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Operational Cost Analysis for the Treatment of Various Textile Effluents by Electrochemical Process Using Stainless Steel and Aluminum Electrodes

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ABSTRACT: *Development of treatment processes from laboratory scale to industries involves a lot of troubles due to the automation of process parameters and fluctuated characteristics of wastewater. In the present study, six different real-time textile effluents of samples such as S1 to S6 are characterized and treated by electrocoagulation process using Stainless Steel (SS) and Aluminum (Al) electrodes. The maximum removal efficiencies of color as 94%, turbidity as 99%, Chemical Oxygen Demand (COD) as 84% and Biological Oxygen Demand (BOD) as 82% is obtained for effluent sample S1 with fixed operational conditions such as the applied voltage of 4V, inter-electrode distance of 3 cm, the surface area of the electrode of 25 cm^2 and agitation speed of 500 rpm respectively. After the electrocoagulation process, the BOD$_5$/COD ratio of all effluent samples is observed as biodegradable limits. Under the fixed conditions, the operational cost for the treatment of effluent sample S1 analyzed as 2.42 and 1.01 \$/m^3 by using SS and Al electrodes respectively.*

KEYWORDS: *COD; Cost; Electrocoagulation; Electrodes; Textile effluents.*

INTRODUCTION

Indian textile industry plays a major role in the total export (14%) with market size of around US\$108 billion which is expected to reach US\$141 billion by 2021. India owns 2nd place in the production of the largest number of spindles, jute, cotton, silk and cotton exports in the world [1]. The production of textile fabrics creates a large quantity of wastewater with different characteristics through the textile processing steps likely the sizing of fabrics generated wastewater with Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The next step of desizing is carried out with waxes, enzymes, and starch that cause BOD and turbidity in effluents. After desizing, the fabrics are scoured with glycol esters that produce high COD contaminated wastewater. Bleaching of fabrics is executed with H_2O_2, sodium silicate, organic stabilizer, and surfactants; these chemicals cause COD, chloride and metal ions in wastewater. After bleaching, the fabrics are mercerized with alkaline solutions such as NaOH and cotton wax and this step produces high pH, COD and Total Dissolved Solids (TDS) in wastewater. The most important textile processing step is dyeing that has been applied for fibers with different types of dyes, salts, surfactants, urea and soda ash. The wastewaters from dyeing unit possess high

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color, COD, BOD, TDS and hardness. Finally, the fabrics are subjected to several items of washing and finishing of fabrics with resins, formaldehyde, PVA (polyvinyl alcohol) and waxes which cause COD and suspended solids in wastewater [2, 3].

In the textile dyeing process, the selection of dyes is varied concerning fibers. Likewise, wool and nylon fibers are dyed with acid and pre-metalized dyes. Cotton and viscose fibers are dyed with azoic, reactive, direct, pigments, vat and sulphur dyes. Polyester and acrylic fibers are dyed with dispersing and modified acrylic dyes [4]. *Ghosh* (2002) has reported that 70% of the water available in India is polluted and it causes water-borne diseases [5].

Numerous treatment methods are used to remove pollutants from textile industry wastewater such as adsorption [6], photocatalysis [7], photo Fenton, Fenton like [8, 9] and biological treatment methods [10]. Few researchers only dealt with the operational cost for the treatment of textile wastewater for either one or two samples. Among this electrocoagulation process gains attention from researchers due to its simple, compact size and easy operational mode. The electrocoagulation process stated as the generation of metal hydroxides from sacrificial electrodes is held by the passage of direct electric current in the electrolytic solution. These metal hydroxides react readily with pollutants present in wastewater. The generation of metal hydroxides from iron (Fe) and aluminum (Al) are shown in following Equations (1-4) [11],

Reactions at SS electrodes

At anode surface,

$$Fe \rightarrow Fe^{2+} + 2e^- \tag{1}$$

At cathode surface,

$$2H_2O + 2e^- \rightarrow H_{2(g)} + 2OH^- \tag{2}$$

Reactions at Al electrodes

At Anode surface,

$$Al \rightarrow Al^{3+} + 3e^- \tag{3}$$

At cathode surface,

$$3H_2O + 3e^- \rightarrow \frac{3}{2}H_{2(g)} + 3OH^- \tag{4}$$

In the existing studies, the textile wastewater is treated by electrocoagulation process through the variation of key process parameters and the color, COD, TOC and turbidity removal efficiencies are analyzed for the treatment of textile wastewater [12, 13]. In the present study, different textile effluents are collected at different industries and time, which are subjected to the electrocoagulation process using two different electrodes (SS and Al) at fixed conditions which are based on our previous studies [14, 15] such as the applied voltage of 4V, inter-electrode distance of 3 cm, the working volume of 0.3L and stirring speed of 500 rpm except for current intensity and time. The results are analyzed physicochemical characteristics of effluents such as color, turbidity, COD and BOD removal efficiencies, economic parameters of energy and electrode consumption, sludge production and operational cost.

EXPERIMENTAL SECTION

The electrocoagulation reactor setup is shown in Fig.1, which consists of DC power supply (Scientific mes-Technik Private Limited) and the reactor is made up of glass by the volume of 0.5L. The metal plates of SS (304) and Al (HE-18) are purchased with the dimensions of 15 x 5 x 0.1 cm and the surfaces of the plates are cleaned with sandpaper, rinsed with dilute HCl and water. During the process, the electrodes are dipped 25 cm^2 into the effluents. The textile effluents are collected before the treatment from different textile dyeing industries in State Industries Promotion Corporation of Tamil Nadu (SIPCOT), Perundurai, which is located at longitude 77°33’22” E and latitude 11°13’14” N. The chemicals used in the current study are purchased from Merck. A standard method[16] is utilized for characterizing textile effluents. The Physico-chemical characterization of textile effluents is shown in Table 1.

The color, COD, BOD and turbidity removal efficiencies (Y %) are calculated using the following formula.

$$Y(\%) = \frac{(x_0 - x_t) \times 100}{x_0} \tag{5}$$

Where x_0 and x_t are the initial and final concentration of color (Pt-Co), COD (mg/L), BOD (mg/L) and turbidity (NTU).

Energy (kWh/m^3) and electrode consumption (kg/m^3) of removal of pollutants from textile wastewater is calculated by Equations (6-7).

Table 1: Physico-chemical Characterization of six untreated textile effluents.

Water quality parameters	Sample No					
	S1	S2	S3	S4	S5	S6
pH	9.77	9.29	9.47	9.75	8.93	9.82
Conductivity (mS/cm)	12.9	20.1	17.3	12.7	14.7	18.5
COD (mg/L)	940	1470	1560	820	2420	2240
BOD (mg/L)	450	448	629	389	606	692
Color (pt-Co)	857	1217	1338	929	1015	1250
TDS (mg/L)	6811	16400	12700	6959	10920	15400
Turbidity (NTU)	394	666	350	104	530	416
Chloride (mg/L)	3850	7595	3535	3725	5535	5970
Sulphate (mg/L)	290	564	1100	377	1180	644
SS (mg/L)	500	1810	780	350	1600	890

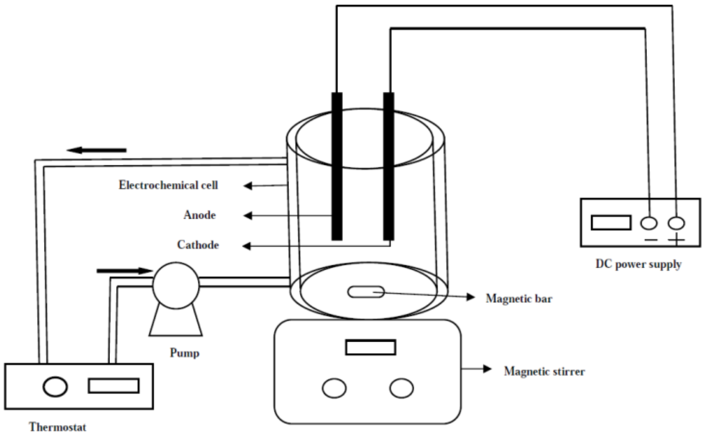

Fig. 1: Schematic diagram of electrocoagulation reactor.

$$\text{Energy consumption}=\frac{UIt}{\nu} \tag{6}$$

$$\text{Energy consumption}=\frac{MIt}{nF\nu} \tag{7}$$

Where *U* is the applied voltage (V), *I* is the current intensity (amps), *t* is the time taken for the process, *v* is the volume of the reactor (L), *M* is the atomic weight of Fe/Al, *n* is the number of electrons (Fe=2, Al=3) and *F* is the Faraday's constant (F=96485.32 coulombs).

The Specific Electrical Energy Consumption (SEEC) (kWh/kg M) is measured by using Equation (8).

$$\text{SEEC}=\frac{nFU}{3.6\times10^{3}\,M\varphi} \tag{8}$$

where φ is the current efficiency which is calculated by following Equation (9),

$$\varphi=\frac{\Delta m_{exp}}{\Delta m_{th}}\times100 \tag{9}$$

Δm_{exp} is the experimental electrode consumption and Δm_{th} is theoretical electrode consumption [17].

RESULTS AND DISCUSSION

pH and conductivity variation in different effluents

The pH and conductivity of untreated and treated samples are shown in Figs. 2 & 3. The pH of untreated samples is observed to be alkaline nature. After the electrocoagulation process, the pH of the treated samples is in higher alkaline nature than the untreated sample

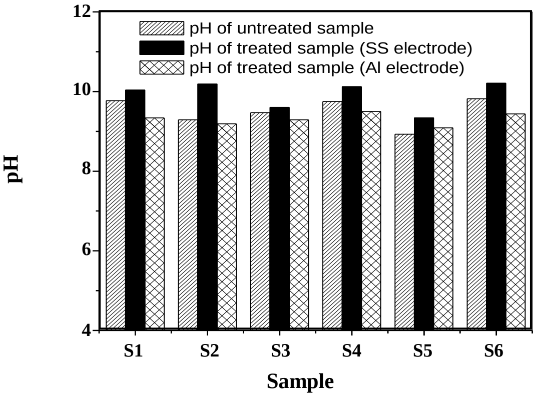

Fig. 2: pH variation of six effluents before and after electrocoagulation process.

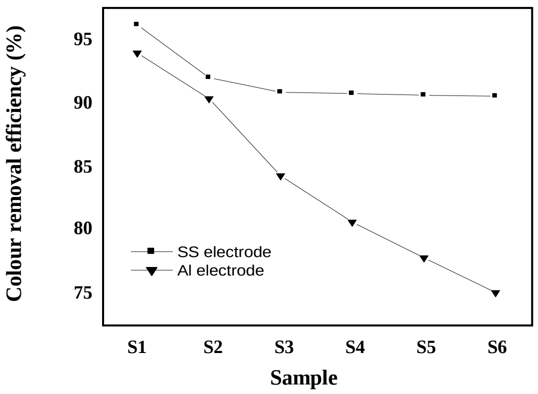

Fig. 4: Color removal efficiency of SS and Al electrodes in the removal of six textile effluents.

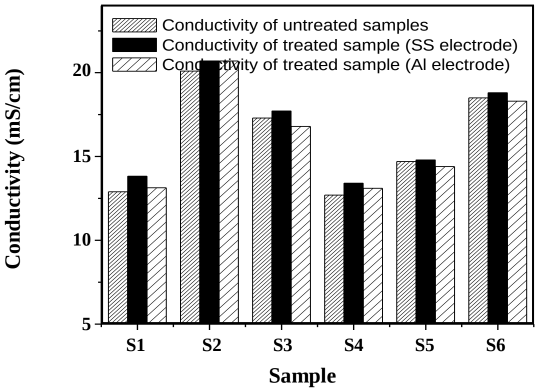

Fig. 3: Conductivity variation on six effluents before and after the electrocoagulation process.

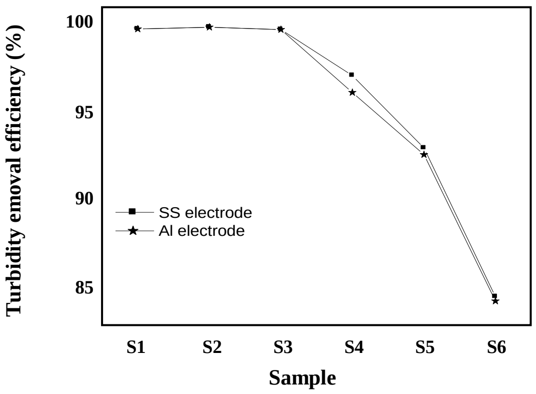

Fig. 5: Turbidity removal efficiency of SS and Al electrodes in the removal of six textile effluents.

when using SS electrodes; it is due to the generation of hydroxyl ions and the evolution of hydrogen ions [18]. In the case of Al electrodes, the pH of the treated samples is observed to be 9 due to the buffering capacity of Al3+/Al(OH)3(aq) system regardless of the initial pH of untreated samples. [19]. The treated samples are observed to be of a high conductivity than untreated samples in all the six effluents because of the formation of charged species of organic and inorganic compounds. From these results, in the industrial level during the automation of the treatment process, the neutralization of treated effluents is comparatively easier for Al electrodes than SS electrodes.

Removal of color and turbidity from textile effluents

The color and turbidity removal efficiency of the electrocoagulation process by the treatment of six different colored effluent samples of S1 to S6 is shown in Figs. 4 & 5. The color and turbidity removal efficiency of SS electrodes is observed in the range of 98.16 to 90.56% and 99.74 to 84.61% for effluent samples S1 to S6 respectively. Similarly, in the case of Al electrodes, 93.97 to 75.12% and 99.74 to 84.34% of color and turbidity removal efficiency are achieved. The highest color removal efficiency of S1 is due to its low color intensity than the other samples (857 Pt-Co). From these results, SS electrodes are found to show better color and turbidity removal efficiency than Al electrodes and the results are consistent with the other researches [13, 20]. The mitigated color and turbidity removal efficiency is observed in Al electrodes due to the generated polymeric hydroxides ($Al_{13}O_4(OH)_{24}^{7+}$) precipitated as $Al(OH)_{3(S)}$. The effluent pH is >9, then the $Al(OH)_{3(S)}$ is converted as $Al(OH)_4^-$ and it is settled as an amphoteric $Al(OH)_3$ which has low adsorption capacity [19].

Table 2: BOD_5/COD ratio.

Sample No	Untreated effluent	After electrocoagulation process	
	BOD_5/COD ratio of untreated effluent	BOD_5/COD ratio of treated sample with SS electrodes	BOD_5/COD ratio of treated sample with Al electrodes
S1	0.48	0.63	0.53
S2	0.31	0.60	0.57
S3	0.40	0.67	0.60
S4	0.47	0.60	0.50
S5	0.25	0.50	0.42
S6	0.31	0.63	0.40

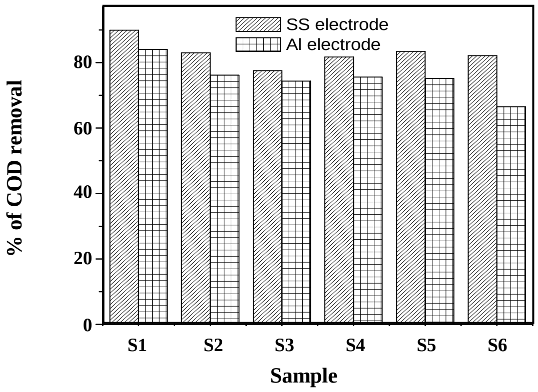

Fig. 6: COD removal efficiency of SS and Al electrodes in six the treatment of textile effluents.

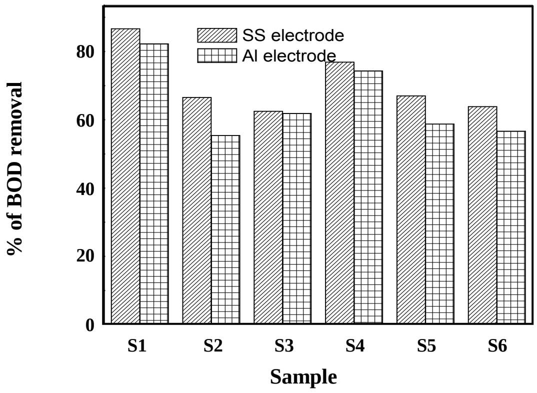

Fig. 7: BOD Removal efficiency of SS and Al electrodes in the treatment of six textile effluents.

Removal of COD and BOD from textile effluents

Various processing steps are involved in textile dyeing and finishing processes use detergents, softeners, emulsifiers, thickeners, dyes, and inorganic salts. These chemicals are discharged with high levels of COD and BOD. The efficiency of the electrocoagulation process on the treatment of different textile, effluent samples are analyzed with COD and BOD. The removal efficiency of COD and BOD of effluent samples S1, S2, S3, S4, S5, and S6 are shown in Figs. 6 and 7. The highest COD and BOD removal efficiency is achieved in S1 for both the electrodes which might be the presence of easily degradable compounds. In the case of S3, the COD and BOD removal efficiencies are observed to be approximately 74% due to the presence of more biodegradable compounds as evidenced by the BOD_5/COD ratio given in Table 2. In COD removal efficiency, S3 and S6 show the lowest removal efficiency than the other samples for both the electrodes due to the presence of heavy pollutants than the other samples. The higher removal of COD and BOD is in SS electrodes than Al electrodes due to the synergistic effect of electrocoagulation and electro-oxidation of textile effluents with the help of chlorine ions and it would support the production of more ferrous/ferric hydroxides (Equations (10) to (12)) to give pronounced performance efficiency [21]. The variation of COD and BOD removal efficiency in both the electrodes is due to the electrodes which follow different removal mechanisms and they are affected by interferences. As seen from Table 2, initially, the textile effluent BOD_5/COD ratio shows that the samples are less biodegradable. After the electrocoagulation process, the biodegradability of the treated samples gets increased in both the electrodes supporting that this process is eco-friendly and the treated effluents are easily subjected to biological treatments.

$$2Cl^- \rightarrow Cl_2 + 2e^- \qquad (10)$$

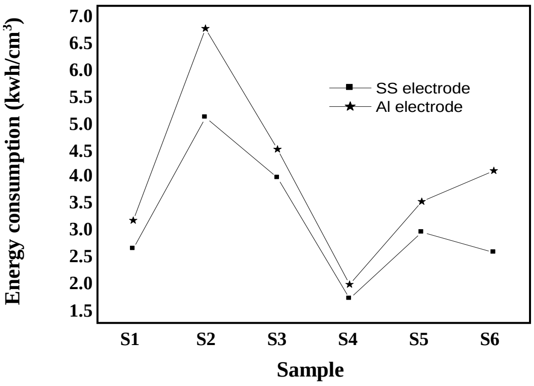

Fig. 8: Energy consumption of SS and Al electrodes in the treatment of six textile effluents.

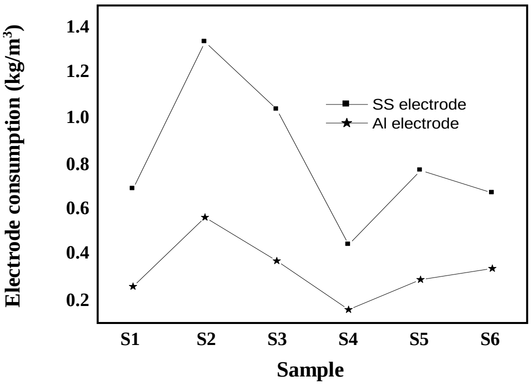

Fig. 9: Electrode consumption of SS and Al electrodes in the treatment of six textile effluents.

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- \quad (11)$$

$$Fe(OH)_2 + HOCl \rightarrow Fe(OH)_{3(s)} + Cl^- \quad (12)$$

Energy and electrode consumption for the treatment of textile effluents using electrocoagulation process

Energy and electrode consumption are the key economic parameters in industries. So, the economical relevance of the electrocoagulation process for six different textile effluents is analyzed in the current study. The energy and electrode consumption have varied concerning the textile effluent samples S1, S2, S3, S4, S5 and S6 which are observed as 2.67, 5.13, 4.00, 1.73, 2.98 & 2.60 and 3.20, 6.80, 4.53, 2.00, 3.56 & 4.13 kWh/m^3 of energy consumption for SS and Al electrodes respectively as shown in Fig. 8. The electrode consumption is observed as 0.69, 1.33, 1.04, 0.45, 0.77 & 0.68 and 0.27, 0.57, 0.38, 0.17, 0.29 & 0.37 kg/m^3 of wastewater for SS and Al electrodes as shown in Fig. 9. Comparatively, Al electrodes show more energy consumption while SS electrodes show high electrode consumption. Sample S2 shows high energy and electrode consumption among all the effluents in both the electrodes. The high electrode consumption of SS electrodes is due to the high electrochemical equivalent mass of iron (18.59 mmol/Ah) than Al (12.43 mmol/Ah) [22]. According to Faraday's law, the SS electrodes (Fe) generate more coagulant than Al at the same electrical charge and remove more pollutants from wastewater. The Specific Electrical Energy Consumption (SEEC) and sludge production after the treatment are shown Figs. 10 & 11. Al electrodes show more SEEC and sludge production than SS electrodes. It is due to the high current intensity passed at the same voltage in Al electrode than SS electrodes and generated

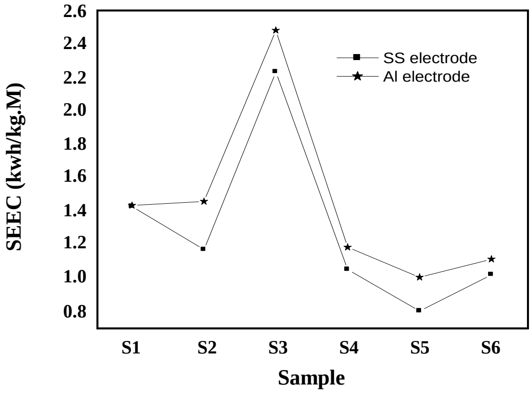

Fig. 10: SEEC of SS and Al electrodes in the treatment of six textile effluents.

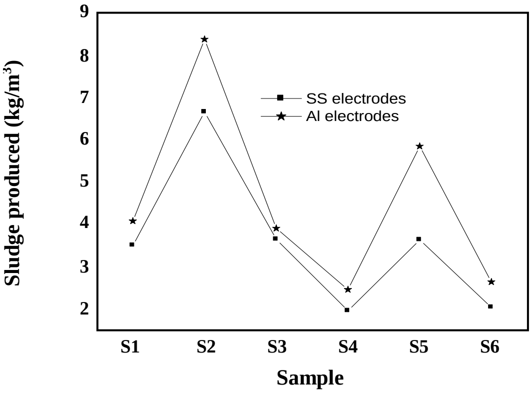

Fig. 11: Sludge production of SS and Al electrodes after the treatment of six textile effluents.

Table 3: Comparison of the efficiency of electrocoagulation process in the removal of various pollutants.

S.NO	Type of pollutant	Electrode used	Operational cost	Reference
1	Dairy	Fe	1.04 $/m3	[23]
2	Tannery	Al	2.92 €/m3	[24]
		SS	8.18 €/m3	
3	Textile wastewater	Fe	1.562 $/m3	[25]
		Al	1.851 $/m3	
4	Textile wastewater	Fe	0.25 $/m3	[26]
		Al	0.4 $/m3	
5	Iron	Al	0.22 $/m3	[27]
6	Nitrate	Al	0.455 $/m3	[28]
7	Fluoride	Al	0.379 $/m3	[29]
8	Acid black 194	Fe	5.04$/kg	[30]
9	Acid orange 7	Fe	13.8 $/kg dye	[31]
		Al	17.4 $/kg dye	
10	Potato chips manufacturing	Fe	6.32 $/m3	[32]

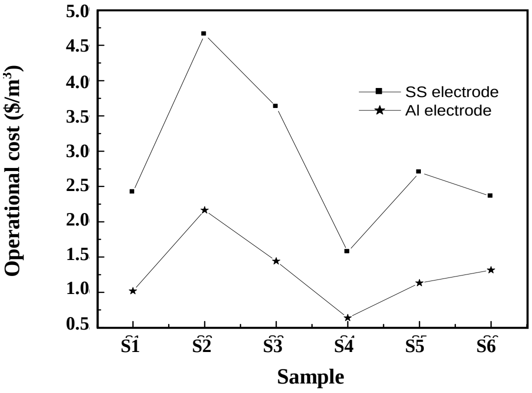

Fig. 12: Operational cost of SS and Al electrodes on six effluents.

Al coagulants are mostly in amphoteric $Al(OH)_3$ and polymeric hydroxides due to the alkaline pH of samples (S1-S6). The highest energy and electrode consumption are observed in S2 for both the electrodes are due to the conductivity of the untreated effluent sample.

Studies on operational cost

The evaluation of the operational cost for the treatment of six textile effluents is shown in Fig. 6. The operational cost is calculated using the following Equation [20].

$$OC = aENC + bELC + cCC \tag{13}$$

Where *OC* is operational cost ($/m^3), *ENC* is energy consumption (kWh/m^3), *ELC* is electrode consumption (kg/m^3) and *CC* is chemical consumption (kg/m^3). In this case, there are no chemicals used for the treatment of textile effluents, so the term chemical consumption neglected in operational cost analysis. From Fig. 12, the operational costs of S1, S2, S3, S4, S5, and S6 are calculated as 2.42, 4.66, 3.63, 1.57, 2.71, & 2.36 and 1.01, 2.16, 1.44, 0.64, 1.13 & 1.31 $/m^{3}for SS and Al electrodes respectively. Among all the effluents, sample S2 shows a high operational cost. Comparatively analyzing SS and Al electrodes, SS electrodes show high operational cost due to the cost of electrode material and electrode consumption. The efficiency of the electrocoagulation process in the removal of various pollutants in terms of operational cost is shown in Table 3. The outcome results are shown that the operational cost is depended on the nature of the pollutant and operational conditions.

CONCLUSIONS

The electrocoagulation process is subjected to the treatment of textile wastewater collected from different textile industries which is located Perundurai SIPCOT. Color and turbidity removal efficiencies are achieved as 75 and 99% for both the types of electrodes and the removal of COD and BOD of the effluents are observed to be more than 89 and 55% in SS and Al electrodes.

The BOD_5/COD ratio supported the increase in the biodegradability of textile wastewater after the process. The difference in COD and BOD removal efficiency of SS and Al electrodes ensured that both the electrodes follow different mechanisms and show selectivity towards the pollutant removal. Al electrodes exhibit more energy consumption while SS electrodes show more electrode consumption. SEEC supported that more sludge production. The operational cost analysis is favored to Al electrodes, but the color, turbidity, COD and BOD removal efficiencies and sludge productions are favored to SS electrodes. In the current study, at fixed operational conditions, the electrocoagulation process is well adopted for industrial level treatment and SS electrodes are suggested for the textile wastewater treatment process due to its high removal efficiency and less sludge generation.

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