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Experimental study on electrocoagulation of textile wastewater by continuous horizontal flow through aluminum baffles

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Abstract–We investigated the feasibility of applying a continuous textile wastewater (TWW) treatment, which was accomplished by using electrocoagulation (EC) unit with zigzag horizontal flow across a series of mono-polar aluminum plate baffles. The effects of operating parameters such as current density (20-80 A/m^2) and detention time (5-40 min) on turbidity, color, chemical oxygen demand (COD), total suspended solids (TSS) and total dissolved solids (TDS) removal were studied. The optimum conditions were determined as 60 A/m^2 and 20 min by monitoring zeta potential (ζ) of effluent. At the optimum conditions, removal efficiencies for turbidity (97.63%), color (87.87%), COD (93.3%), TSS (94.02%), and TDS (52.13%) were observed. Further, addition of 4 mg/L of NaCl dose in the TWW modified conductivity suitably, thereby reducing electrical energy consumption per cubic meter of waste water and specific electrical energy consumption (SEEC) from 13.33 to 2.67 kWh/m^3, and 23.84 to 4.77 kWh/kg Al, respectively. Comparing the EC with conventional coagulation process, EC showed better pollutant removal efficiency.

Keywords: Electrocoagulation, Continuous Flow Unit, Textile Wastewater, Aluminum Baffles, Zeta Potential

INTRODUCTION

Textile industries consume considerable amounts of water and produce nearly the equivalent in wastewater. The textile wastewater consists of strong color, suspended particles, non-biodegradable materials as well as high chemical oxygen demand (COD). So, it has the potential to cause severe water pollution. Further, the textile wastewater is likely to contain chemicals that are toxic, carcinogenic, and mutagenic to various microbiological or animal species. Therefore, an appropriate treatment of the textile wastewater is inescapable prior to its discharge into a river to comply with effluent standards set by the regulatory authorities.

Photo-oxidation by UV/H_2O_2 or UV/TiO_2 calls for supplementary chemicals and, therefore, may also cause a secondary pollution. Although the biodegradation process is cheaper than other methods, it is less effective because of the toxicity of the dyes, which induces an inhibiting effect on bacterial development. At present, electrocoagulation (EC) has drawn considerable attention, being a simple, efficient and eco-friendly process [1-3]. Several authors applied batch as well as continuous mode EC process to remove colloids, COD and TSS from TWW. According to Zodi et al. (2009), higher removal of pollutants is achieved at higher current densities and lower flow rates with higher energy consumption. In the EC process, generally, iron (Fe) or aluminum (Al) electrodes are used, and at optimum conditions, removal efficiencies by Al are found to be higher than that of Fe [4,5].

García-García et al. (2015), successfully used solar cells for EC of industrial waste water [16]. So, the EC process possesses potential to be obviously sustainable technology, if solar energy is used. Majority of earlier works reported that EC technology was dependable due to high quality of effluent, reasonable initial cost, easy operation and maintenance, no need of chemicals, and ability to deal with variation in the waste streams. However, it is essential to explore the EC process to determine design and operating parameters, as the same are yet to be established. However, the continuous mode of the EC process has been less investigated with dependable design for commercial success, except in a few studies [2,6]. The present study deals with continuous mode EC process using dependable design of EC reactor. EC reactor design adopted in the present study can be suitable for use on field scale. Further, in the present study real textile wastewater is used for evaluating the EC reactor.

The electrode material used in EC process is aluminum. The main reactions are as follows:

$$\text{Anode: } Al(s) \rightarrow Al^{3+} + 3e^- \quad (1)$$

$$\text{Cathode: } 3H_2O + 3e^- \rightarrow \frac{3}{2}H_2(g) + 3OH^- \quad (2)$$

Al^{3+} and OH^- ions generated by electrode reactions (1) and (2) react to form various monomeric species, which finally transform into $Al(OH)_3(s)$ according to complex precipitation kinetics:

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3^+ + 3H^+ \quad (3)$$

Freshly formed amorphous $Al(OH)_3(s)$ "sweep flocs" exhibit large surface areas which are beneficial for a rapid adsorption of soluble organic compounds and for trapping colloidal particles. Finally, these flocs are removed easily from aqueous medium by sedimentation and, flotation induced by the H_2 bubbles generated at the cathode [6,7], which is referred to as electro-flotation.

Our main objective was to study the applicability of continuous mode EC in removal of pollutants from characteristic wastewater of a cotton textile factory. Continuous EC process was carried out

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in the horizontal baffled wall EC cell characterized by simpler electrode geometry than that reported in earlier works [8,9]. Experiments were conducted to examine the effects of wastewater pH and operating parameters, such as current density and detention time on removal efficiency of color, COD, turbidity, TSS and TDS to optimize the operating conditions of EC process pursuing maximum removal of pollutants, and optimal consumption of energy as well as electrodes. The degree of destabilization can be monitored more precisely through zeta potential (ζ) measurements. So, ζ measurements of electrically coagulated effluent were applied to optimize operational parameters such as current density and detention time.

Table 1. Characteristics of textile wastewater

Parameter	Value (±variation)
pH	7.31±0.35
Temperature (°C)	30±3.2
Conductivity (mmho/cm)	3.3±0.2
Turbidity (NTU)	320±80
COD (mg/L)	2240±220
BOD_5 (mg/L)	330±40
TSS (mg/L)	1910±210
TDS (mg/L)	2700±200
Zeta potential (mV)	−27.9±−10.2

MATERIALS AND METHODS

1. Wastewater

In this study, textile wastewater (TWW) from a cotton textile factory at Ichalkaranji (India) was treated by EC. TWW was collected carefully from equalization tank holding neutralized TWW and strained through sieve mesh - 1.7 mm to remove insoluble coarser particles. The collected TWW was kept closed at 0 °C until its use. The TWW effluent was sampled each week for four months. The characteristics of TWW based on 20 samples are presented through the average values and ±variation (Table 1).

2. Experimental Setup

The lab scale experimental setup constructed and operated in the study is shown schematically in Fig. 1. The continuous-flow system consists of a feed tank (50 L, capacity), EC unit of Flexi glass, Settling tank, DC power supply, Floc collector and Effluent collector. The TWW is pumped into the EC unit containing 12 Al electrode plates (10×1×13.5 cm). The six electrode plates are intended to act as anodes, whereas the other six electrode plates are to function as cathodes. Inter-electrode gap between the electrode plates is kept constant at 1cm throughout the study. The electrodes were connected in monopolar mode to a laboratory DC power supply (Make: Aplab -7162) characterized by 0-25 A for current and 0-35 V for voltage. One of the vertical sides of each electrode plate is attached to flexi glass bolt section (1×1×13.5 cm). The flexi glass holding sections having height of 1.5 cm is fixed 12 cm above the bottom of the EC unit. The electrode plates are held in the holding sections placed alternatively on vertical walls of EC unit as shown in the Fig. 2(a) and 2(b). This arrangement helps in easy removal of electrode plates from EC unit for washing, cleaning and

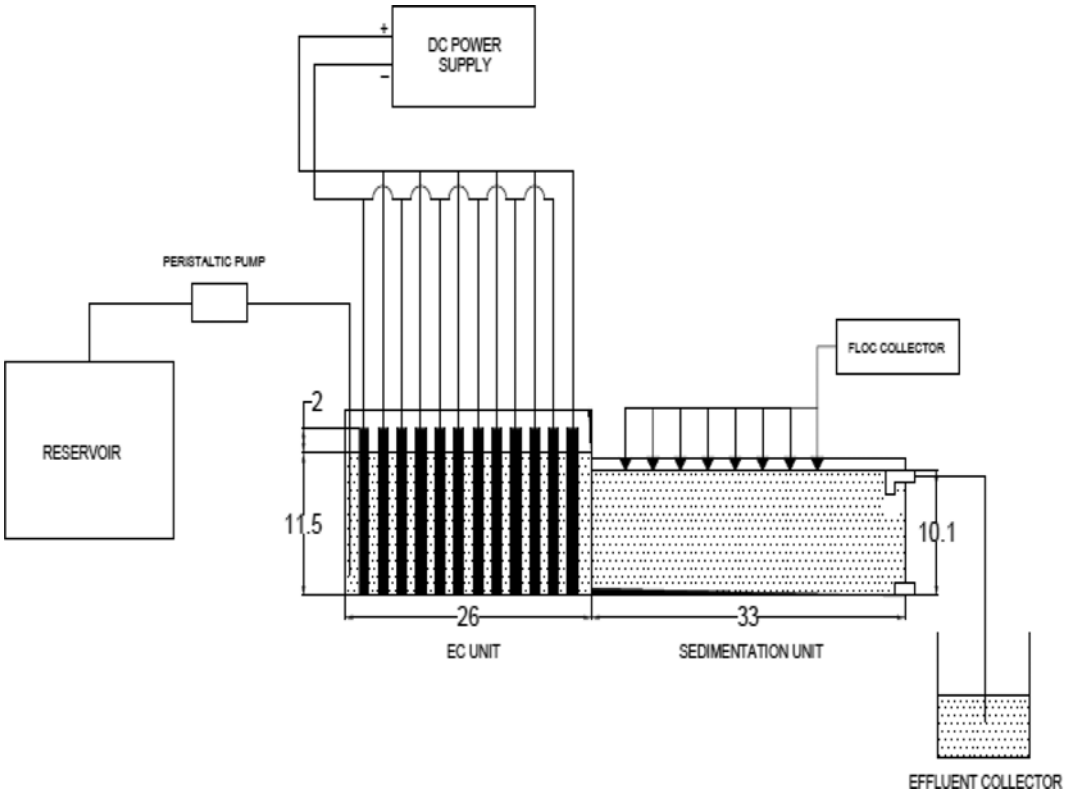

Fig. 1. Typical experimental setup.

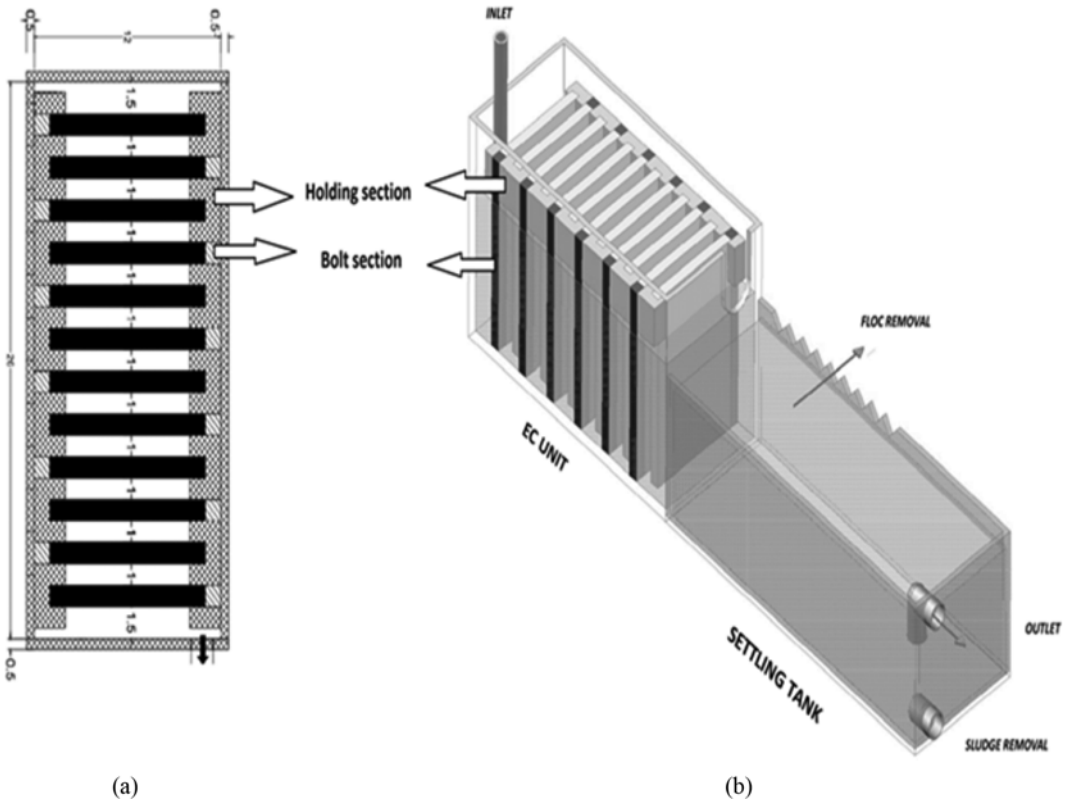

Fig. 2. (a) Plan of EC unit (b) perspective view of EC unit and settling tank.

weight measurement. This arrangement of electrodes in EC unit makes them act as baffle walls, resulting in horizontal zigzag flow through them. The pattern supported enhanced mixing in the EC unit, due to the liquid flow and H_2 micro-bubbles produced. So, in fact the micro-bubbles formed at electrodes, the liquid phase and the solid particles flowed all together in this EC unit. The formation of H_2 micro-bubbles was large enough due to large surface area of electrodes. In fact this fostered a homogeneous dispersion of the gas phase and the liquid phase and further promoted floc removal by electroflotation in the settling tank. The EC unit having effective volume of 2 L is attached with settling tank of 4 L. A peristaltic pump is used to control the flow rate of the influent.

3. Experimental Procedure

The EC experiments were carried out on TWW samples, in continuous mode. Each sample was feed to the EC unit through feed tank with predetermined flow rates to avail detention times of 5, 10, 15, 20, 25, 30, 35 and 40 min. For every detention time, different current densities varying between 20-80 A/m^2 were applied. After the EC process, the effluent leaving the EC unit was drawn in the settling tank and was provided with detention time of 30 min. The heavy solids settled at the bottom of settling tank and the floating flocs got removed off through the notches provided at the top edge of one of the vertical walls of the settling tank and were collected in the floc collector. Supernatant from the settling tank was collected in effluent collector and was tested for usual characteristics. All the runs were performed at room temperature.

The electrodes were removed from EC unit and washed neatly with tap water, prior and subsequent to every run. Then electrodes were placed back in the unit and HCl solution (5% v/v) was poured and kept in the unit for 20 min. Then the unit and electrodes were again washed with water neatly. The weight of each electrode was noted, before and after every run.

4. Analytical Method

The samples for influent and effluent of the lab treatment unit were routinely collected and tested for their characteristics. pH and conductivity were measured by digital pH Meter (Systronics, 335) and conductivity meter (Systronics, 304) respectively. A turbidity meter (HACH, 2100 Q) was used to measure turbidity. Color was measured by absorbance of each sample at the wavelength of 360 nm with UV-VIS Spectrophotometer (HACH, DR 6000). COD (Closed Reflux Method), TSS and TDS (gravimetric analysis) were also calculated for every sample. Zeta potential for every sample was measured by Zeta-Meter System 4.0 (Zeta-Meter, Inc. U.S.A.).

The removal efficiency was calculated as,

$$\text{Removal efficiency } (\%) = \frac{(C_o - C)}{C_o} \times 100 \quad (4)$$

where, C_o and C are, respectively, the initial and final turbidities, absorbance of sample, concentration of TSS, TDS and COD before and after EC process.

The current performance is an important parameter that affects the overall electrode life in the EC process. Electrical energy consumption (C_{energy}) and specific electrical energy consumption (SEEC) are essential parameters in the EC process to rate the cost economics. Current efficiency can be calculated as [10]:

$$\varphi = \frac{\Delta M_{exp}}{\Delta M_{th}} \times 100, \quad (5)$$

where, ΔM_{exp} is the experimental weight loss of Al (g). The theoretical amount of Al (ΔM_{th}) released into solution by electrolytic oxidation of the anode was estimated from the Faraday's law [11]:

$$\Delta M_{th} = \frac{I \cdot t \cdot M}{z \cdot F}, \quad (6)$$

where, I is the current (A), t is the detention time (s), M is the molecular weight of Al (26.98 g mol^{-1}), z is the number of electrons involved in the reaction, and F is Faraday's constant (96500 C per mole of electrons). The experimental amount of Al (ΔM_{exp}) released into wastewater by electrolytic oxidation of the anode was estimated by the weight difference of electrodes for each run.

The specific electrical energy consumption (SEEC) is calculated as a function of aluminum electrodes weight consumption during EC process in kWh/kg Al [10]:

$$SEEC = \frac{z \cdot F \cdot U}{3600 \cdot M \cdot \varphi} \quad (7)$$

The C_{energy} of the EC unit for treating the wastewater is calculated in (kWh/m^3) as [4]:

$$C_{energy} = \frac{U \cdot I \cdot t}{v}, \quad (8)$$

where, U is the cell potential (V) and v is volume of sample treated, in m^3.

RESULTS AND DISCUSSION

1. Effects of Current Density and Detention Time

Current density applied at electrodes, and inlet flow rate values in continuous EC system are the vital parameters influencing the performance and economy of electrocoagulation process. To study the effects of current density, and detention time, different experiments were conducted for EC by varying current density and detention time. The observed removal efficiencies for turbidity, color, COD, TSS and TDS for different current densities and detention time values are shown, respectively, in Fig. 3, Fig. 4, Fig. 5, Fig. 6, and Fig. 7. The results show the favorable effect of current density and detention time on EC process.

Fig. 3 shows that for the lowest current density, 20 A/m^2, the removal efficiencies were poor up to a detention time of 25 min. In this case, turbidity removal increased from 26.52% to 97.55% when detention time was increased from 5 min to 40 min. When the flow rates decreased, the turbidity removal efficiency increased for the same current densities since the quantity of dissolved aluminum per unit volume was higher. The removal efficiency was above 97% for detention time of 30-40 min at 60-80 A/m^2. It is understood that the removal efficiency increases with current density and detention time [12]. It is because the sufficient amount of Al^{3+} cations are released at higher current density resulting in enough formation of $Al(OH)_3$, which ultimately boosts coagulation and flocculation.

Fig. 4 shows the efficiency of EC in removal of color from TWW. The color removal efficiency is enhanced with current densities of 20 to 60 A/m^2 and detention time of 5 to 40 min. It is due to the adsorption of flocs to the produced coagulant and hydrogen microbubbles. The current densities of 70 A/m^2 and 80 A/m^2 ensued the

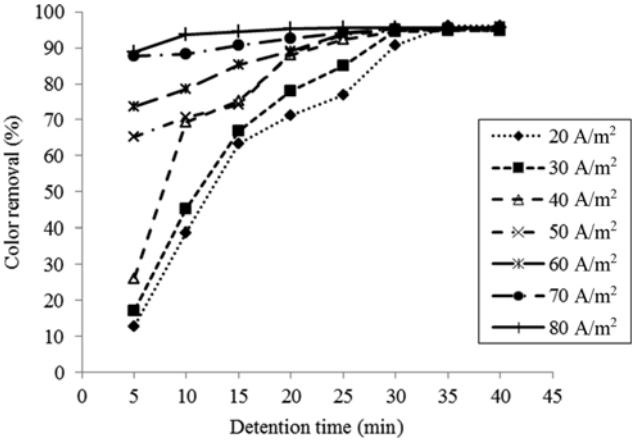

Fig. 4. Effect of current density on color removal for varying detention time values.

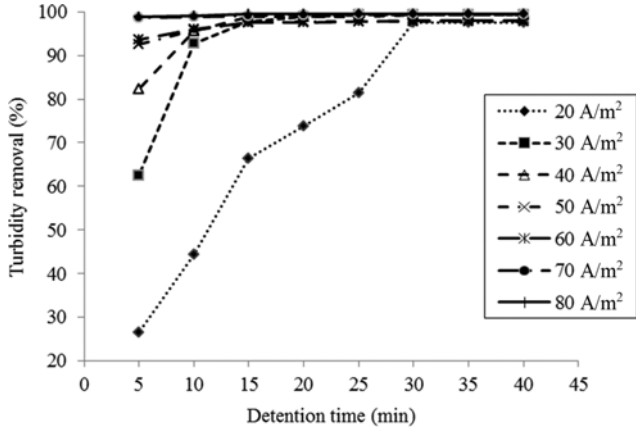

Fig. 3. Effect of current density on turbidity removal for varying detention time values.

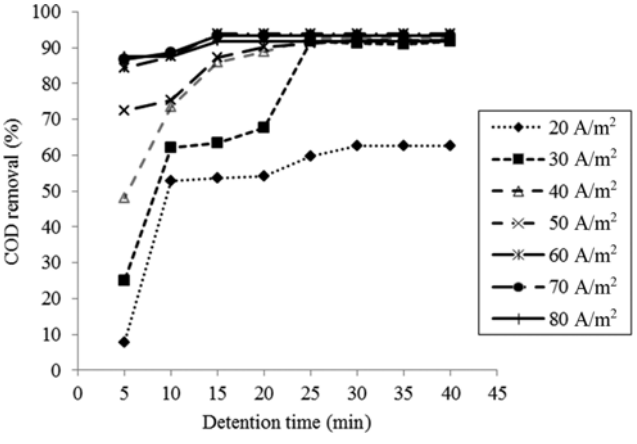

Fig. 5. Effect of current density on COD removal for varying detention time values.

higher color removal of 87.5% and 86.67% at detention time of 5 min, and 93.32% and 93.67% at detention time of 40 min respectively. So, it can be inferred that at higher current densities, it is possible to achieve considerable color removal even at lower detention time.

Fig. 5 shows that COD Removal was significant for current density from 60 A/m^2 to 80 A/m^2 with varying detention times of 5 min to 40 min. For the current density of 20 A/m^2, COD removal was relatively less due to lesser production of $Al(OH)_3$ and H_2 microbubbles, and the failure in attachment of oxidizable chemicals to $Al(OH)_3$ particles. Current density determines the coagulant dosage, and size of the bubble production, and hence affects the growth of flocs [5,13].

TSS removal efficiency was 19.19% at 20 A/m^2 and 92.02% at 80 A/m^2 for detention time of 5 min (See Fig. 6). As per expectations when the current density increases for fixed detention time, the amount of Al^{3+} cations released by an anode increases and therefore amount of $Al(OH)_3$ coagulants also increases [7].

TDS removal efficiency for EC process is shown in Fig. 7. Highest TDS removal achieved was 62.75% at current density of 80 A/m^2, for 40 min. TDS removal was above 60% for detention time 30 min-40 min at 70 A/m^2, and 25 min-40 min at 80 A/m^2. The reason for the observation is the hydrogen gas liberated at the cathode helped to float the contaminants, which influenced the removal of TDS.

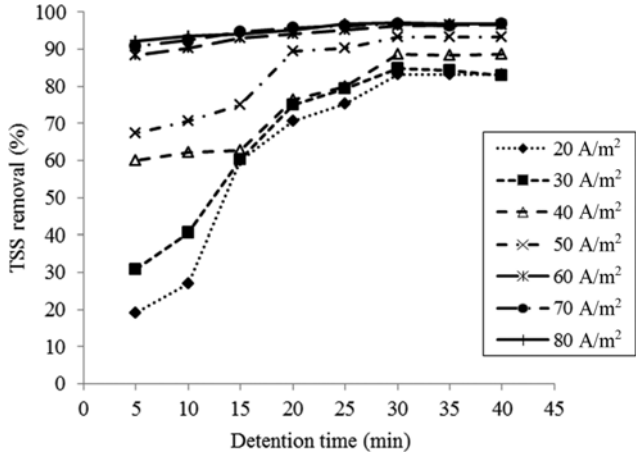

Fig. 6. Effect of current density on TSS removal for varying detention time values.

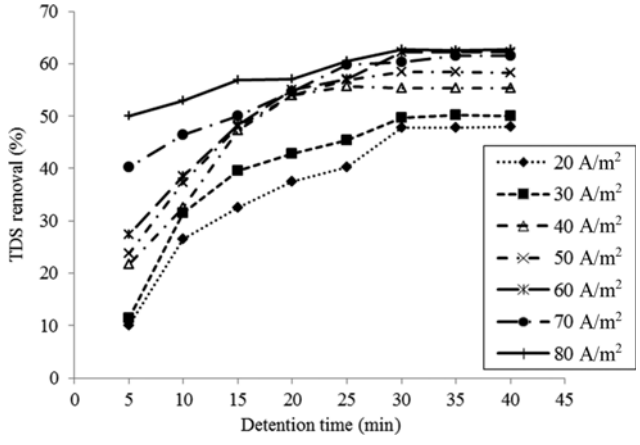

Fig. 7. Effect of current density on TDS removal for varying detention time values.

2. Selection of Optimal Current Density and Detention Time

It was observed that at higher current densities and detention times, the removal efficiency of pollutants was higher. However, for higher values of current density, there was marginal increase in removal efficiencies with increase in detention time (See Fig. 3-7). The working at high current densities and detention times results in significant consumption of the electrode material. Further, energy consumption rises as the square of current density value and induces heating by Joule effect [7]. For lower detention times the volumes of EC unit as well as metal electrodes required would be too large. So, optimization of current density and detention time is indispensable.

The ζ being the precise tool to rate destabilization of coagulated flocs, ζ measurements of EC effluent were carried out. It is known that degree of destabilization increases as ζ approaches to zero. So, the operating conditions that produce EC effluent with ζ closer to zero would be the optimal in order to maximize the removal.

Observed ζ values for EC effluent for different detention times and current densities are shown in the Fig. 8. As is evident, at lower detention times, poorer formation of coagulants causes lower destabilization of particles, and so, more negative ζ values of EC effluent

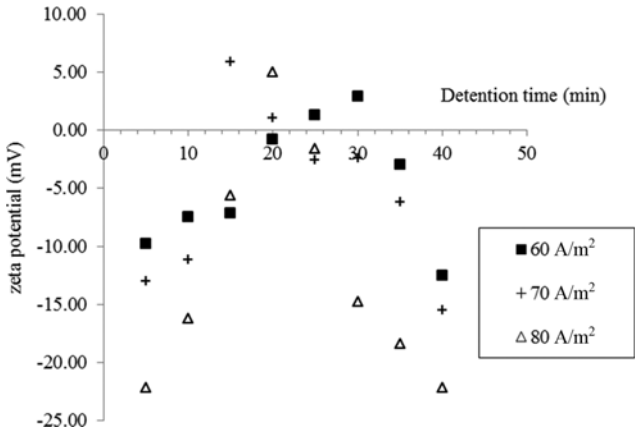

Fig. 8. Variation of zeta potential with time for different current densities.

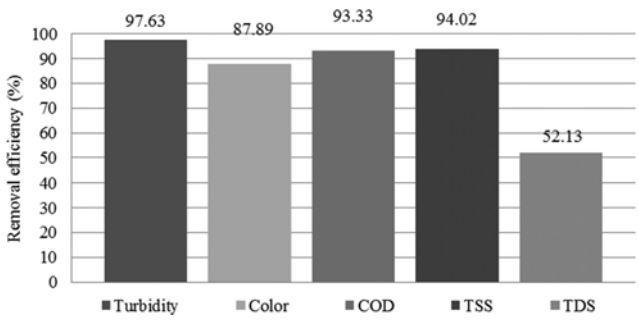

Fig. 9. Pollutant removal at optimum operating conditions.

Table 2. Effects of NaCl concentration on conductivity, voltage drop, and removal of color, COD and TSS

NaCl concentration (mg/L)	Conductivity (mmho/cm)	Voltage drop (V)	Removal efficiency (%)		
			Color	COD	TSS
0	3.5	20	96.1	93.2	95.2
0.5	4.5	17	95.6	91.5	90
1	5.5	12	95.8	91.5	92.2
1.5	6.5	9.8	95.1	91.2	93.7
2	7.5	8	95	92.3	96.3
2.5	8.5	6.3	94.2	90.1	96.5
3	9.5	5.1	95.6	93.2	95
3.5	10.5	4.8	95.5	91.6	96.8
4	11.5	4	95.9	91.2	93.2
4.5	12.5	4	95.1	91.7	90.1
5	13.5	4	95	92.2	95.3

were observed. Optimum detention time and current density were selected as 20 min and 60 A/m^2, respectively, corresponding to the lowest ζ (−0.82 mV) observed. Pollutant removal efficiencies observed at optimum operating conditions, i.e., current density of 60 A/m^2 and detention time of 20 min, are shown in Fig. 9.

3. Effects of Wastewater Conductivity

Effect of wastewater conductivity on color, COD, and TSS removal was investigated by adding NaCl as electrolyte at current density of 60 A/m^2 having 20 min detention time. The NaCl was added to TWW in different doses. Conductivity, voltage drop as well as removal efficiencies observed are listed in Table 2.

No significant change was observed in color, COD and TSS removal due to addition of NaCl. However, by adding NaCl concentration, the variation of wastewater conductivity affected the energy consumption (C_{energy}) (see Fig. 10). C_{energy} decreased from 13.33 kWh/m^3 to 2.67 kWh/m^3 with increasing NaCl concentration from 0 mg/L to 4 mg/L. Similarly, SEEC also decreased from 23.84 kWh/kg Al to 4.77 kWh/kg Al for the same NaCl concentration variation. Increase in NaCl concentration caused an increase in the ion concentration in the sample, thereby reducing the resistance between the electrode sheets. So, increase in NaCl concentration decreased the required voltage and reduced the power consumption. However, the dose of NaCl used as an electrolyte was too small to increase the overall TDS of TWW significantly.

Though, few earlier works report trivial change in power consumption due to addition of NaCl to waste water to be treated [1,14], in the present study for real life TWW, it was found to be significantly helpful to reduce the power consumption. It would be because of less initial conductivity of the TWW used in the present study.

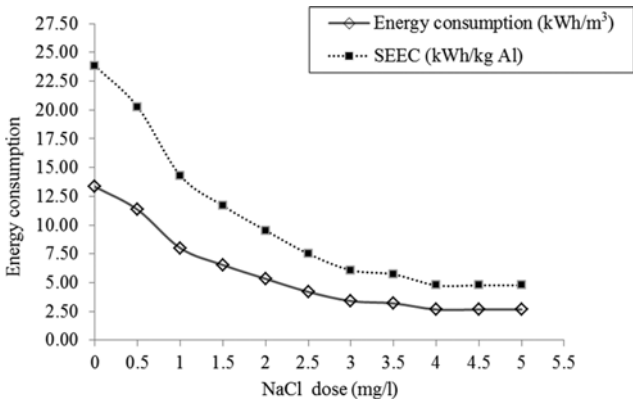

Fig. 10. Variation of C_{energy} for Al electrode with the NaCl dose (optimum condition: current density: 60 A/m^2, time: 20 min).

4. Comparison with Conventional Coagulation Process

Conventional coagulation treatment was performed using aluminum hydroxide ($Al_2(SO_4)_3 \cdot 18H_2O$) as coagulant, to find the optimal coagulant dose using jar test. Optimal coagulant dose observed was 1,250 mg/L. The EC process and conventional coagulation process were compared under the optimal conditions previously determined. The results of these tests are summarized in Table 3.

During TWW treatment by conventional coagulation process the pH increased to 9.2, which is comparatively more alkaline than the EC-treated effluent having pH 8.45. Color removed in the EC process was 95.9%, which is fairly higher than the conventional coagulation process. Turbidity removal recorded in both the processes was above 87%, but the EC process was relatively higher: 99.21%. Considerable difference was observed in COD, TSS and TDS reduction in both the processes, since the floc formation rate is relatively higher in EC. Moreover, these flocs have porous and tenuous structures which are prone to reformation and compaction [15]. So, it can be said that the EC process can remove the

Table 3. Comparison between conventional coagulation treated effluent and EC treated effluent

Parameters	Textile wastewater effluent	
	EC treated	Conventional coagulation
pH	8.45	9.2
Color removal (%)	95.9	72
Turbidity removal (%)	99.21	87.4
COD removal (%)	93.3	41.1
TSS removal (%)	94.64	38
TDS removal (%)	50.10	9.7

pollutants from wastewater with higher efficiency, compared to the conventional coagulation process.

CONCLUSION

A series of experiments were performed to find the effects of operating parameters, namely current density and detention time for turbidity, TSS and TDS removal, COD reduction and decolorization of textile wastewater by electrocoagulation under steady-state conditions. Results emphasize the opportunity to apply a compact model of continuous EC process for the efficient removal of pollutants from wastewater. The following conclusions can be drawn:

- Compact continuous EC process demonstrated in the present study was found significantly effective.
- At optimal operating parameters, i.e., current density of 60 A/m^2 and detention time of 20 min for EC of wastewater observed removal efficiencies for turbidity, color, COD, TSS, and TDS were (97.63±0.5%), (87.87±0.5%), (93.3±0.5%), (94.02±0.5%), and (52.13±0.5%) respectively.

The conductivity of the influent being treated by EC governs the energy consumption. The reduction in energy consumption was possible by addition of NaCl as an electrolyte. For the optimum operating condition, C_{energy} and SEEC decreased from 13.33 kW·h/m^3 to 2.67 kW·h/m^3 and, 23.84 kWh/kg Al to 4.77 kWh/kg Al, respectively, by addition of 4 mg/L of NaCl dose in the TWW.

Electrochemical coagulation shows better pollutant removal efficiency than conventional coagulation process for textile wastewater treatment.

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NOMENCLATURE

C : current concentration of a given pollutant
C_o : initial concentration of a given pollutant
C_{energy} : electrical energy consumption
F : Faraday's constant
Q : detention time [L/h]
M : molecular weight of Al (26.98 g/mol)
t : detention time [min]
U : voltage potential
z : number of electrons involved in reaction
ζ : zeta potential [mV]

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