treatment is required to prevent the deterioration of the active sites and the detrimental interference of the catalyst used (Ochiai & Fujishima 2012). In the Fenton process, the pH range has to be controlled greatly (Giroto et al. 2006). Other processes like reverse osmosis, ultrafiltration, and other membrane separation techniques have their limitations of high cost and low output (Marcucci et al. 2001, Sridhar et al. 2002, Voigt et al. 2001).

Even though the electrocoagulation process has merits and demerits, it almost suits the processing of textile dyeing effluents compared to other techniques. The equipment used in the EC process is easy to handle, and there is less need for adding chemicals throughout the process (Kobya et al. 2017). Some of their demerits include high electrical energy consumption, restoration of the sacrificial anodes at regular intervals, and passivation could occur due to the development of oxide film on the negative electrode. Sludge is generated when dye contaminants are removed, but less sludge is created in the EC than during flocculation or chemical coagulation procedures (Barrera-Diaz et al. 2011, Moussa et al. 2017).

The primary goal of this work is to remove the dye particles from the simulated Coralene Rubine GFL 200% dye solution using different metal electrodes to lower the overall process' operational costs. Studies have been done on operating parameter optimization, COD removal, operating cost, and color removal efficiency (CRE%). Through the phytotoxicity investigations, attention has also been paid to the treatment dye solution's toxicity assessment and potential for reuse.

MATERIALS AND METHODS

Experiment

The experimentations were done using the simulated dye solutions of Coralene Rubine GFL 200% dye. The characteristics and structure of the dye are specified in Table 1 and Fig. 1.

Table 1: Characteristics of the dye.

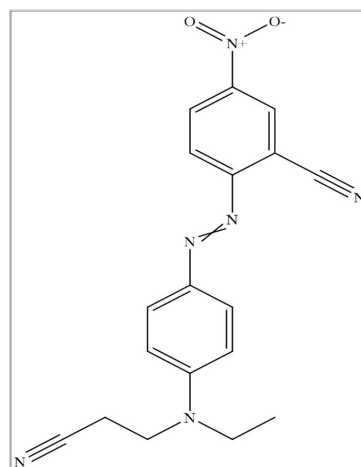| C. I name	Disperse Red 73, Allilon Rubine FL, Chemilene Rubine SE-GFL
Empirical formula	$C_{18}H_{16}N_6O_2$
Molecular weight	348.36
IUPAC name	2-[[4-[(2-cyanoethyl)ethylamino]phenyl]azo]-5-nitro benzonitrile
Melting point	149-150°C
Boiling point	614.2 ± 55°C
Density	1.22 ± 0.1 g.cm^{-3}
Absorption maximum	618 nm

Fig. 1: Structure of the dye.

The aqueous solution of the dye was made with a 110 mg.L^{-1} dye, which required dissolving 0.022 g of dye in 200 mL of double-distilled water. 1 g.L^{-1} (0.2 g) of sodium chloride was added to the simulated dye solution, which acts as an electrolyte and facilitates the movement of ions and formation of flocs. 0.1 N hydrochloric acid was used to make the solution acidic, and to make it alkaline, 0.1 N sodium hydroxide was used. For electrocoagulation, aluminum and copper plates with a length of 9 cm, width of 3.5 cm, and thickness of 0.5 mm were used as an anode and cathode, respectively. The interelectrode distance was kept at about 4 cm. Every experiment was conducted at room temperature using a magnetic stirrer to speed up the movement of ions, and an external DC power supply was used. The area submerged in the solution is about 5.1 cm. Fig. 2 shows the EC setup and simulated dye solution before and after the EC process. The experiments involved changing the pH. (4, 5, 6, 7, 8, 9, 10), voltage (4, 6, 8, 10, 12, 15), reaction time (5, 10, 15, 20, 25, 30 min), initial dye concentration (70 mg.L^{-1} to 130 mg.L^{-1}), and the concentration of electrolyte (0.1, 0.15, 0.2, 0.25, 0.3, 0.35 g) and the color removal efficiency (CRE%) was calculated. After each reaction, the treated dye solution was filtered, and the sludge was air-dried and given for further analysis. The COD digester (HACH DRB 200 Digital Reactor) was used to calculate the COD. The other apparatus required were the COD vials, burette, and 250 mL conical flask. 2.5 mL of the treated dye solution was taken in the COD vial. 0.25 N of standard potassium dichromate ($K_2Cr_2O_7$) solution was added to the sample. Then, the vials added a pinch of mercuric sulfate ($HgSO_4$) and 3.5 mL of concentrated sulphuric acid (conc. H_2SO_4). It was then tightly closed and kept at the COD digester at 150°C for 2 h. It was then allowed to cool down to room temperature and transferred into the conical flask. The burette was then filled with 0.1 N standard ferrous ammonium sulfate (FAS) [$Fe(SO_4)(NH_4)_2$], and 2 drops of ferroin indicator were added to the sample. It was titrated against the FAS solution. The final point was marked by a color change from green to reddish brown, and the COD was determined.

Analytical Methods

UV-Visible Spectrophotometer

The absorption maximum of the dye was measured using a UV-Visible spectrophotometer [JASCO V-650]. From the absorbance values, the color removal efficiency was calculated by the formula,

$$CRE\% = \frac{C_0 - C}{C_0} \times 100 \qquad \dots(1)$$

where,

C_0 is the initial absorbance of the dye

C is the final absorbance of the treated dye solution

Chemical Oxygen Demand (COD)

The COD was calculated for the simulated dye solution and the treated sample with maximum CRE% obtained. It is then compared with the blank, i.e., the double distilled water, and calculated using the formula,

$$COD = \frac{(a-b) \times N \times 8 \times 1000}{Volume\ of\ sample} \qquad \dots(2)$$

where,

a is the volume of FAS consumed for the titration of blank (mL)

b is the volume of FAS consumed for the titration of the sample (mL)

N is the normality of titrant (FAS)

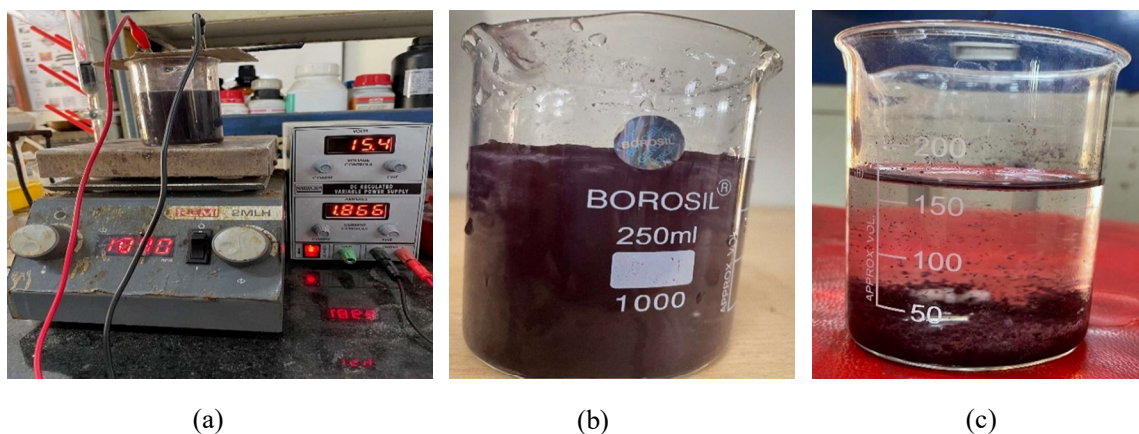8×1000 is the milli equivalent weight of oxygen (mL.L^{-1})

Fig. 2: (a) EC set up, simulated dye solution (b) before EC (c) after EC.

X-Ray Photoelectron Spectroscopy (XPS)

The sludge of the treated dye solution with the highest CRE% of 99.78 (at pH 7, contact time of 15 min, at 4 V, initial dye concentration of 110 mg.L^{-1} and 1 g.L^{-1} of electrolyte concentration) was secluded, air-dried, and investigated for the hydroxides formed during the EC process using X-ray Photoelectron Spectroscopy (XPS). The spectrum was obtained using Al monochromatic light as the source and energy of 1486.6 eV in the Scienta Omicron Nanotechnology by Oxford Instrument.

High-Performance Liquid Chromatography (HPLC)

The HPLC analysis was carried out to determine the number of dye components present in the dye solution before the EC process and the treated sample following the EC process. The Shimadzu SPD-M20A generated the HPLC chromatogram with acetonitrile as the filtrate's solvent.

Liquid Chromatography-Mass Spectrometry (LC-MS)

The plausible degradation of the dye can be studied through the intermediate product peaks formed when the samples are subjected to LC-MS. The simulated and treated dye solutions were analyzed through LC-MS, and the mass spectrum was captured from Shimadzu Japan 2020.

Energy Dispersive X-Ray Analysis (EDX)

During electrocoagulation, the metals used as electrodes may undergo dissolution, and the metal ions may combine with the sludge particles. Therefore, to know the percentage of the elemental composition of the metals in the sludge, the sludge obtained from the EC process was subjected to EDX analysis.

Phytotoxicity Studies

Even a meager concentration of the dyestuffs in the treated water can exhibit a major effect on plant growth and drastically affect the photosynthesis process (Kalivel et al. 2021). In the electrocoagulation process, the dyes are not completely removed. Instead, they form many transitional compounds. These compounds should be less toxic for the plant to attain its normal growth (Kalivel et al. 2020). Therefore, to check the feasibility of reusing the treated dye solution, phytotoxicity studies were carried out with *Trigonella foenum-graecum* seeds. 50 seeds were taken in three different pots.

Fenugreek is an annual plant cultivated worldwide, and India is its largest producer. It can flourish in almost every climatic environment and booms well in places with moderate showers and temperatures. Even though fertile soil is the epitome for its growth, it can also sustain in acidic to neutral soil. Therefore, these seeds were chosen for the studies. An equal volume of tap water (control), simulated dye solution, and treated dye solution with Al/Cu electrodes were taken and watered for about 10 days. The shoot and root length and the germination percentage were calculated for the dye and treated dye solution and was compared with the control. The formula calculated the germination percentage.

$$\textit{Germination percentage} = \frac{number\ of\ seeds\ germinated}{total\ number\ of\ seeds\ sown} \times 100 \qquad \ldots(3)$$

RESULTS AND DISCUSSION

Influence of Operational Parameters on CRE %

The color removal efficiency is largely altered by many operational parameters such as pH, voltage, contact time, electrolyte concentration, initial dye concentration, interelectrode distance, and electrode surface area dipped in the solution. The simulated dye solution was taken, and a few parameters were varied. The maximum CRE% from the optimized results was determined; the findings are in Fig. 2.

Influence of pH

In the electrocoagulation process, one of the key criteria is the preliminary pH of the dye solution (Hutcherson 2015). The pH of the solution affects the electrical conductivity. Therefore, pH, either lower or higher than the optimal range, alters the color removal efficiency of the solution (Canizares et al. 2009). The pH was optimized by varying from acidic to alkaline medium, i.e., 4 to 10. The dye concentration, electrolyte concentration, and voltage were kept constant at 110 mg.L^{-1}, 1 g.L^{-1}, and 15 V, respectively. Fig. 3(a) shows the graph for each pH (4, 5, 6, 7, 8, 9, 10) varying the time (5, 10, 15, 20, 25, 30 min). For pH 4, the CRE% was 97.24 at 5 min; as the time escalated, the CRE% also escalated to 98.95% at 30 min. The same increment in the CRE% was observed for the pH 5, 6, 7, 8, 9, and 10. At pH 5 and 6, the CRE% was 98.72 and 98.25, respectively, at 5 min, and it raised to 99.44% and 99.36% at 30 min. At a neutral pH, the CRE% was 99.62 at 5 min, constantly increasing as the time increased to 30 min. At pH 8, 9, and 10, the same elevation in CRE% was seen. By comparing the CRE% of all the pH at different times, the CRE% was high in acidic and alkaline mediums. But, when the optimal pH is taken as acidic or alkaline, the usage of chemicals to alter the pH will be required. Therefore, the EC process becomes more effective when a neutral medium is taken as an optimal range. For pH 7, the CRE% obtained for time 5, 10, 15, 20, 25, and 30 min are 99.62, 99.68, 99.87, 99.87, 99.87, and 99.89, respectively. The CRE% remains constant for 15 min to 25 min, so the minimal time of 15 min with a CRE% of 99.87 is taken as the best optimum time for the abstraction

of dye from the aqueous solution of the dye.

Influence of Voltage

The time was varied for different voltages to ascertain the optimal voltage for the abstraction of the dye particles from the aqueous dye solution. The experiments were carried out at optimized pH 7 at a time of 15 min and constant initial dye concentration of 110 mg.L^{-1}, and electrolyte concentration at 1 g.L^{-1}. The amount of current given through the DC power supply greatly influences the CRE%. Therefore, the voltage is changed and taken as the varying parameter to achieve a specific electric current. As the voltage was tuned, the corresponding current was also noted. When the electric current increases, the dissolution of the anode also increases, thereby producing a high operational cost. If the electric current is lowered or raised from the optimal value, the CRE% also fluctuates (Yadav et al. 2012, Shankar et al. 2014). The experiments were performed by varying voltage from 4 V to 15 V (4, 6, 8, 10, 12, and 15 V), shown in Fig. 3(b). At 4 V for 5 min, the CRE% was 99.33 and gradually increased to 99.79% at 30 min. The same pattern of change was observed for 6, 8, 10, 12, and 15 V. At the optimized time of 15 min. The CRE% was 99.78, 99.78,

99.78, 99.85, 99.86, and 99.87 for 4, 6, 8, 10, 12, and 15 V, respectively. When the voltage was increased at 15 min, there was no significant difference in the CRE%, so the optimal value was 4 V with the CRE% of 99.78. This shows that, even at a very low voltage, the color removal efficiency was high, yielding a low energy consumption and electrode dissolution.

Influence of Initial Dye Concentration

Given that the coloring chemicals' concentration in the textile industry varies widely, the initial dye concentration also significantly affects the electrocoagulation process (Golder et al. 2006). The experimentations were done by varying the dye concentration from 70 mg.L^{-1} to 130 mg.L^{-1} at constant pH of 7, time 15 min, and 4 V, and the graph is shown in Fig. 3(c). The CRE% decreased as the dye concentration increased. At 70 mg.L^{-1}, the CRE% was 99.84 and decreased to 99.42% at 130 mg.L^{-1}. The CRE% at 110 mg.L^{-1} is 99.78, which showed a slight elevation to the other lower concentrations. So, the optimum initial dye concentration was taken as 110 mg.L^{-1}. This decreasing pattern may be due to the development of intermediary compounds, which may reduce the performance of the electrodes by blocking their active sites (Modirshahla et al. 2007).
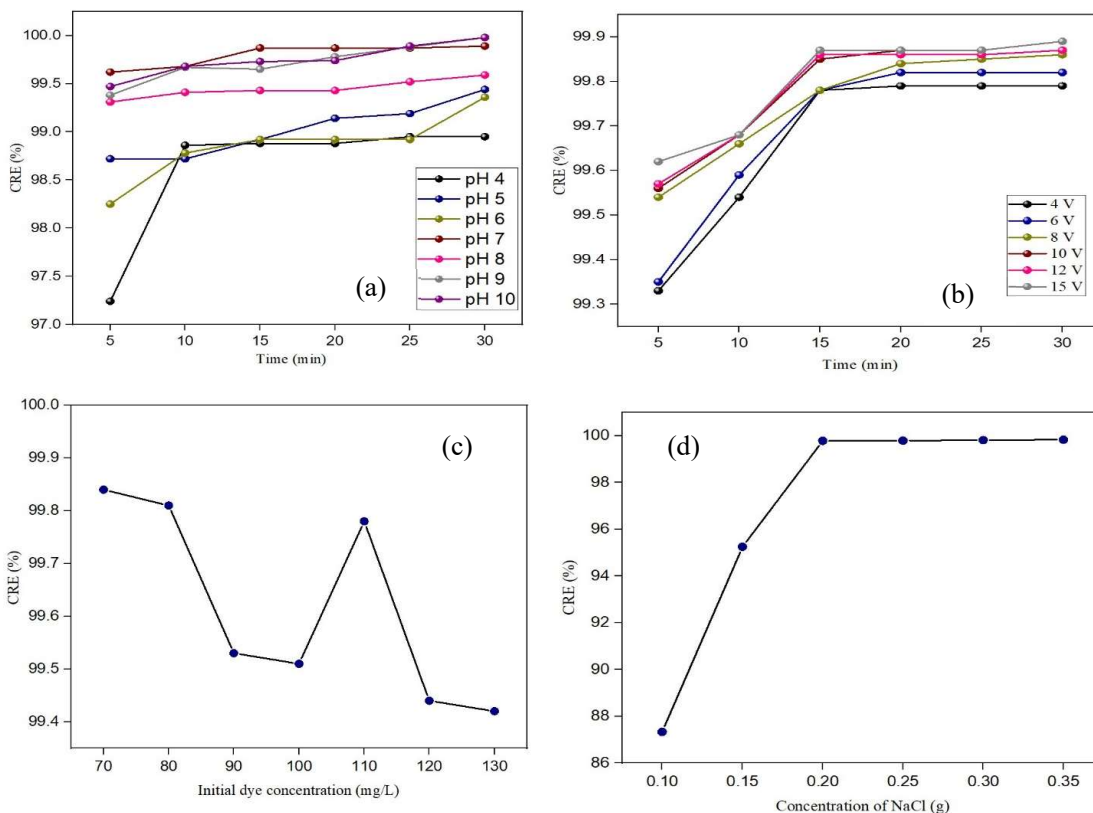

Fig. 3: Effect of CRE% on (a) pH vs. time, (b) voltage vs. time, (c) initial dye concentration, (d) electrolyte concentration.

Influence of Concentration of the Electrolyte

The electrolyte is added to the EC process to facilitate the conductivity and the movement of ions in the solution. The higher the electrolyte concentration, the greater its conductivity and current density. When the strength of the electrolyte is high, the conductivity may increase with the same cell voltage applied (Sengil & Ozacar 2006, Mollah et al. 2001). The experiments were performed using NaCl as an electrolyte by varying its concentration at 0.5, 0.75, 1, 1.25, 1.5, and 1.75 g.L^{-1} (i.e., 0.1, 0.15, 0.2, 0.25, 0.3, 0.35 g) under the optimized conditions of pH 7, 15 min, 4 V and 110 mg.L^{-1} and the graph is shown in Fig. 3(d). The CRE% increased as the concentration of the electrolyte increased. At 0.5 g.L^{-1}, CRE% was 87.33, increasing to 99.83% at 1.75 g.L^{-1}. There were minute differences in the CRE% from 1 g.L^{-1} to 1.75 g.L^{-1}, so the minimum concentration of 1 g.L^{-1} was optimal for the dye removal process.

Economical Parameters

Consumption of Energy and Electrode

The energy and electrode consumption is plotted against different voltages, and the graph is given in Fig. 4(a) and (b), respectively. The plots indicate that the amount of energy and electrode consumed for the EC process increases when the voltage increases. At 4 V for 15 min, the energy consumption and electrode were 0.29 kWh.m^{-3} and 0.035 kg.m^{-3}. When the voltage was tuned constantly (6, 8, 10, 12, 14, 16, 18, and 20 V), an elevation was observed, giving 9.28 kWh.m^{-3} and 0.253 kg.m^{-3} of consumption of energy and electrode, respectively, at 20 V. Therefore, with a very low voltage, a maximum CRE% (99.78) was obtained.
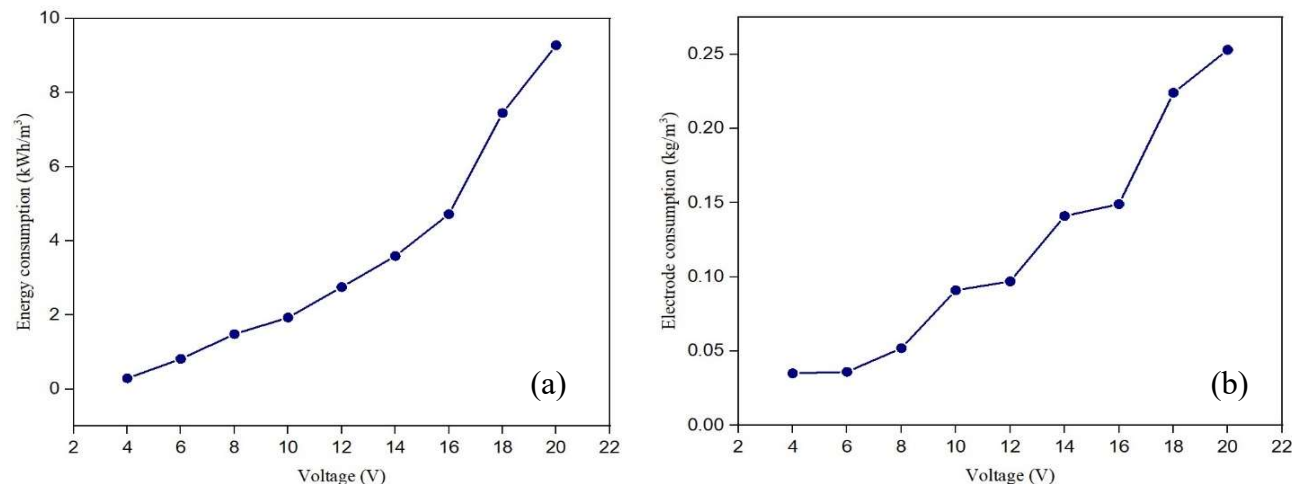
Operating Cost

The operational cost analysis is one of the major economical parameters in electrocoagulation. The cost analysis includes the cost of electrodes, the cost of energy used during the EC process, the cost of the equipment, and other fixed costs. As the equipment used in the EC process is very cost-effective and easy to maintain, the operating cost mainly depends on the other two categories (Daneshvar et al. 2006). The operating cost was calculated using the formula,

Operational cost, $C_{op} = a\ C_{energy} + b\ C_{electrode}$ ...(4)

where,

C_{energy} and $C_{electrode}$ are energy and electrode consumption

a is the cost of current per unit (US$ 0.077)

b is the cost of a single plate of the electrode (US$ 0.13)

The operating cost analysis was done after the optimization of the operational parameters. The cost calculated was around 0.028 US$/m^3. As in the literature, when aluminum and iron electrodes were used, the operating cost was 1.5 US$/m (Bener et al. 2019). Similarly, when aluminum was used as an anode and cathode, the operating cost analysis was reported as 0.7 US$/m^3 (Villalobos-Lara et al. 2021). While using copper sheets as electrodes, the cost reported was 0.803-3.03 US$/m^3 (Shaker et al. 2021). The above data proves that, while using dissimilar electrodes of Al/Cu, the cost is much lower than other conventional electrodes.

EDX Studies

From the EDX analysis of the sludge, it is clear that the metal ion from the anode has been released, which is the main source for the formation of the metal hydroxide coagulants

Fig. 4: Voltage vs. (a), (b) Energy, Electrode consumption.
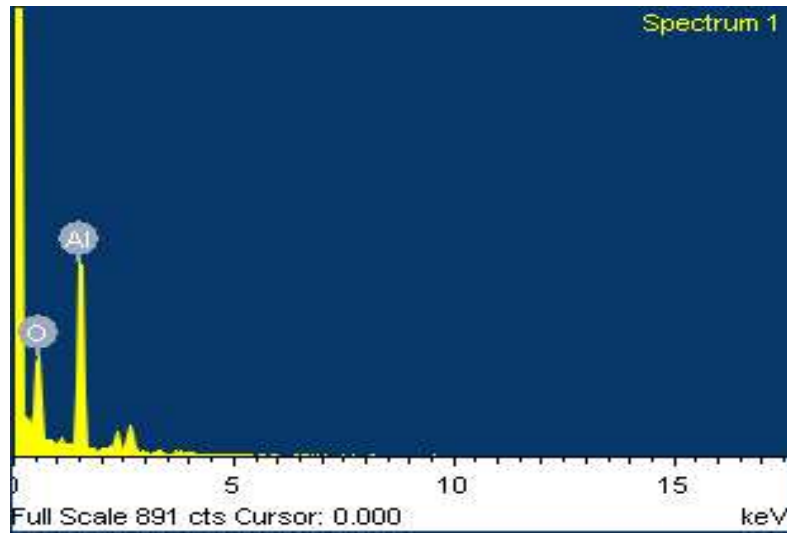
Fig. 5: EDX spectrum of the sludge obtained.

having high adsorbing capacity, which then acts as the floc and binds with the dye components from the simulated dye solution thus producing a clear solution (Chen 2004). From the Fig. 5 EDX graph, 31.38 atomic percentages of aluminum and 68.62 atomic percentages of oxygen are present in the sludge obtained after filtration of the treated dye solution.
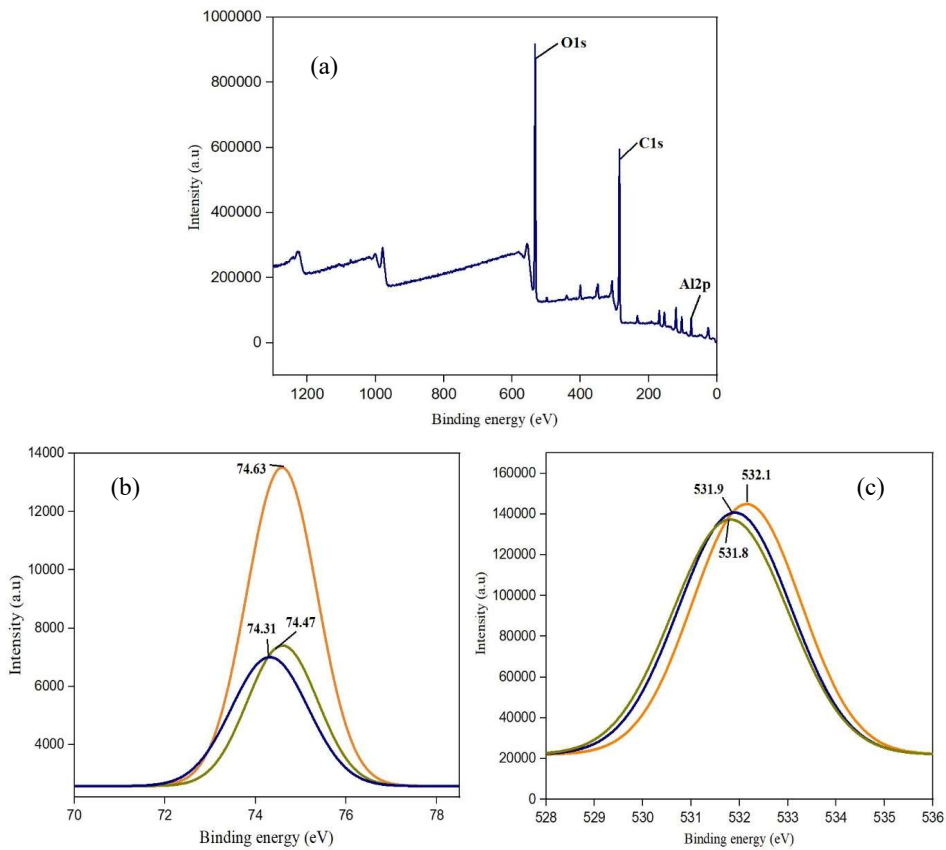

Fig. 6: XPS spectra of sludge (a) core line spectra of Al (b) Al 2p (c) O 1s.

XPS Analysis of Sludge

In electrocoagulation, the metal hydroxide flocs are responsible for the dye removal. More metal hydroxides, if formed, will facilitate high color removal efficiency. The formation of the metal hydroxides can be confirmed from the XPS data of the sludge obtained from the treatment of dye solution using Al/Cu electrodes. Fig. 6 shows the XPS core line spectra. From Fig. 6(b), the formation of Bayerite $Al(OH)_3$ at a binding energy of 74.31 eV, Gibbsite at 74.63 eV, and Boehmite at 74.47 eV were confirmed (Sherwood 1998). From Fig. 6(c), the O1s transitions for the Gibbsite were observed at 531.8 eV, Bayerite at 531.9 eV, and Boehmite at 532.1 eV (Kloprogge et al. 2006). This showed the O-H binding energy, thus substantiating the formation of aluminum hydroxides, enhancing the electrocoagulation process.

HPLC Analysis

The untreated and treated dye solution was subjected to HPLC analysis at the wavelength of about 254 nm from the UV detector. The HPLC chromatograms are shown in Fig. 7. In the chromatogram of the dye solution, three major compounds were formed at a retention time of 1.849, 3.002, and 7.476 min with the percentage area of about 31.685, 37.42, and 25.884 respectively, as shown in Fig. 7(a). After the process of electrocoagulation, the HPLC chromatogram, as in Fig. 7(b), compared with that of the dye, and it was found that the eluted peaks of the dye with a large percentage area decreased drastically from 31.685 to 27.89 at RT 1.849, 37.42 to 5.482 at RT 3.002 and 25.884 to 2.284 at RT 7.476. The other peaks that were eluted at the wavelength of 254 nm in the HPLC chromatogram of the treated dye solution with Al/Cu electrodes were at the retention time of 2.073, 2.24, 2.429, 2.755, 3.374, 4.659, and 5.8 min with percentage area of 24.026, 8.579, 9.502, 1.639, 1.856 and 3.471 respectively. These peaks indicate the bonds were cleaved, and the chromophoric groups present in the dye responsible for its color had been removed and converted into smaller colorless molecules, thus giving a high CRE% of 99.78.
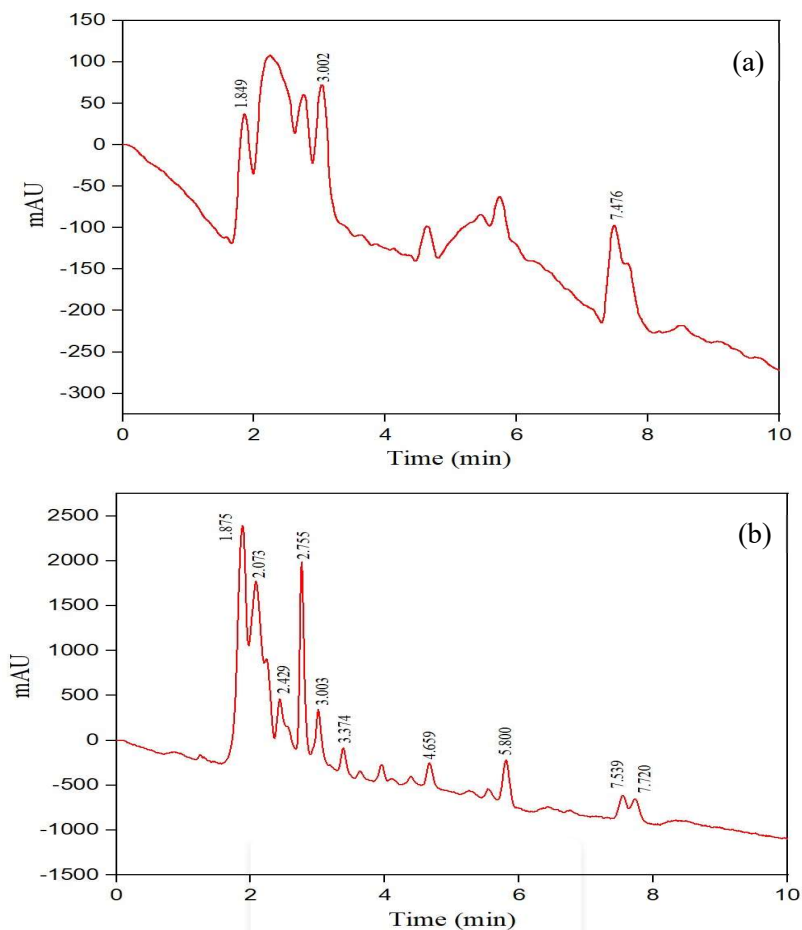

Fig. 7: HPLC chromatogram (a) Dye solution (b) Treated dye solution.

Mass Studies

The mass spectrum of the treated Coralene Rubine GFL was 200% compared to the mass spectrum of the raw dye. Fig. 8(a) shows the mass spectra of the dye, in which it is obvious that the peak that appeared at 347.2 is associated with the actual molecular weight of the dye. The base peak here is the peak that appeared at 726.05, which may be due to the dimer formation of the dye components. The other molecular ion peaks formed at 446.55, 537, 695.3, and 752.25 are due to various organic components responsible for the dye's color. When this is compared with the mass spectrum of the
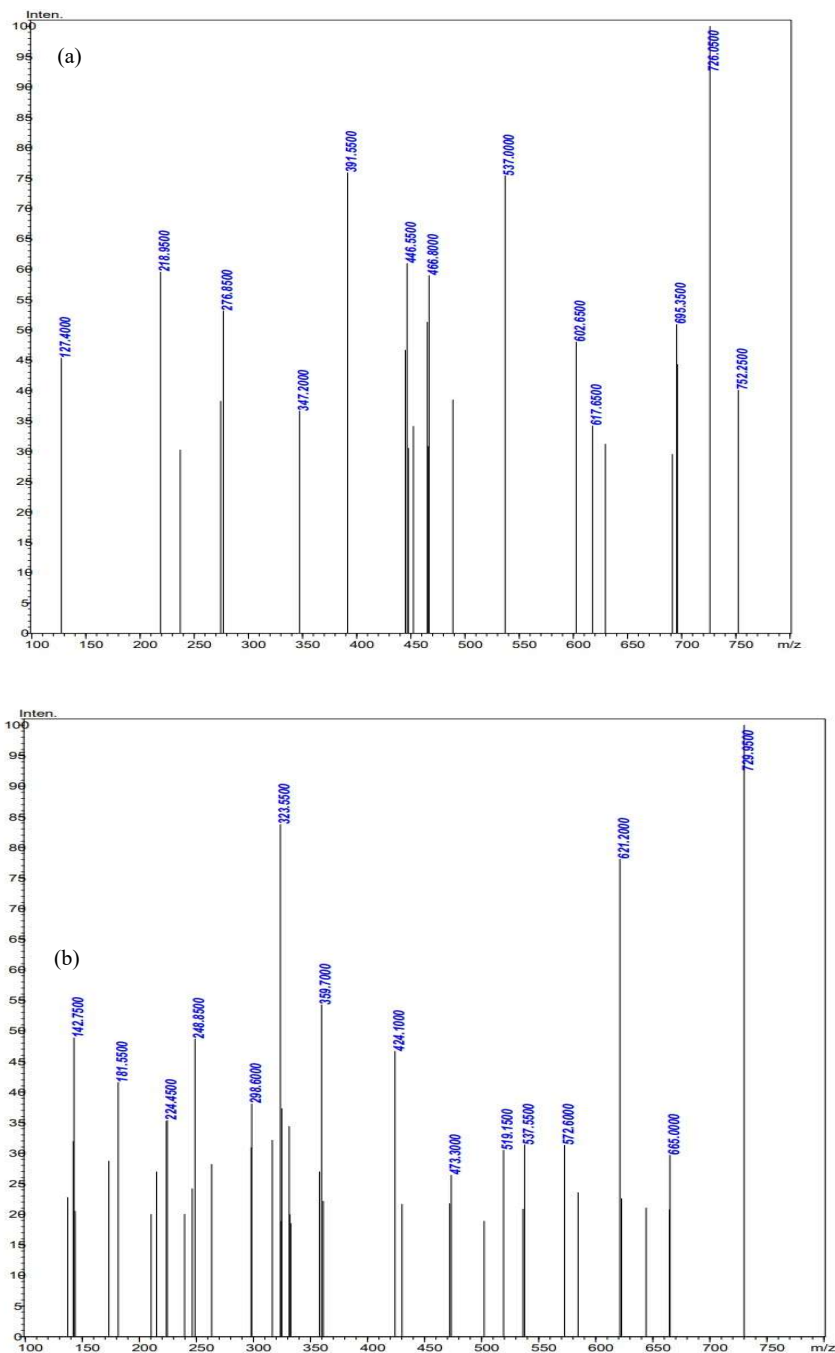

Fig. 8: Mass spectrum (a) Dye solution (b) Treated dye solution.

treated dye solution with Al/Cu electrodes that are shown in Fig. 8(b), it is evident that the peak at 347.2 has disappeared, indicating the cleavage of the bonds in the dye, thus giving other molecular ion peaks. Further, the peaks at 323.55 and 298.6 show the elimination of the cyanide group in the dye, eventually leading to the harmless nature of the treated water. The HPLC analysis also coincides with the fact that the major peaks present before the EC process were decomposed into colorless small molecular weight compounds.

Phytotoxicity Studies

The simulated dye solution was treated by electrocoagulation to remove the dye components. During this process, many intermediary compounds may be formed, which may or may not be toxic. Therefore, to evaluate the toxic levels in the dye solution treated using Al/Cu electrodes and the untreated Coralene Rubine GFL solution, *Trigonella foenum-graecum* was taken for the studies. These were compared with the control, i.e., tap water. Fig. 9 shows the phytotoxicity images. The length of the root and shoot in the control and treated dye solution was almost similar, as shown in Fig. 9(a) and (b). The length of the root for the control and treated dye solution was found to be 10.5 cm and 9 cm, respectively.

Similarly, the shoot length for the control and treated dye solution was 16.2 cm and 15.8 cm. Fig. 9(c) shows the image of the plant in the dye solution, with the root and shoot

length of 4 cm and 9.4 cm, respectively. The germination percentage was calculated for control, untreated, and treated dye solutions, which were found to be 99%, 50%, and 96%, respectively. Table 2 shows the parameters such as germination percentage, root length, and *Trigonella foenum-graecum* shoot. From these studies, it is conspicuous that the length of the root and shoot of the control and treated dye solution with Al/Cu electrodes is very similar compared to the dye solution, thus indicating that the intermediary compounds are non-toxic to the environment.

CONCLUSION

The present work analyzes the efficacy of the EC process for eliminating dye components from the simulated dye solution using Al/Cu electrodes. Under the optimized pH 7, 15 min, and 4 V, the maximum CRE% of 99.78 and COD removal of 92.86% were obtained. The EDX analysis proved the anodization of the electrode, which paved the way for forming metal hydroxide flocs. The HPLC analysis indicates the degradation of the dye, thus forming intermediary products which are not lethal. The mass analysis shows the cyanide removal, which approves the removal of toxic nature in the treated water. XPS studies using the sludge established the formation of aluminum hydroxide coagulants making the EC process effective. The phytotoxicity and ecotoxicity studies affirm that the treated water is not noxious and thus can be reused. Compared with the literature, the cost

Table 2: Parameters of *Trigonella foenum-graecum*.

Parameters	Control	Untreated Coralene Rubine GFL solution	Treated Coralene Rubine GFL solution with Al/Cu
Germination percentage [%]	99	50	96
Length of the shoot [cm]	16.2	9.4	15.8
Length of the root [cm]	10.5	4	9

(a)   (b)   (c)

Fig. 9: Growth of *Trigonella foenum-graecum* in (a) Tap water, (b) treated dye solution, (c) untreated dye solution.

of electrocoagulation using Al/Cu electrodes was 98.12% lower, indicating this process's cost-effectiveness. Therefore, this method may remediate dye effluents in small dying textile operations.

ACKNOWLEDGEMENTS

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