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Treatment of Textile Wastewater by Electrocoagulation Method: Case Study; Odiba Textile, Dyeing & Finishing Company

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Abstract: At the present time, Textile processing is predominant in the industrial sector in Egypt. These technologies are depending on dyeing process, which required a huge amount of pure water, and generates a bulky quantity of wastewater. The wastewater resulted from Textile processing industry is demonstrated high pH and chemical oxygen demand (COD), immense color, high salinity, and suspended particles. In this study, Electrocoagulation method has been used for the treatment of real textile wastewater obtained from a textile factory in 10th of Ramadan city in Egypt (Odiba), using iron electrode as sacrificial electrode. The influence of main working variables such as initial pH of textile wastewater, operation time, and current density were tested to appreciate higher removal efficiency, and less operating cost. The experimental results showed that 95.7%, 99.5% and 84.75% for color, turbidity and COD removal efficiencies, respectively, at the optimum operating condition 10.2 pH, 15 min, and 11.97 mA/cm^2. The treated wastewater consumed 0.526 Kg Fe/m^3, specific electrical energy 4.8 KWh/Kg Fe, and the operating cost were 9.9 Egyptian pound (LE) /m^3 of treated wastewater. The removal takes place in acidic pH via precipitation mechanism, but in alkaline pH via adsorption and precipitation mechanism.

Keywords: Industrial; Textile; Wastewater; Dyeing process; Electrocoagulation.

1 Introduction

Water pollution is one of the biggest problems facing the world, because it causes serious damage to the environment and human beings [1-5]. In Egypt, the problem of water shortage is faced (water scarcity), water misuse, in addition the problem of water pollution. Textile dyeing is one of the most widespread industries in Egypt and the most consuming water. The discharging of textile wastewater without treatment, cause many environmental and health damage [6-15]. Traditional methods of industrial wastewater treatment are insufficient to treat textile wastewater due to their containment of toxic substances, and some dyes is non-biodegradable, also these methods produce large quantity of sludge and may produce toxic materials [16-33].

Textile industry processes have different steps in the pretreatment, dyeing, and finishing processes these steps consumes a large amount of pure water sequence produces huge amount of wastewater [34-39]. The textile

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wastewater is rich in color, inorganic salts, Oils, pectin, Waxes, knitting, de-Grable surfactants, adsorbable organic halogens (AOX) [1] and variable pH [2].

Textile industry is the largest industries polluting all forms of environment, air, soil and water [40-43]. Wastewater is the most environmentally damaging, and the effluent from textile plants is classified as the most polluting of all the industrial sectors [44-52]. An estimated 200,000 tons of dyestuff is expelled into the global environment every year [19-20]. The concentration of Azo dye in textile effluent can reach 500 (ppm). The smallest amount of dyes in wastewater can adsorb and reflect the sunlight entering the water (rivers, lakes, ect.), thereby, affecting on the aquatic species growth and hindering photosynthesis and hence, the food chain of the aquatic environment will be affected. The textile wastewater contains high amounts of sodium chloride and in the case of discharging or leaking the untreated wastewater into the soil, this leads to the sodium ions replacing Ca^{2+} and Mg^{2+} in the soil that damages soil structure mainly permeability [1]. Akshaya Kumar Verma et al. [3] divided the harmful effects of textile wastewater into direct and indirect effects.

Textile wastewater is characteristics by its high concentration of organic matter, high COD, high color, high salinity and variation in pH. The textile wastewater treatment is not depended only on color removal (de-colorization), but also in the degradation of organic materials including dyes, auxiliaries and finishing materials, also removing of inorganic materials including salts and heavy metals. De-colorization is a color removal from textile wastewater by removing a dye molecule from the solution (e.g. Adsorption and coagulation), or by breaking chromophore bonds (e.g. Oxidation). The textile wastewater treatment technologies can be divided into biological [4-5], physicochemical [6-7], physical [8-12], chemical [13-16], and electrochemical processes [17-19].

The previous researches indicated that, the conventional methods for textile wastewater treatment are characterized by less removal efficiency, high volume of hazardous sludge, and not economically feasible [9-17, 45]. Nowadays, there are numerous effective methods are applied for wastewater treatment such as membrane separation technology [8-12], activated sludge [4-5], and electrocoagulation [31-52]. The selection of applied technology depends on wastewater type and its characterization. Electrocoagulation is an operative method used to eliminate color and organic pollutants from wastewater, consequently the sludge generation decreases, and reduces chemicals and energy consumed.

Electrochemical technologies; is a branch of physical chemistry, are one of the ideal processes for solving the environmental problems. The main reagent used for electrochemical processes are electron, which are a clean reagent and decrease using of chemical reagents [20]. Electrochemical processes have been used for the treatment of many kinds of wastewater such as a tannery, electroplating, textile processing [21]. Electrochemical processes are including electro-flotation, electro-oxidation, and electrocoagulation [21]. High expensiveness and shortage of electricity at that time lead to decrease using of electricity in these processes [22].

Electrocoagulation [23] is a simple and highly effective process for treatment of different kinds of wastewater from different industry effluent such as paper industry wastewater, food industry wastewater, and textile wastewater. In this process direct current (DC) is passed through two sacrificial electrodes immersed into treating solution, leading to dissolution of sacrificial anode (electrical oxidation) formed soluble and insoluble species (hydroxide metal) which act as a coagulant to adsorb and remove soluble or colloidal pollutants by sedimentation or flotation. In electrocoagulation process, the coagulant ions have generated in situ and continuously formed. Electrocoagulation is an effective technique, due to adsorption of hydroxide on mineral surface formed in situ is 100 times greater than on pre-precipitated hydroxides when metal hydroxides have used as coagulant [24]. There are many factors affecting on the efficiency of electrocoagulation process such as pH, current density, electrode materials, electrolytic time and distance between electrodes.

Electrocoagulation is simple and effective processes for treatments, both drinking water and wastewater from different industrial effluents. The electrocoagulation process is more effective than chemical coagulation due to the anodized aluminum (resulting from the electrical dissolution of anode) was more effective than the aluminum ion introduced in the form of aluminum sulfate solution [25].

Electrochemical processes, specially, electrocoagulation (EC) has been widely used for the treatment of textile wastewater. Literature reports several studies on the use of EC and electrochemical techniques for dyeing wastewater treatment [26-29, 31-52]. Therefore, in this study the electrocoagulation technique has applied for treatment of real textile wastewater from a textile factory in 10th of Ramadan city, Egypt.

2 Materials and Method

2.1 Materials

All chemicals used in this work are analytical reagent grade and used for COD determination, pH adjusting, and other tested parameters. Silver sulfate (Ag_2SO_4) has M.W= 311.79 g/Mol from Poland. Mercuric sulfate ($HgSO_4$) has (assay min. 98.0%) and M.W= 296 g/mol from India. Potassium dichromate ($K_2Cr_2O_7$) (general-purpose grade)

M.W= 294.19 g/mol (Fisher chemical UK). 1,10 phenanthroline monohydrate ($C_{12}H_8N_2.H_2O$) redox indicator, M.W=198.22 g/mol (India). 3.1.2.5 Ammonium ferrous sulfate (FAS) extra pure 99.0% $(NH_4)_2$ $Fe(SO_4)_2.6H_2O$, M.W=392.14 g/mol Merck (Germany). Ferrous sulfate $FeSO_4.7H_2O$ BDH laboratory reagent, M.W= 278.02 g/mol (England). Sodium hydroxide pellets A.R NaOH 98.0%, M.W=40g/mol, Cambrian chemicals. Sulfuric acid analytical reagent grade H_2SO_4, density (ρ) =1.83 g/cm^3 (Fisher scientific UK limited). Ethyl alcohol commercial, C_2H_6O, M.W= 46.07 g/mol.

2.1.1 Sample

The textile Wastewater has obtained from a tank containing a mixture of exhaust dyeing and finishing solutions at a textile factory in 10th of Ramadan city (Odiba Textile Dying & Finishing). The sample was collected for one shift and then mixed to homogenize the wastewater before applying it in electrocoagulation treatment unit.

The textile wastewater sample characterization was depicted in Table (1). The untreated sample was first filtered via a screen filter to remove large suspended solids before it was used.

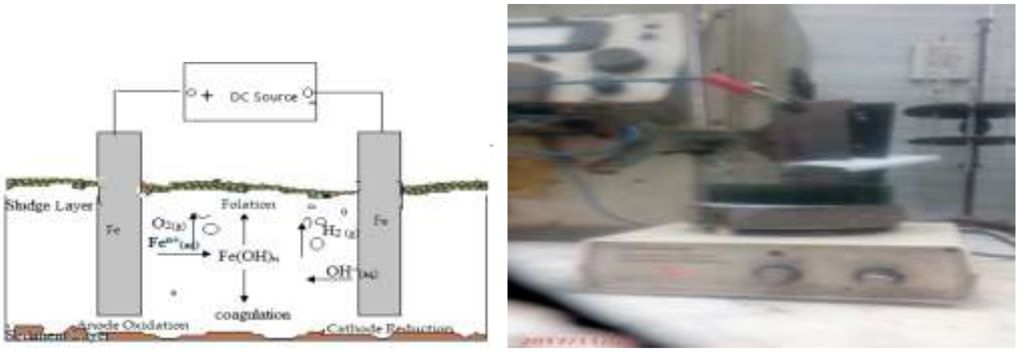
2.1.2 Electrodes Material

The cathode and anode consist of two separated iron sheets (low carbon steel) of rectangular shape each one with dimensions of (15.3cm×5.1cm×0.084cm), the submerged surface area of each electrode plate was 25.84 cm^2. The chemical compositions of the iron electrodes are shown in Table (2).

2.2 Method

In this work, three variables have studied in the process of textile wastewater treatment, namely, time, pH, and current density. The distance between the electrodes has stabilized to be constant at 3.2 cm, which the best distance between the two electrodes according to the previous researches [19-22]. In addition, the effect of these factors on the removal of organic matter expressed in chemical oxygen demand (COD), as well as the removal of color and turbidity, has studied. Also, the effect of these factors on physical and economical parameters were tested via electrocoagulation unit.

The electrocoagulation unit consists of an electrochemical reactor, which is a glass beaker with a diameter of 11cm and high of 6.5cm, magnetic stirrer was used for mixing the solution during electrolysis with constant stirring speed 600 rpm, and two iron electrodes (99.3%) with dimensions of (153mm× 51mm ×0.84mm). The total effective electrode area (submerged surface area) is 25.84 cm^2, and the spacing between the electrodes was 3.2 cm. The two electrodes were connected to electro-analyzer as a source of direct current (DC). Figure (1) shows the electrocoagulation set-up. The electrochemical characteristics of electrochemical reactor used in the experiment were depicted in Table 3.



(a) Electrocoagulation unit. (b) Electrocoagulation cell set-up.

Fig. 1: Electrocoagulation set-up.

Table 1: Characteristics of wastewater used.

Parameters	Unit	Value
pH		10.2
Color	Hazen	2670
Appearance		Dark blue
Chemical oxygen demand (COD)	mg/l	9000
Total dissolved slat (TDS)	g/l	18.2
Conductivity	mS/cm	30.3
Salinity	g/l	14.0
Turbidity	NTU	140.2
Total suspended solids (TSS)	ppm	112
Total phosphorous	ppm	6.02
Total nitrogen	ppm	0.898
Chromium (Cr)	ppm	0.043
Copper (Cu)	ppm	0.019
Nickel (Ni)	ppm	0.086
Iron (Fe)	ppm	0.524
Manganese (Mn)	ppm	0.046
Zinc (Zn)	ppm	0.059
Cadmium (Cd)	ppm	0.026

Table 2: chemical compositions of iron electrodes

Element	C	Si	S	P	Mn	Ni	Cr	Mo	Al	Co	Ti	Cu	Fe
%	0.06	0.03	0.01	0.01	0.35	0.05	0.04	0.006	0.08	0.007	0.002	0.06	99.3

Table 3: Properties of the electrochemical reactor used.

Property	Unit	Description
Dimensions	(cm)	11×6.5
Volume	(ml)	٤٠٠
Material		Glass
Anode		Iron (99.3%)
Cathode		Iron (99.3%)
Electrode thickness	(mm)	٠.٨٤
Electrode dimensions	(mm)	(153 mm× 51 mm ×0.84 mm)
Active (submerged) surface area	cm^2	25.84
Electrode arrangement		Parallel

Electrode gap	(cm)	3.2
Current range	(A)	(0-10)
Voltage range	(v)	(0-10)

All the runs of wastewater treatment via electrocoagulation were accomplished at room temperature (23°C). Firstly, the two electrodes were washed with diluted HCl (35%) (1:10), ethyl alcohol and distilled water to remove surface grease and impurities on the iron electrode surface, then dried at 105°C in chamber dryer, after that weighted (w_1). In each run, 250ml of wastewater solution was placed into electrolytic cell. The current was adjusted to a desired value and the operation was started. At the end of electrocoagulation, the solution was filtered with filter paper 40 ash less and the electrodes were washed thoroughly with water to remove any solid residues on the surfaces, then dried and weight again (w_2). The difference between the weight of anode after and before run is the experimental weight loss is calculated from the following equation:

$$\Delta W_{experimental} = w_1 - w_2 \qquad (1)$$

Where;

$\Delta W_{experimental}$: Weight loss in grams (gm) of iron electrode, w1 and w2 are dry weights of iron electrode in grams (gm) before, and at end of each run respectively.

The same experiments were run with both electrode materials with changing one variable from the three main variables (pH, time and current density), for comparative purpose, and to determine optimum conditions. The pH was adjusted to a desirable value using NaOH or H_2SO_4. The treated solution after filtered was analyzed to determine COD, color, turbidity, TDS, conductivity and Salinity.

On one hand, Fe^{2+} ion; is an active coagulant precursor, is produced from an anodic oxidation for Iron (Fe) at iron anode. on the other hand, OH^- ion is generated from cathodic reduction for H_2O at the Cathode, as represented in (reactions (2) and (3)). The unsolvable iron hydroxides ($Fe(OH)_{2(s)}$, and $Fe(OH)_{3(s)}$) are formed as a result of Fe^{2+} ion, as represented in reactions (4) and (5). These iron Hydroxides play as coagulant/flocculent for the suspended solids and yield high-density flocs which sediment afterward, as represented in figure 1,a.

Anode reaction:

$$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^- \qquad (2)$$

Cathode reaction:

$$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)} \qquad (3)$$

Hydroxide formation: $$Fe^{2+}_{(aq)} + 2OH^-_{(aq)} \rightarrow Fe(OH)_{2(s)} \qquad (4)$$

$$4Fe^{2+}_{(aq)} + 10H_2O + O_{2(g)} \rightarrow 4Fe(OH)_{3(s)} + 8H^+_{(aq)} \qquad (5)$$

2.3 Data Analysis and Characterization

- pH (H18424) microcomputer pH meter, pH range (0 to 14), mV 0 to ± 399.9 and temperature 0.0 C° to 100 C°. HANNA instruments, made in Romania, measured pH.
- The D.C current source is FISHER controlled potential Electro-analyzer from Fisher scientific Co. model 9-265-6, made in the USA. The current ranged from 0 to 10 A and volte ranged from 0 to 10 V.
- The samples were treated keep in constant stirring using magnetic stirrer, regulator hot plate, Gallenkamp, made in England.
- The electrode material was analyses by using optical emission model applied research laboratories (ARL) 3460 Fison's instruments, made in Switzerland.
- The dryer used is (Heraeus), Thermo Electron Corporation, type UT6, 250°C, 230V, 5.5A and 1.27Kw, made in Germany.
- The electronically balanced is Mettler AE 160 (d=0.0001gm), type AE 160 115/220 V, 50/60 HZ and used 10vA made in Switzerland by Mettler instrument AG .
- Reflux apparatus consisting of 250ml Pyrex (made of heat-resistant glass) Erlenmeyer flasks with ground-glass 24/40 neck and equivalent condenser with 24/40 ground-glass joint, and elctromantle, made in USA by Fisher Co.

2.4 Chemical Oxygen Demand (COD) Determination

The chemical oxygen demand (COD) of all samples was determined by the dichromate open reflux method according to the Standard Methods for the Examination of Water and Wastewater [2].

2.5 Color Measuring

The color of the samples was measured by Nano-color 300D 20741 Instrument, Machrey-Nagel, made in Germany.

2.6 Turbidity Measuring

The turbidity of the samples was measured by Turbidity meter, model micro 1000 turbid-meter, made in USA by HF Scientific, inc.

2.7 Conductivity, total Dissolved Solid (TDS), and Salinity Measuring

The conductivity, TDS, and salinity of the samples were measured by conductivity meter, model 4520 JENWAY, designed and manufactured in the UK by Bibby scientific ltd.

2.8 IR- analysis

The infrared analysis of the prepared dye was performed by using NICOLET AVATAR 330 FT-IR from Thermo Electron Corporation made in USA. The sludge formed through electrocoagulation process was investigated by dispersing the samples in spectroscopic grade KBr to record the spectra (sample: KBr = 1: 100); the IR spectra were recorded over the range of 4000–400 cm^{-1}.

2.9 Theoretically Calculations

2.9.1 Removal Efficiency

The mathematical equations and calculations were used to estimate the removal efficiency of color, turbidity, and COD. The removal efficiencies (*R (%)*) were determined from the following equation:

$$R\ (\%) = \frac{Ce - Ci}{Ci}\ X\ 100 \tag{9}$$

Where, C_i and Ce are the COD or color or turbidity concentrations in the inlet and the exit streams of the electrocoagulation cell, respectively.

2.9.2 Electrode Weight loss or Electrode Consumption

The electrode consumption (EC) was calculated as Kg Fe (Anode) per one cubic meter (m^3) of treated wastewater (Kg Fe/m^3). EC was calculated from the following equation:

$$\text{EC (Kg Fe/m}^3\text{)} = \frac{(W - W_o) \times 10^{-3}}{250\ (ml) \times 10^{-6}} \tag{10}$$

Where; EC: Electrode Consumption in Kg Fe/m^3, W and W_o: are the weight of anode after and before running the electrocoagulation process by (Kg) respectively, 250 ml is the volume of treated wastewater in (ml), and 10^{-3} to convert from gram (gm) to kilogram (Kg), also 10^{-6} to convert from (ml) to cubic meter (m^3).

2.9.3 Current efficiency (ϕ)

Current efficiency (ϕ) was calculated as:

$$\text{Current efficiency } (\phi) = \frac{\Delta W_{experimental}}{\Delta W_{theoretical}} \times 100 \tag{11}$$

The theoretical amount of iron dissolution $\Delta W_{theoretical}$ was calculated according to the Faraday's law as**:**

$$\Delta W_{theoretical}\ (Kg/m^3) = \frac{M \times I \times t_{EC}}{n \times F \times V}\ [28] \tag{12}$$

Where*;* M is the molecular weight of the iron (0.05585 Kg/mol), n is the number of electron moles (n_{Fe}=2), F is the Faraday constant (F= 96,487 C/mol), and t_{EC} is the time (s) of electrocoagulation process, and V is the volume of treated wastewater. Where, $\Delta W_{experimental}$ is the experimental weight loss of iron anode as in equqtion1.

2.9.4 Specific Electrical Energy Consumption (SEEC)

SEEC was premeditated as a function of iron electrodes weight consumption through the electrocoagulation process in kW h/(kg Fe). **SEEC** was calculated according to the following equation:

$$SEEC = \frac{n \times F \times U}{3600 \times M \times \phi} \quad (13)$$

Where; M is the molecular weight of the iron, n is the number of electron moles, F is the Faraday constant, ϕ is the current efficiency, U is the cell voltages, and 3600 is the operating time in sec for one hour. In addition, **SEEC** can be calculated as a function of the volume of wastewater treatment, and expressed in kWh/m^3, according to the following equation:

$$SEEC = \frac{I \times t \times U}{V} \quad [28] \quad (14)$$

Where; **SEEC** in kW h/(kg Fe), U is the operating voltage (volt), I is the operating current (A), t is the time of reaction (s), and V is the volume of wastewater (m^3).

3 Results and Discussion

3.1 Effect of Initial Ph

Wastewater from dyeing and finishing processes is characteristic by high chemical oxygen demand (COD), strong dark color, high strength and variable pH ranges. In this work, the electrocoagulation process was applied for treatment of real textile wastewater, which obtained from a textile factory in 10th of Ramadan city in Egypt (Odiba), via iron electrode as sacrificial electrode. This work focused on determination of optimum operating conditions of treatment process as pH, current density, and operating time. For that challenge, the effect of these parameters on removal efficiency (COD, color, and turbidity), physical parameters, and economical parameters were tested via electrocoagulation cell.

3.1.1 Effect of Initial pH on Removal Efficiency

Textile wastewater pH after dying processes was attuned to the anticipated value for each tests by addition either sodium hydroxide (NaOH) or sulfuric acid (H_2SO_4). The experiments were operated with testing different of pH ranges with constant the other factors, as operating time (15min.), current density (29.94 mA/cm^2), inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

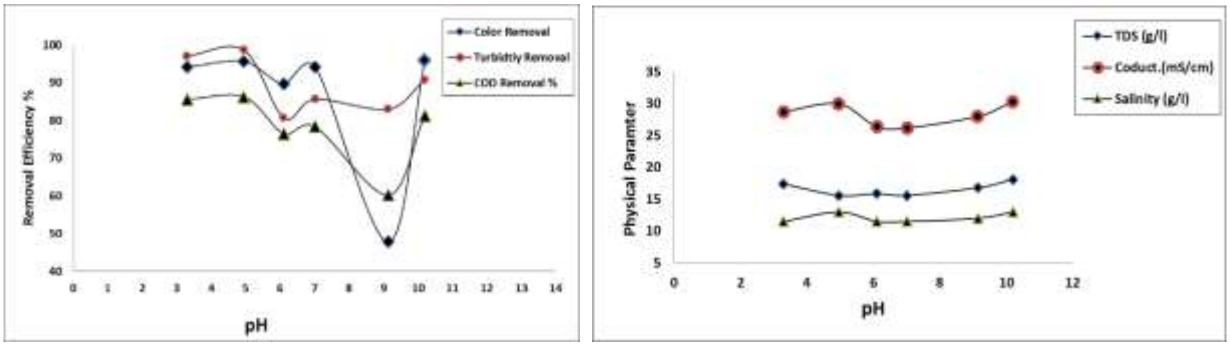
The effect of initial pH on the color, COD, and turbidity removal efficiencies is presented in Figure (2a). The results showed that, the best color, turbidity, and COD removals efficiencies are better in acidic pH (3.3 and 4.95), and at alkaline pH (10.2) than the neutral and nearly the alkaline solution as represented also in Table 4. However, at pH 9.14 the removal efficiency of color, turbidity, and COD were dropped dramatically. At pH 10.2, which the initial pH of textile wastewater effluent the removal efficiency of color, turbidity, and COD are high.

Table 4: Functional groups present in treating textile wastewater of Sunfron Blue SN-R.

Number in IR pectrum	**Wavenumber (cm^{-1})**	**Functional groups**	**Bonds**
1	3330	OH water	O-H stretching
2	1630	C=O in ketone, carboxylic acids,	C=O stretching
3	1080	C=O in carbonates	
4	1458	CH_3 in aliphatic compounds	CH_3 antisym deformation

3.1.2 Effect of Initial pH on Physical Parameters

Effect of on physical parameters such as conductivity, TDS, and salinity were shown in Figure (2b). From this figure, it was obvious that the physical parameters nearly do not change with pH; due to electrocoagulation, process has no effect for removal of TDS and salinity.



a. Effect of pH on removal efficiency%. b. Effect of pH on Physical parameters.

Fig.2: Effect of initial pH on electrocoagulation process at constant operating condition 15min, 29.94 mA/cm^2 current density, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

3.1.3 Effect of Initial pH on Economical Parameters

The economic parameters are the most important factors that should be studied in the treatment of textile wastewater, these factors affected on the cost of treatment. The economic parameters include the electrode consumption as kilogram of iron per cubic meter of treated wastewater (Kg Fe/m^3), current efficiency as well as the SEEC.

3.1.3.1 Effect of Initial pH on Electrode Consumption

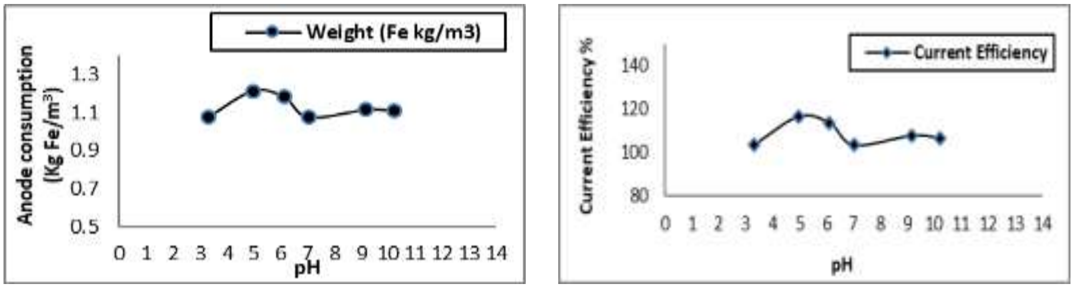
The relation between pH and electrode consumption as kilogram of iron per one cubic meter (m^3) of treated wastewater (Kg Fe/m^3), is illustrated in Figure (3a). It may be noted from this figure that at lower pH (3.3) the consumption of the electrode is lesser than that at pH (4.95 and 6.11), even if at pH 3.3 is more acidic than 4.95 and 6.11, and Fe is dissolved in acidic medium, this may be due to the formation of a passive oxide layer on Fe electrode. Meanwhile, at higher pH the electrode consumption drop dramatically gives low electrode consumption at 7.02 and 10.2. As the electrode, consumption increases the operating cost increase.

3.1.3.2 Effect of Initial pH on Current Efficiency (Φ)

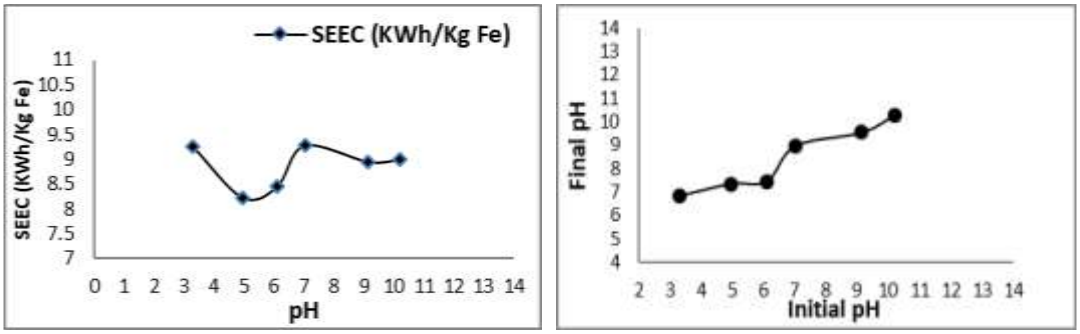
Figure (3b) shows the effect of pH on Current efficiency (Φ). As shown in this figure, the current efficiency was increased from 103.57% to 116.62% as the pH changed from 3.3 to 4.95 respectively, then decreased to 113.63% at pH 6.11, and dropped to 103.38% at neutral pH (7.02), after that at pH 9.14 was increased to 107.8%, and decreased again to 106.72% at pH 10.2. These varieties of current efficiency from up to down as the pH changed confirmed that, the great effect of pH on anode dissolved and current efficiency. Guohua Chen et al. [21] shown that the current efficiency of aluminum electrode could be 120–140%, while for iron is around 100%. The increases of current efficiency at some pH reading in this study attributed to the pitting corrosion effect of chlorine ions on iron electrodes. Figure (3 a,b) showed that the two graphs are identical due to the anode consumption was the only changed variable.

3.1.3.3 Effect of pH on Specific Electrical Energy Consumption (SEEC)

One of the significant economically limits in electrocoagulation treatment process is Specific electrical energy consumption (SEEC). SEEC is determined as a function of iron electrodes weight consumption during the electrocoagulation process in [kW h/ (kg Fe)]. Figure (3c) showed the influence of pH on specific electrical energy consumption. From Figure (3c) it was observed that, as the current efficiency decrease the specific electrical energy consumption increase i.e., reversal proportional. So at pH 4.95 yields high current efficiency (116.62%) and less electrical energy consumption 8.23kWh/(Kg Fe). The SEEC ranges from 8.23 kWh/ (kg Fe) at pH 4.95 to 9.28 kWh/ (kg Fe) at pH 7.02.



a:Effect of pH on weight loss of anode b: Effect of pH on current efficiency (Φ)



c: Effect of pH on (SEEC) d: Relation between initial and final pH .

Fig. 3: Effect of initial pH on economical parameters at constant operating condition 15min, 29.94 mA/cm^2 current density, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

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3.1.3.4 Relation between Initial pH and Final pH

The final pH at the end of the reaction at operating time 15 min increased to 6.82 and 7.34, 7.46, and 8.98, for initial pH values of 3.3, 4.95, 6.11, and 7.02, respectively as demonstrated in Figure 3d. This is one of the advantages of this process. However, at alkaline medium, initial pH, change is a very slightly increased, when initial pH was 9.14, and 10.2 the final pH were 9.55 and 10.3 respectively. These results proved that the electrocoagulation process displays some pH buffering capacity, particularly in an alkaline medium.

It was clearly from the above results of Figs. (2, 3) that the higher removal efficiency of color, turbidity and COD were obtained in acidic medium at pH (3.3 and 4.95). In addition, the low electrode consumption was obtained at pH 3.3, 7.02, and 10.2, but low SEEC was obtained at pH 4.95 (8.23 KWh/Kg Fe), while at pH 10.2 was (8.99 KWh/Kg Fe) with a 0.76 KWh/Kg Fe difference between them. Consequently, initial pH 10.2 of the treated wastewater, was considered as the optimal pH in the current work, intended for no addition of chemicals for adjustment or management the initial pH values, hence decreasing the operating cost.

3.2 Effect of Operating Time

3.2.1 Effect of Operating Time on Removal Efficiencies

The operating time is a significant parameter in the electrocoagulation process. The effect of operating time was explored_at a constant current density of 29.94 mA/cm^2, initial pH 10.2, inter electrode distance (3.2 cm), stirring speed 600 rpm and at room temperature.

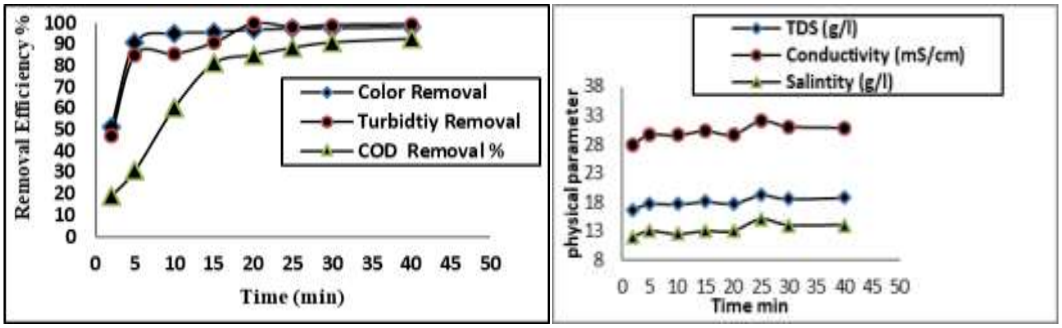
The effect of operating time on the color, COD, and turbidity removal efficiencies is presented in Figure (4a). As depicted in this figure, an increase in the operating time from 2.0 to 40.0 min. yields an increase in the removal efficiencies from (18.7%, 46.93%, and 84.95) to (92.8%, 99.3%, and 98.12) for COD, turbidity and color respectively. The removal efficiencies, increase with operating time because as the operating time increases the concentration of coagulating species (metal ions Fe^{2+} and Fe^{3+}) and their hydroxide flocs increases. The removal efficiencies depended directly on the concentration of metal ions produced on the electrodes. According to figure (4a), it was observed after 15 min operating time, the removal efficiencies of color, turbidity and COD were remained almost constant. So that 15.0 min operating time considered as optimal operating time in the present study. The obtained results were in good agreement with the recorded results by M. Kobya et al. [30], which obtained nearly the complete decolorization efficiency (92.3%) of leva-fix orange reactive textile dye at 12 min operating time. M. Bayramoglu et al. [31] obtained good removal efficiencies of textile wastewater at operating time 10 min using iron electrode.

3.2.2 Effect of Operating Time on Physical Parameters.

The effect of operating time on physical parameters such as conductivity, TDS, and salinity is shown in Figure (4b). It was observed from Figure (4b) that as the operating time changes, the physical parameters are not changed due to the electrocoagulation process is not suitable for removal of TDS and salinity.

3.2.3 Effect of Operating Time on Economical Parameters

Economical parameters are very important parameters in determining the operating cost of electrocoagulation process. Economical parameters such electrodes consumption (Kg Fe/m^3), current efficiency (%), and SEEC **(**KWh/Kg Fe)**.**



a:Effect of time on removal efficiency b: effect of time on physical parameter.

Fig. 4: Effect of operating time on Electrocoagulation process at constant operating condition; current density 29.94 mA/cm^2, initial pH 10.2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

3.2.3.1 Effect of Operating Time on Electrode Consumption

The effect of operating time on electrode consumption is determined and displaced in figure (5a). As the operating time increased from 2.0 **to** 40.0 min the anode weight consumption increased from 0.1054 Kg Fe/m^3 to 2.974 Kg Fe/m^3, the operating time increases, the rate of anode dissolution increases formed Fe^{2+} and Fe^{3+}. Figure **(**5a**)** demonstrated the relationship between the operating time, experimental, and theoretically anode weight consumption (Kg Fe/m^3). This figure illustrated that a good agreement was obtained between the calculated amount of anode dissolved as a result of passing a definite quantity of electricity at different operating time, and the experimental amount of anode dissolution determined.

3.2.3.2 Effect of Operating Time on Current Efficiency (Φ)

The Effect of Operating time on current efficiency (Φ) is recorded and depicted in Figure (5b). It is observed from Figure (5b) that the current efficiency was about 109%, 111%, 109% at operating time 5, 10, 25 min respectively, while the current efficiency is decreased to approximately 107% at 15, 20, 30, and 40 min. Thus, 10.0 min operating time yields high current efficiency (111%).

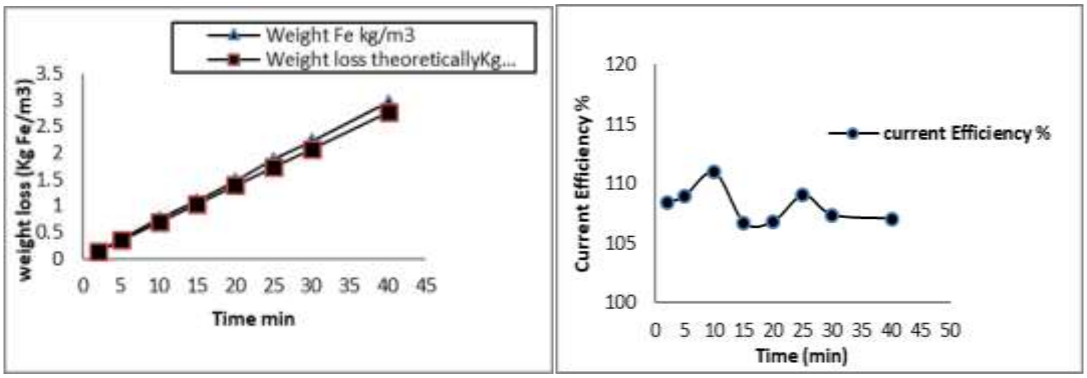
3.2.3.3 Effect of Operating Time on Specific Electrical Energy Consumption (SEEC)

Figure (5c) illustrated relation between operating time and specific electrical energy consumption kWh/(Kg Fe). Current efficiency is reversal proportional with specific electrical energy consumption. Consequently, at 10.0 min operating time yields high current efficiency (111%) and less electrical energy consumption 8.65 kWh/ Kg Fe, as shown in figure (5c).

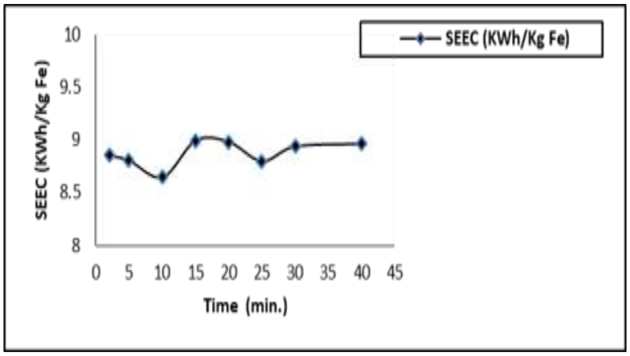
3.3 Effect of Current Density

3.3.1 Effect of Current Density on Removal Efficiencies

Current density is one of the main significant variables, for monitoring the reaction rate within the reactor for electrochemical method. For that challenge, the electrocoagulation process was carried out using various current densities at constant operating time 15.0 min, pH 10.2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature, to investigate the effect of current density on Removal Efficiencies for color, turbidity and COD. The obtained date was depicted in Figure (6a).The current density is the most important parameter for determines the coagulant dosage rate. Figure (6a) shows removal efficiency percentage against current density applied. From the figure, removal efficiencies were increased from 92.13%, 98.44% and 84.01% to 95.69%, 99.5% and 84.75% for color, turbidity and COD respectively, by raising current density from 5.99 to 11.98 mA/cm^2. However, it should be noted that, an increase in current density from 11.98 to 17.964 mA/cm^2 yielded an increase in removal efficiencies of color, turbidity and COD from 95.69%, 99.5% and 84.75% to 96.33%, 99.6% and 85.06%, for color, turbidity and COD respectively, that it was not a significant change. This due to as the current increase the applied potential increased (Ohm's law $I(A) = \frac{V(volet)}{\mathrm{R(ohm)}}$) leading to heating up the treated water. Consequently, a large current means a small electrocoagulation unit. Therefore, 11.98 mA/cm^2 was the optimal current density in this work. S. Song et al. [32] obtained 94% color removal of solution containing an azo dye (C.I. Reactive Black 5) at 10 mA/cm^2 in 15.0 min. Similarly, M. Bayramoglu et al. [31] recorded good removal efficiencies of textile wastewater at 10 mA/cm^2 current density.



a:effect of time on anode weight consume b: effect of time on current efficiency,

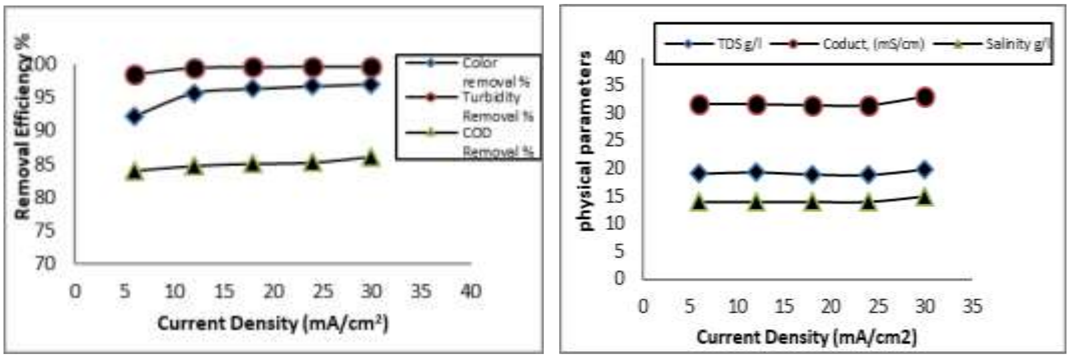


c. effect of time on SEEC.

Fig. 5: Effect of operating time on economical parameters at the constant of current density 29.94 mA/cm^2, initial pH 10.2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature,.

3.3.2 Effect of Current Density on Physical Parameters

Like pH and operating time, current density has no effect on physical parameters such as conductivity, salinity and TDS as shown in Figure (6b).



a. Effect of current density on removal efficiency

b. Effect of current density on physical parameters

Fig. 6: Effect of current density on removal efficiencies, and physical parameters at operating condition time 15.0 min, initial pH 10.2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

3.3.3 Effect of Current Density on Economical Parameters

The efficiency of electrocoagulation processes has not determined by removal efficiencies only, but by economical parameters also. Economical parameters include electrode weight consumption (Kg Fe/m^3), current efficiency (%), and SEEC **(**KWh/Kg Fe), plus chemical added cost, sludge disposal cost, and maintenance.

3.3.3.1 Effect of Current Density on Electrodes Weight Consumption

The influence of current density on electrodes weight consumption has studied and demonstrated in Figure (7a). **It** illustrated the relation between experimental electrode weight consumption (weight loss) by Kg Fe/m^3 of treated wastewater and theoretically electrode weight consumption against current density. From the figure, as the current density increased from 5.988 to 23.952mA/cm^2**,** the electrode weight consumption increased from 0.5264 to 1.4384 Kg Fe/m^3, in this range of current density. Thus, there are a good agreement was obtained between the calculated amount of electrode weight consumption and experimental electrode weight consumption. However, at a current density 29.94 mA/cm^2 the increase in electrode weight consumption is not significant and **was not in good agreement** with theoretically electrode weight consumption, this is recognized to at high current density there is a high chance of loss of electrical energy in heating up the wastewater treated.

3.3.3.2 Effect of Current Density on Current Efficiency

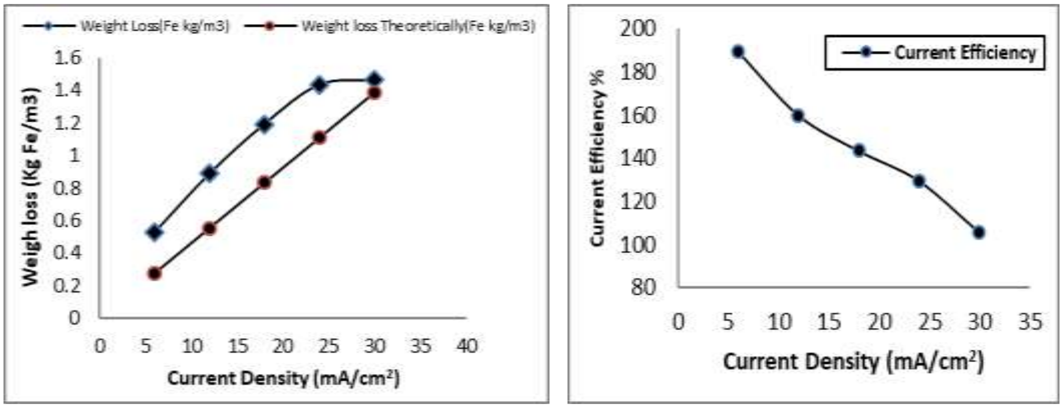
The influence of current density on current efficiency has recorded, and displayed in figure (7b). It is obvious from the figure that the current density is reversal proportional with current efficiency, thus as the current density increased the current efficiency decreased, this is attributed **that** when a high current is applied there an excessive possible of losing electrical energy in heating up the treated wastewater and even a decrease in current efficiency. Thus, there is attuned range of operating for current density, which if surpassed; the quality of treated water does not display an important development.

3.3.3.3 Effect of Current Density on SEEC

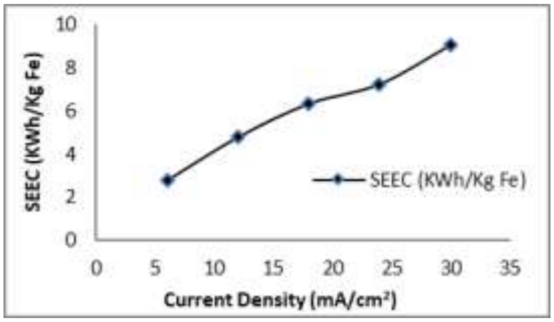
The effect of current density on SEEC **(**KWh/Kg Fe) has determined and depicted in Figure (7c). It was clearly from the obtained curve, as the current density increased, the SEEC **(**KWh/Kg Fe) increased, and this ascribed to electrode consumption values increase, with increasing current density. As the specific electrical energy consumption increased, the operating cost increased. At the optimum current density (11.976 mA/cm^2), the value of the specific electrical energy consumption was 4.8 KWh/Kg Fe.

3.4 Relation between Current and Voltage of Electrocoagulation Cell.

Figure (8) shows relation between current (A) passed through the electrocoagulation cell and volt (V) of the cell. As the current increased, the volt of the cell increased (ohm's law) this increase in volt lead to heating up the treated wastewater, and loss in electrical energy, consequently increasing the operating cost.



a. Effect of Current density on electrodes weight consumption. b. Effect of Current density on current efficiency



c. Effect of Current density on SEEC.

Fig. 7: Effect of Current density on economical parameters, at operating condition time 15.0 min, initial pH 10.2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

3.5 Removal Mechanism

The textile wastewater contains high level of chloride ions that results due to using of sodium chloride in reactive dyeing processes. These chloride ions play an important role in the degradation of dyes and organic contaminations by using electrocoagulation process. Chloride ions in acidic medium converted into hypochlorous acid, but in alkaline medium chloride ions converted into hypochlorite. The oxidation potential of hypochlorous acid is (1.49 v) which more than hypochlorite ions (0.94 v). On the other hand, the concentration of chloride ions (Cl^-) in treating wastewater that has been treated in acidic condition (pH 4.13) about 18522 ppm, while the concentration of chloride ions (Cl^-) which treated in alkaline medium about 20633 ppm. The different between them, due to large amount of chloride ions have been consumed in degradations of dyes and organic contaminations in acidic medium as a result of the formation of hypochlorous acid. Another test was used to determine the removal mechanism is infrared spectrum of treated wastewater of textile wastewater containing Sunfron Blue SN-R dye. Figures (9) and (10) shows the infrared spectrum of treated textile wastewater containing Sunfron Blue SN-R at pH 4.13 and pH 10.2 respectively at constant of operating time 15.0 min, current density 29.94 mA/cm^2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature. In table (5), there are the principal functional groups. From two figures, it was obvious that the peaks of functional groups of treated textile wastewater at acidic pH are more clear and sharp than that at alkaline pH. These results indicated that the removal taken place in acidic pH via precipitation mechanism, but in alkaline pH via adsorption, and precipitation mechanism as shown in the following equations [25]:

- **Precipitation**

$$\text{Dyes} + \text{Monomeric Fe} \longrightarrow [\text{Dyes monomeric Fe}]_{(s)} \tag{15}$$

$$\text{Dyes} + \text{polymeric Fe} \longrightarrow [\text{Dyes polymeric Fe}]_{(s)} \tag{16}$$

- **Adsorption**

$$\text{Dyes} + \text{Fe (OH)}_{3\,(S)} \longrightarrow [\text{particle}] \tag{17}$$

$$[\text{Dyes polymeric Fe}]_{(s)} + \text{Fe (OH)}_{3\,(s)} \longrightarrow [\text{particles}] \tag{18}$$

At higher pH more than 9.5 the formed insoluble $Fe(OH)_2$ precipitates were remained in equilibrium with Fe^{2+} or with monomeric species such as $Fe(OH)^+$, $Fe(OH)_2$, and $Fe(OH)_3$.The flocs of $Fe(OH)_3$ had formed, they might eliminate the soluble dye by surface complexation or electrostatic attraction. It supposed that the contaminant might work as a ligand to bind hydrous iron moieties using precipitation and adsorption mechanisms. Additionally, the removal mechanism of the azo dye may have actually complexes with the iron hydroxide-forming ionic bonds as follows [33]:

$$R{-}SO_3Na + (OH)_3(H_2O)\,Fe \longrightarrow R{-}SO_3{-}\,(OH)_2\,H_2OFe + Na^+ + OH^- \tag{19}$$

This result agreed with the studies carried out by Nasser M Abu Ghalwa et al. [34], and with J. Castañeda-Díaz et al. [33].

3.6 Comparison with the Literature

There are numerous researchers indicated the treatment of synthetic and real textile wastewater by electrocoagulation using iron or aluminum electrodes. These studies have focused on the factors affecting, removal efficiency, and energy consumed and operating cost. In table (6) a comparison between the current study and some literatures work, which used the electrocoagulation process for treatment of synthetic and real textile wastewater using iron electrodes as sacrificial electrodes. The comparison focused on three main operating parameters pH, time and current density, also removal efficiencies and SEEC. The comparison shows that some of literature work are agree with the present study in most operating parameters, on the other hand, some of literature work are not agree with this study due to the great difference between synthetic, and real textile wastewater in both chemical composition and physical properties.

3.7 Preliminary Economic Analysis

Cost analysis is an important factor in the treatment process, because it determines the usefulness of the method used to treat wastewater. The operating cost includes electrical energy consumption, electrode consumption, chemicals used, sludge disposal, and cost of maintenance. The costs of energy, and sacrificial electrodes were taken into consideration as major cost items. The operating cost was calculated using equation (20):

$$OC = a\ ENC + b\ ElC \tag{20}$$

Where, OC is the operating cost, ENC is the energy consumption as (kWh/Kg Fe) or as (kWh/m^3), and ElC is the cost of iron electrode consumption by Kg/m^3. The letters (a) and (b) are unit prices in the Egyptian market in December 2018, as follows (a) electrical energy (b) cost of Kg of the low alloy iron sheet. In this study, at optimum conditions one cubic ($1m^3$) treated wastewater consumed 0.526 Kg Fe/m^3 and electric energy consumed for 1Kg Fe was 4.8 KWh/Kg Fe. Accordingly, treating 1 m^3 of the real textile wastewater under the optimum conditions obtained from the earlier runs of the experiment consumed 0.526 kg Fe/m^3 wastewater treated, and 2.52 kWh/m^3 of energy. The cost of electrical energy is 0.9 LE/ KWh, and cost of Kg low alloy iron sheet is 14.5 LE/Kg Fe. The operating cost of one cubic wastewater treated has calculated to be 9.9 LE /m^3.

This price is approximate, and is not a final price, because the price can be reduced by 31.64 % [20] if solar cells are used as the sources of electrical energy. In addition, the electrode consumption rate has not been properly evaluated, as the electrodes used in the final set of trials have not been used up sufficiently to make an accurate estimate of the consumption rate. The information acquired from the patent holder of this technology is that the cost of the electrodes consumed is approximately \$ 0.03 – 0.05/m^3 of treated wastewater [47]. This price does not include the maintenance and sludge disposal cost, but final sludge contains relatively high levels of iron metal. Therefore, the sludge formation is not a problem because it can be sold.

If we consider that the cost of electrodes consumed is \$ 0.05/m^3, therefore the operating cost of one cubic wastewater treated has calculated to be 3.2 LE /m^3. The treated wastewater can be used in washing machines and floors so that we provide in the water used for this purpose, which saves money expenses. Otherwise, the treated water needs to remove the salts using the reverse osmosis method, until it becomes used again in dyeing processes. The results obtained indicates that electrocoagulation is one of the most effective and economically feasible techniques in wastewater treatment especially, textile wastewater.

Table 5: Comparison between the present study and a literature, which used iron electrodes.

Reference	Optimal Conditions				Removal Efficiencies %		
	pH	C.D mA/cm^2	Time min.	SEEC	Color	COD	Turbidity
Present Study	**١٠.٢**	**11.976**	**15.0**	**4.8 KWh/Kg Fe**	**٩٥.٦٩**	**٨٤.٧٥**	**٩٩.٥**
U.D. Patel et al. [26]	9.0	6.0	60.0	29.0 kWh/kg dye	90.0		
M. Bayramoglu et al. [31]	7.0	3.0	15.0	0.63 kWh/m^3		65.0	83.0
N. Abu Ghalwa et al. [34]	7.2	20.0	14.0		99.6	91.5	
M. Chafi et al. [35]	7.0	7.5	5.0	8.3 kWh/kg dye	98.0		
N. Daneshvar et al. [36]	5.8	8.0	5.0	7.57 kWh/ kg dye removal		75.0	
M. Kobya et al. [37]	7.0	3.0	15.0			65.0	83.0
M. Kobya et al. [38]	9.0	10.0	10.0	1.25 kWh/ kg COD		72.0	98.0
I. Zongo et al. [39]	9.0	10.0	10.0	1.75 kWh/m^3		74.0	98.0
M. Kobya et al. [40]	6.8	6.5	80.0	6.35 kWh/m^3		85.0	95.0
B.K. Körbahti et al. [41]	12.7	12.39	180.0	193.1 kWh/kg COD	99.3	53.5	
S. Song et al. [42]	10.0	10.0	10.0		96.0		
M.Y.A. Mollah et al. [43]	8.2	15.95	10.0		98.5		
C. Phalakornkule et al. [44]	9.6	30.0	5.0	1.0 kWh/m^3	95.0		
B.K. Nandi et al. [45]	4.0	4.17	30.0	3.11 KWh/Kg Fe	99.59		
A. Pirkarami et al. [46]	7.0	2.5	13.0	3.48 kWh/m^3	97.0		

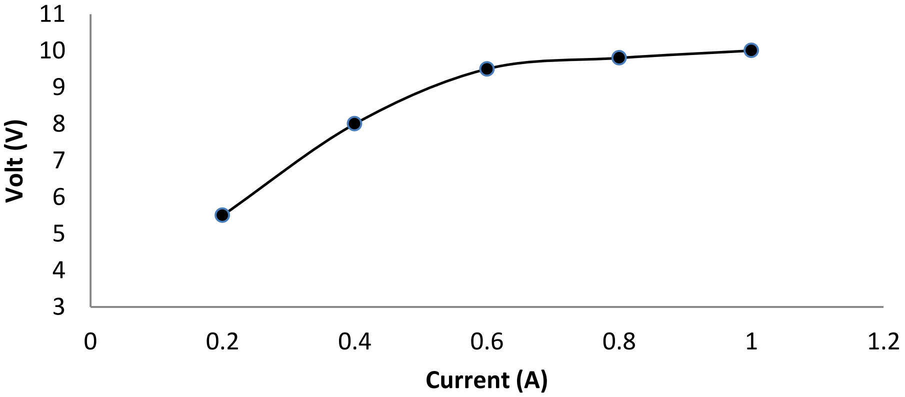


Fig. 8: Relation between current (A) and volt (V) of electrocoagulation cell, at the constant of operating time 15.0 min, initial pH 10.2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

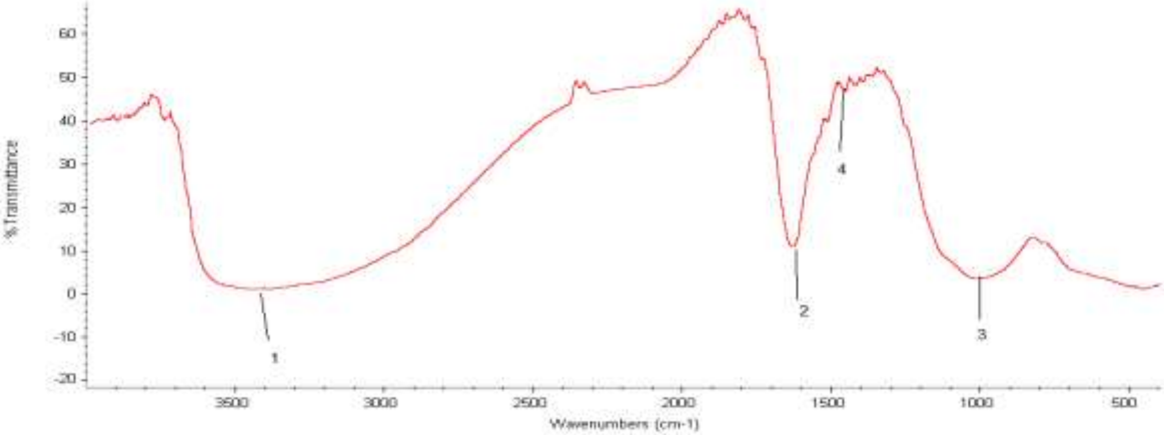


Fig.9: The infrared spectrum of treated textile wastewater containing Sunfron Blue SN-R at pH 4.13, operating time 15.0 min, current density 29.94 mA/cm^2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

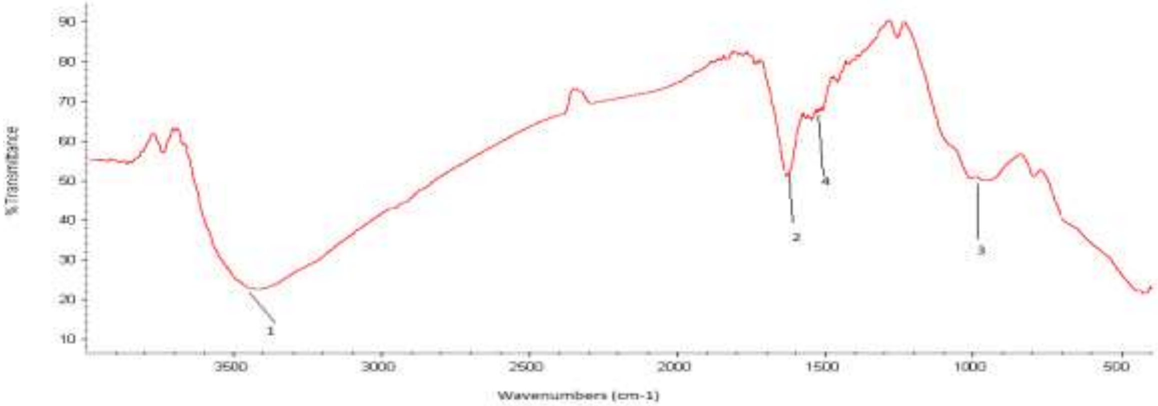


Fig. 10: The infrared spectrum of treated textile wastewater containing Sunfron Blue SN-R at pH 10.2, operating time 15.0 min, current density 29.94 mA/cm^2, inter electrode distance (3.2cm), stirring speed 600 rpm, and at room temperature.

4 Conclusions

The conventional methods of textile wastewater treatment are including the biological, adsorption, coagulation, flocculation, ozonation, and advanced oxidation processes. In general, most of these methods are characterized by less removal efficiency, high volume of hazardous sludge and high cost that makes their large-scale adaptation non-feasible. The electrocoagulation process is one of the operative methods can be used to separate color, turbidity, and organic contaminants from textile wastewater. In this study, higher removal efficiency of color, turbidity and COD have been obtained in acidic media with pH (3.3 and 4.95), and at pH 10.2. The optimum pH for the highest removal efficiencies were either 3.3 or 10.2. The experimental results indicated that removal efficiencies of color, turbidity, and COD are 95.7%, 99.5%, and 84.75% respectively at pH 10.2, 15 min of operation time, and current density 11.97 mA/cm^2. The electrocoagulation processes have no effect on the removal of physical parameters such as TDS, conductivity, and salinity. The treated wastewater was consumed 0.526 Kg Fe/m^3, specific electrical energy 4.8 KWh/Kg Fe, and the operating cost was 9.9 LE/m^3 of treated wastewater.

References

[1] Mashura Shammi, Mohammad Abul Kashem, Md. Mostafizur Rahman, Md. Delwar Hossain, Rashadur Rahman, M. Khabir Uddin, Health risk assessment of textile effluent reuses as irrigation water in leafy vegetable Basella alba, Int. J. Recycl. Org. Waste Agricult. (2016) 5:113–123.

[2] Zongping Wang, Miaomiao Xue, Kai Huang and Zizheng Liu, Textile Dyeing Wastewater Treatment, Advances in Treating Textile Effluent, (2011).

[3] Akshaya Kumar Verma, Rajesh Roshan Dash, Puspendu Bhunia, A review on chemical coagulation/flocculation technologies for removal of color from textile wastewaters, Environmental Management 93 (2012) 154-168.

[4] Khalida Muda , Azmi Aris, Mohd Razman Salim , Zaharah Ibrahim , Mark C.M. Van Loosdrecht, Azlan Ahmad, Mohd Zaini Nawahwi, The effect of hydraulic retention time on granular sludge biomass in treating textile wastewater, water research 45 (2011) 4711 -4721.

[5] R.G. Saratale, G.D. Saratale, J.S. Chang, S.P. Govindwar, Ecofriendly degradation of sulfonated diazo dye C.I. Reactive Green 19A using Micrococcus glutamicus NCIM-2168, Bioresource Technology 100 (2009) 3897–3905.

[6] Akshaya Kumar Verma, Rajesh Roshan Dash, Puspendu Bhunia, A review of chemical coagulation/flocculation technologies for removal of colour from textile wastewaters, Environmental Management 93 (2012) 154-168.

[7] Nurudeen Abiola Oladoja, Headway on natural polymeric coagulants in water and wastewater treatment operations, Water Process Engineering 6 (2015) 174–192.

[8] Mrinmoy Mondal, Sirshendu De, Treatment of textile plant effluent by hollow fiber nanofiltration membrane and multi-component steady state modeling, Chemical Engineering 285 (2016) 304–318.

[9] J.M. Arnal, M.C. León, J. Lora, J.M. Gozálvez, A. Santafé, D. Sanz, J. Tena, Ultrafiltration as a pre-treatment of other membrane technologies in the reuse of textile wastewaters, Desalination 221 (2008) 405–412.

[10] Erkan Sahinkaya 1, Nigmet Uzal, Ulku Yetis, Filiz B. Dilek, Biological treatment and nanofiltration of denim textile wastewater for reuse, Hazardous Materials 153 (2008) 1142–1148.

[11] Emna Ellouze, Nouha Tahri, Raja Ben Amar, Enhancement of textile wastewater treatment process using Nanofiltration, Desalination 286 (2012) 16–23.

[12] Ahmed Mohamed Farid Shaaban, Azza Ibrahim Hafez, Mona Amin Abdel-Fatah, Nabil Mahmoud Abdel-Monem, Mohamed Hanafy Mahmoud, Process engineering optimization of nanofiltration unit for the treatment of textile plant effluent in view of solution diffusion model, Egyptian Journal of Petroleum 25 (2016) 79-90

[13] Meiqiang Cai, Jie Su, Yizu Zhu, Xiaoqing Wei, Micong Jin, Haojie Zhang, Chunying Dong, Zongsu Wei, Decolorization of azo dyes Orange G using hydrodynamic cavitation coupled with heterogeneous Fenton process, Ultrasonics Sonochemistry 28 (2016) 302–310.

[14] Virendra Kumar Saharan, Mandar P. Badve, Aniruddha B. Pandit, Degradation of Reactive Red 120 dye using hydrodynamic cavitation, Chemical Engineering Journal 178 (2011) 100– 107.

[15] Mohan M. Gore, Virendra Kumar Saharan, Dipak V. Pinjari, Prakash V. Chavan ,Aniruddha B. Pandit, Degradation of reactive orange 4 dye using hydrodynamic cavitation based hybrid techniques, Ultrasonics Sonochemistry 21 (2014) 1075–1082.

[16] Xiaoning Wang, Jinping Jia, Yalin Wang, Degradation of C.I. Reactive Red 2 through photocatalysis coupled with water jet cavitation, Hazardous Materials 185 (2011) 315–321.

[17] Enling Hu, Xinbo Wu, Songmin Shang, Xiao-ming Tao, Shou-xiang Jiang, Lu Gan, Catalytic ozonation of simulated textile dyeing wastewater using mesoporous carbon aerogel supported copper oxide catalyst, Cleaner Production 112 (2016) 4710-4718.

[18] Ali Kamel H. Al jibouri, Jiangning Wu, Simant Ranjan Upreti, Continuous ozonation of methylene blue in water, Water Process Engineering 8 (2015) 142–150.

[19] Jiangning Wu, Huu Doan, Simant Upreti, Decolorization of aqueous textile reactive dye by ozone, Chemical Engineering Journal 142 (2008) 156–160.

[20] José M. Aquino, Gabriel F. Pereira, Romeu C. Rocha-Filho, Nerilso Bocchi, Sonia R. Biaggio, Electrochemical degradation of a real textile effluent using boron-doped diamond or β-PbO_2 as anode, Hazardous Materials 192 (2011) 1275– 1282.

[21] Guohua Chen, Electrochemical technologies in wastewater treatment, Separation and Purification Technology 38 (2004) 11–41.

[22] Environmental Water, chapter 6 Water Treatment by Electrical Technologies, (2013) 155- 170 Elsevier B.V. All rights reserved.

[23] Erick Butler, Yung-Tse Hung, Ruth Yu-Li Yeh, and Mohammed Suleiman Al Ahmad, Electrocoagulation in Wastewater Treatment, Water 3 (2011) 495-525.

[24] V.Khandegar, Anil K. Saroha, Electrocoagulation for the treatment of textile industry effluent - A review, Environmental management 128 (2013) 949-963.

[25] Huijuan Liu, Xu Zhao, Jiuhui Qu, Electrochemistry for the environment, chapter 10 Electrocoagulation in water treatment, 2010.

[26] Upendra D. Patel, J.P. Ruparelia, Margi U. Patel, Electrocoagulation treatment of simulated floor-wash containing Reactive Black 5 using iron sacrificial anode, Hazardous Materials 197 (2011) 128– 136.
[27] M.Kobya, E. Gengec, E. Demirbas, Operating parameters and costs assessments of a real dyehouse wastewater effluent treated by a continuous electrocoagulation process, Chemical Engineering and Processing 101 (2016) 87–100.
[28] Farshid Ghanbari, Mahsa Moradi, A comparative study of electrocoagulation, electrochemical Fenton,electro-Fenton and peroxi-coagulation for decolorization of real textile wastewater: Electrical energy consumption and biodegradability improvement, Environmental Chemical Engineering 3 (2015) 499–506.
[29] Bassam Al Aji, Yusuf Yavuz, A. Savaş Koparal,Electrocoagulation of heavy metals containing model wastewater using monopolar iron electrodes, Separation and Purification Technology 86 (2012) 248–254.
[30] M. Kobya, E. Demirbas, O.T. Can, M. Bayramoglu, Treatment of levafix orange textile dye solution by electrocoagulation, Hazardous Materials B132 (2006) 183–188.
[31] Mahmut Bayramoglu, Mehmet Kobya, Orhan Taner Can, Mustafa Sozbir, Operating cost analysis of electrocoagulation of textile dye wastewater, Separation and Purification Technology 37 (2004) 117–125.
[32] Shuang Song, Zhiqiao He, Jianping Qiu, Lejin Xu, Jianmeng Chen, Ozone assisted electrocoagulation for decolorization of C.I. Reactive Black 5 in aqueous solution: An investigation of the effect of operational parameters, Separation and Purification Technology 55 (2007) 238–245.
[33] J. Castañeda-Díaz, T.Pavón-Silva, E.Gutiérrez-Segura, and A. Colín-Cruz, Electrocoagulation-Adsorption to Remove Anionic and Cationic Dyes from Aqueous Solution by PV-Energy, Journal of Chemistry Volume 2017, Article ID 5184590, 14 pages.
[34] Nasser M Abu Ghalwa, Alaa M Saqer and Nader B Farhat, Removal of Reactive Red 24 Dye by Clean Electrocoagulation Process Using Iron and Aluminum Electrodes, Chemical Engineering & Process Technology (2016).
[35] M. Chafi, B. Gourich , A.H. Essadki, C. Vial, A. Fabregat, Comparison of electrocoagulation using iron and aluminium electrodes with chemical coagulation for the removal of a highly soluble acid dye, Desalination 281 (2011) 285–292.
[36] N. Daneshvar, A. Oladegaragoze, N. Djafarzadeh. Decolorization of basic dye solutions by electrocoagulation: An investigation of the effect of operational parameters, Hazardous Materials B129 (2006) 116–122.
[37] Mehmet Kobya, Mahmut Bayramoglu, Murat Eyvaz, Techno-economical evaluation of electrocoagulation for the textile wastewater using different electrode connections. Hazardous Materials 148 (2007) 311–318.
[38] Mehmet Kobya, Orhan Taner Can, Mahmut Bayramoglu, Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes, Hazardous Materials B100 (2003) 163–178.
[39] Inoussa Zongo, Amadou Hama Maiga, Joseph Wéthé, Gérard Valentin, Jean-Pierre Leclerc, Gérard Paternotte, Francois Lapicque, Electrocoagulation for the treatment of textile wastewaters with Al or Fe electrodes: Compared variations of COD levels, turbidity and absorbance, Hazardous Materials 169 (2009) 70–76.
[40] M.Kobya, E. Gengec, E. Demirbas, Operating parameters and costs assessments of a real dyehouse wastewater effluent treated by a continuous electrocoagulation process, Chemical Engineering and Processing 101 (2016) 87–100.
[41] Bahadır K. KÖrbahti, Abdurrahman Tanyolac, Continuous electrochemical treatment of simulated industrial textile wastewater from industrial components in a tubular reactor, Hazardous Materials 170 (2009) 771–778.
[42] Shuang Song, Jie Yao, Zhiqiao He, Jianping Qiu, Jianmeng Chen Effect of operational parameters on the decolorization of C.I. Reactive Blue 19 in aqueous solution by ozone-enhanced electrocoagulation, Hazardous Materials 152 (2008) 204–210.
[43] Mohammad Y.A. Mollah, Saurabh R. Pathak, Prashanth K. Patil, Madhavi Vayuvegula, Tejas S. Agrawal, Jewel A.G. Gomes, Mehmet Kesmez, David L. Cocke,Treatment of orange II azo-dye by electrocoagulation (EC) technique in a continuous flow cell using sacrificial iron electrodes, Hazardous Materials B109 (2004) 165–171
[44] Chantaraporn Phalakornkule , Suprangpak Polgumhang, Warangkana Tongdaung, Benjawan Karakat, Thanawin Nuyut, Electrocoagulation of blue reactive, red disperse and mixed dyes, and application in treating textile effluent, Environmental Management 91 (2010) 918–926.
[45] Barun Kumar Nandi, Sunil Patel, Effects of operational parameters on the removal of brilliant green dye from aqueous solutions by electrocoagulation, Arabian Journal of Chemistry (2017) 10, S2961–S2968.
[46] Azam Pirkarami, Mohammad Ebrahim Olya, Removal of dye from industrial wastewater with an emphasis on improving economic efficiency and degradation mechanism, Journal of Saudi Chemical Society (2017) 21, S179–S186.

[47] Alena Tetreault, Electrocoagulation Process for Wastewater Treatment, Meat & Livestock Australia Limited ACN, February 2003.

[48] F. Orts, A.I. del Río, J. Molina, J. Bonastre, F. Cases, Study of the Reuse of Industrial Wastewater After Electrochemical Treatment of Textile Effluents without External Addition of Chloride, Int. J. Electrochem. Sci., 14 (2019) 1733 – 1750

[49] Maryam Khadim Mbacké, Cheikhou Kane, Ndeye Oury Diallo, Codou Mar Diop, Fabien Chauvet, Maurice Comtat, Theo Tzedakis, Electrocoagulation process applied on pollutants treatment- experimental optimization and fundamental investigation of the Crystal violet dye removal. Environmental Chemical Engineering, 4 (2016) 4001-4011.

[50] Y. Mountassir, A. Benyaich, P. Berçot, M. Rezrazi, Potential use of clay in electrocoagulation process of textile wastewater: Treatment performance and flocs characterization, Environmental Chemical Engineering 3 (2015) 2900–2908.

[51] Jamshid Behin, Negin Farhadian, Mojtaba Ahmadi, Mehdi Parvizi, Ozone assisted electrocoagulation in a rectangular internal-loop airliftreactor: Application to decolorization of acid dye, Water Process Engineering 8 (2015) 171–178.