TREATMENT OF TEXTILE WASTEWATER USING ELECTROCOAGULATION

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It is certified that contents and form of thesis entitled "Treatment of Textile Wastewater using Electrocoagulation" submitted by Aaminah Imran, Muhammad Hassan Rasheed, Mujeeb Sikandar and Wasiq Attique have been found satisfactory for the requirement of the degree.

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List of Abreviations

^{o}C	Degree Celsius
%	Percentage
COD	Chemical Oxygen demand
DC	Direct Current
EC	Electrocoagulation
EF	Electro-floatation
FAS	Ferrous Ammonium Sulfate
Fe	Iron
HRT	Hydraulic Retention Time
kg	Kilogram
mg/L	Milligram per liter
mL	milliliter
Rs.	Rupees
SDG	Sustainable Development Goals
TDS	Total Dissolved Solids
V	Volts

Abstract

Electrocoagulation is a rapidly emerging technique for wastewater treatment due to its capability of removing contaminants like hydrocarbons, suspended solids and emulsified oils that are difficult to remove by filtration or other conventional chemical treatment techniques. This treatment technique is efficient because of the production of hydrogen gas bubbles at the cathode. Organic froth is formed on the top of wastewater treated which can additionally be used to produce alcohols and ketones as energy fuels. In this research work, iron anode and copper cathode were used throughout the experiments. Initially 800 mL of textile wastewater sample was used and the impact of voltage, pH and temperature on the removal efficiency of chemical oxidation demand (COD) was tested and studied on a lab scale. It was noticed that the COD removal efficiency increased with an increase in voltage and pH. Optimization of the system was done at 12 volts. Wastewater at pH values from 6 to 10 was tested and it was found from the results that basic conditions favored the case of electrocoagulation. The COD removal efficiency of the textile wastewater sample decreased with an increase in temperature. A pilot scale study was done in a batch system using renewable energy from the solar panel in order to assess the removal efficiency with respect to time. Wastewater samples were taken from the same sampling point at different time intervals and their COD percentage removal was calculated. The removal efficiency increased with an increase in treatment time. Furthermore, electrocoagulation was performed in a continuous system at a flow rate of 3.36 L/h. The removal efficiency obtained from this system was found out to be 84%. Hydrogen gas generated due to the electrocoagulation process was collected and analyzed through gas chromatography. The cost of treating textile wastewater of 6 L in the electrocoagulation unit was found to be Rs. 0.02/Liter.

Keywords: Electrocoagulation, Textile wastewater, pH, Temperature, Voltage, Chemical oxidation-demand

Chapter 1

Introduction

Water is an essential element of our life. Providing clean water to the world population is the most important challenge humanity is facing today as it is used for domestic as well as industrial purposes. Domestic uses of water include drinking, washing and food preparation while industries use water for fabricating, cooling, diluting and other processes. Proper management and distribution of water resources is necessary in order to conserve water for future generations. Effective water management relies on the participation of stakeholders, including local communities. According to sustainable development goal (SDG) No. 6 "Ensure the availability and sustainable management of water and sanitation to all". Water scarcity affects more than 40% of the people around the world which is an alarming situation. In 2011, 41 countries were experiencing water stress-10 that their fresh water sources are depleting and must now rely on alternative resources. By 2050, it is projected one in four people will be affected by water shortage. In order to discharge effluent wastewater from industries into water bodies' preliminary treatment is essential to keep water sources safe from pollutants. There is a demand for new treatment techniques as world population is increasing, so does the demand for water consumption. Waterborne diseases are common in developing countries due to lack of knowledge for the wastewater treatment (Perlman, 2017). The conventional physio-chemical treatment processes are coagulation, filtration and reverse osmosis but these processes generate huge amount of waste sludge that is difficult to manage later on.

Electrocoagulation is an emerging electrochemical process consisting anodes and cathodes to treat effluent wastewater. It requires less area, and has less bound water in their sludge as compare to conventional methods. It has proven to be effective in removing contaminants from the wastewater that are difficult to remove by filtration and other chemical treatment processes. It removes COD, BOD, suspended solids, heavy metals, refractory oils and emulsified oils. One of the industries that produces toxic pollutants is a textile industry whose effluent wastewater is difficult to treat using other conventional treatment techniques, but electro-coagulation is one efficient technology to treat textile wastewater. Electrochemical methods have various benefits over other treatment techniques including environmental compatibility, energy efficiency, selectivity, amenability to automation and cost effectiveness. It has simple equipment, easy operation and rapid settling. Considering the effectiveness of electrocoagulation in removing COD and other parameters from the wastewater this work is proposed to test the technology on textile industrial wastewater of Pakistan.

1.1 Main reactions

Electrocoagulation has several similarities with chemical coagulation method, but also significantly different due to side reactions at the anode and cathode. Chemical coagulation requires an addition of a chemical coagulant but electrocoagulation doesn't require the input of any chemical coagulant. Whereas in the case of electrocoagulation, the coagulant is introduced from the anode. The dissolution of the metal takes places at the anode which produces metal ion that act as a coagulant. The equation for the dissolution of the metal such as iron anode can be seen from equation 1. Moreover, the other reaction happening during electrocoagulation is the formation of hydrogen, which can be seen from equation 2 and 3. (Vepsäläinen, 2012).

$$Fe_{(s)} \longrightarrow Fe^{2+}_{(aq)} + 2e^{-} \quad \text{(eq. 1)}$$

$$H_2O \longrightarrow 2H^{+} + \frac{1}{2} O_{2(g)} + 2e^{-} \quad \text{(eq. 2)}$$

$$2H^{+} + 2e^{-} \longrightarrow H_{2\,(g)} \quad \text{(eq. 3)}$$

There are generally three steps involved in electrocoagulation process (Gomes et al., 2007):

1. Formation of coagulant by electrolytic dissolution of sacrificial electrodes such as iron or aluminum.
2. Destabilization of suspended solids
3. Formation of flocs that is flocculation

These steps can be viewed from the figure 1.1 below.

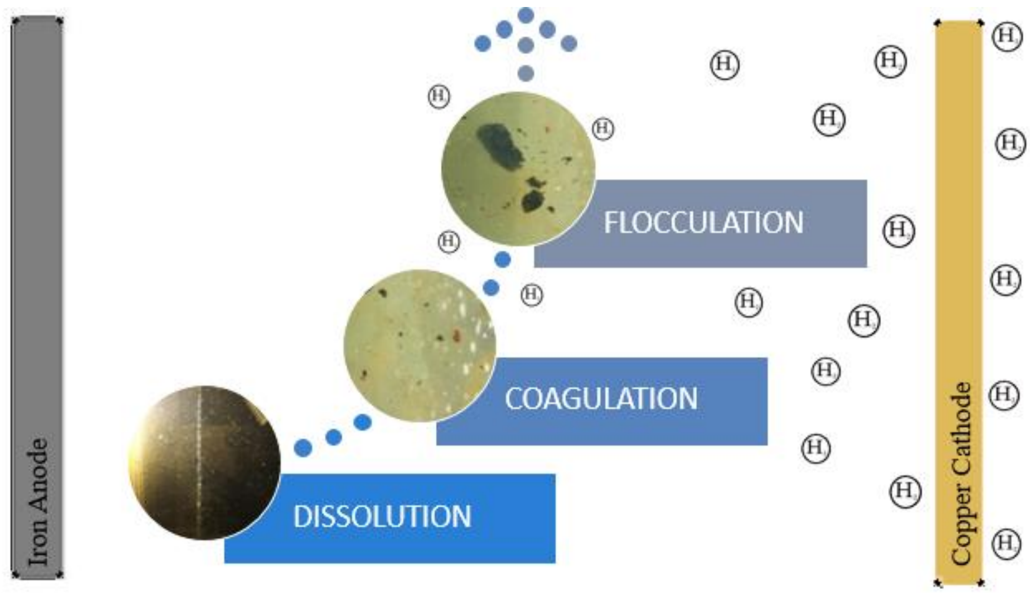

Figure 1.1: An illustration of the three steps of electrocoagulation

An electrode which produces coagulant in the solution consists of iron or aluminum. In case of iron it can be dissolved to give divalent ion Fe(II) or trivalent ion Fe(III). Divalent ion is further oxidized to trivalent ion that increases the removal efficiency of pollutants. These ions act as coagulation agents for suspended solids present in the solution. This reaction takes place at anode. The reaction first starts by neutralizing the charges of the particles due to release of metal ions in the water. Other electrochemical reactions that take place are:

- Production of hydrogen gas at cathode
- Reduction of metal ions at cathode

There is a term called electro-flotation (EF) in which oxygen bubbles are produced while in case of electro-coagulation (EC) only hydrogen bubbles are produced on the cathodes with which flocs float to the surface. The efficiency of flotation depends on the size of the bubbles formed. Smaller size of the bubbles gives more surface area for particles to attach then larger bubbles (Emamjomeh, 2006).

1.2 Problem statement

Chemical coagulation generates large volumes of sludge with high bound water content that can be slow to filter and difficult to dewater. These treatment processes also tend to increase the total dissolved solids (TDS) content of the effluent, making it unacceptable for reuse within industrial applications.

An electro-coagulated floc contains less bound water, is more shear resistant and is more readily filterable or can easily be separated from the top.

1.3 Objectives of project

Following are the objectives of this project:

- The removal of COD from wastewater
- Optimization of the system using different parameters
- Production and analysis of hydrogen gas

1.4 Electrocoagulation sludge

Settling characteristics of sludge are important in order to determine the performance of sludge dewatering system. In conventional treatment techniques, it takes a lot of cost and space to dispose of sludge but in electrocoagulation organic froth produced on top can be treated to get alcohols and ketones and they can be used as energy fuels. The flocs formed in electrocoagulation as compared to chemical coagulation are large and are more stable making them amenable to separation.

1.5 Scope of project

The purpose of the project is to ensure safe water quality to the community using electrocoagulation as a treatment technique. This project focuses on textile industry which is a backbone of Pakistan having large amount of effluent wastewater. The effluent wastewater should be treated before discharging it into water bodies. Electrocoagulation was used in order to remove COD content in the wastewater which is the most important objective of this project. On a lab scale 6 L of wastewater was treated which can be upscale to pilot study as a future work.

Chapter 2

Literature Review

2.1 Treatment of the textile wastewater by combined electrocoagulation using Aluminum and Iron electrodes

This study was carried out by Mehmet Kobya, Orhan Taner Can and Mahmut Bayramoglu from Gebza Institute of Technology, Turkey in 2005. The study was carried out to investigate the treatment of textile wastewater through electrocoagulation with the use of Iron and Aluminum electrodes. The main objective of this study was to investigate the effects of different parameters like pH, current density and operating time on the removal efficiency of Chemical Oxygen Demand (COD) and turbidity.

The findings of this study are shown below in figure 2.1.

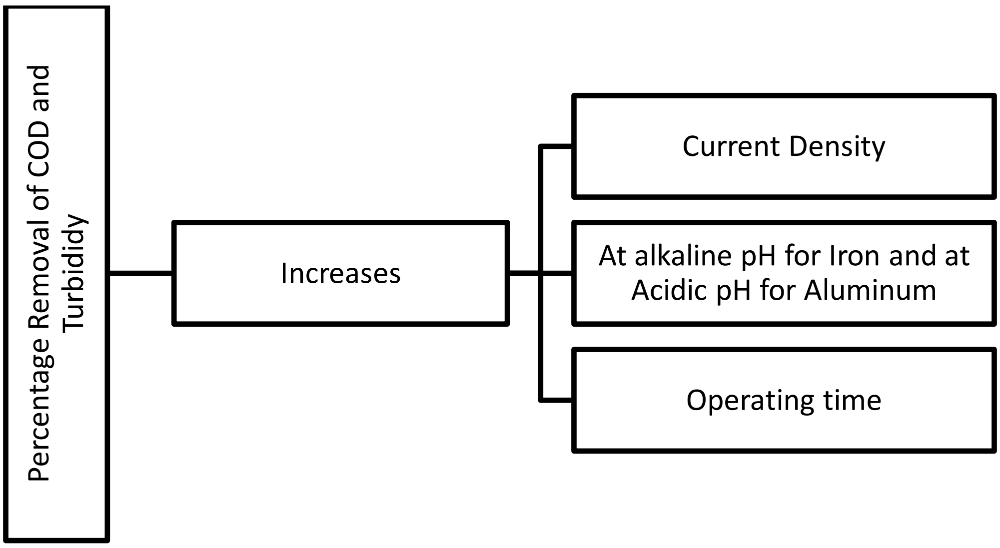

Figure 2.1: Conclusions drawn from Kobya et al. (Kobya et al., 2003)

COD removal and turbidity removal was high in acidic medium for aluminum and in basic medium for iron. Similarly, experiments were conducted at different current densities and it was found that the removal efficiency for both COD and turbidity increased with increase in Current Density. Same trend was noticed for operating time. But with the operating time and current densities increased, charge loading and energy consumption also increased. So Kobya et al. concluded that the electrocoagulation is pH dependent process and iron electrodes consume less energy at low current densities than aluminum electrodes. So, the decision for use of sacrificial electrodes is largely dependent on these operating costs (Kobya et al., 2003).

2.2 Hydrogen Gas Production from Tannery Wastewater by Electrocoagulation of a Continuous Mode with Simultaneous Pollutants Removal

This study was done by Abdalhadi Deghles and Ugur Kurt from Yildiz Technical University, Istanbul, Turkey. The objective of this study was to investigate the removal efficiencies of different pollutants (color, COD, Chromium) under different operating parameters but Hydrogen gas was also analyzed simultaneously and the factors affecting its production rate.

The results Deghlas et al. concluded were when aluminum electrodes were used, at pH 6 with current density of $14mA/cm^2$ and an operating time of 125 minutes, the removal efficiencies were 73,94 and 100% for COD, color and Cr respectively. The hydrogen energy yield was 16% of total electrical energy provided to the system. Whereas, when iron electrodes were used in the experimental runs at pH 7 with same current density and time, the efficiencies achieved were 67, 93 and 100% for COD, color and Cr respectively. The hydrogen energy yield was 15% of total electrical energy provided to the system.

The study shows that EC continuous mode is an effective treatment system for wastewater (because of pollutants removal) and energy recovery because of hydrogen gas production (Deghles and Kurt, 2017).

2.3 Hydrogen recovery from the electrocoagulation treatment of dye-containing wastewater

This study was done by Chantaraporn Phalakornkule, Pisut Sukkasem and Chinnarat Mutchimsatthab. The study emphasized on the hydrogen gas recovery from a continuous EC system treating textile wastewater. To do so, continuous electrocoagulator was connected to sedimenters and a tank in which gas was being separated. The separation gas tank's configuration was same to that of anaerobic sludge bed. The hydrogen yields were collected from theory-based formulas. The dyes present in the wastewater were Reactive Blue 140 and Direct Red 23. The electrical energy demand for reactive blue 140 was higher i-e 1.42 kWh_em^{-3} then for Direct Red 23 which came out to be 0.69 kWh_em^{-3}. The energy yield of hydrogen gas harvested from the system was $0.2kWhm^{-3}$. (Phalakornkule et al., 2010)

In addition to hydrogen gas recovery, the experiments were run to check the quality of treated wastewater. The color removal efficiency came out to be 99% which is excellent as no additional chemicals are needed for such high removal. The COD removed from the wastewater was 93% and Total Solids removal was also satisfactory i-e 89%

2.4 Treatment of colored and real industrial effluents through electrocoagulation using solar energy

This study was done by Pirkarami A., Olya ME and Tabibian S. in 2013 to investigate the removal of two specific dyes from both synthesized and real industrial effluents through Electrocoagulation. The dyes were Acid Orange 2 with formula [sodium 4-[(2E)-2-(2-oxonaphthalen-1-ylidene) hydrazinyl] benzenesulfonate] and Reactive Blue 19 with formula [2-Anthracenesulfonicacid,1-amino-9,10-dihydro-9,10-dioxo-4-[[3-[[2-(sulfooxy) ethyl] sulfonyl] phenyl] amino]-,sodium salt (1:2)] . The system ran using solar cells for economic efficiency.

Like other studies, this study also tested the effects of different parameters upon the removal efficiency of COD and TOC. These parameters included pH, temperature, type of anode used and current density. The optimum current density was same for both dyes which was 45 A/m^2. Other parameters were also optimized. Iron anode was used at 25^0C temperature, pH at 7 and electrolyte concentration was optimized at 15 mg/L (Pirkarami et al., 2013).

2.5 Electrocoagulation process to Chemical and Biological Oxygen Demand treatment from carwash grey water in Ahvaz megacity, Iran

This study was undertaken by Mohammad Javad Mohammadi, Afshin Takdastan, Sahand Jorfi and others in Iran in 2017. This study is different from other reviewed industries as in this study, the authors didn’t use industrial wastewater but they collected carwash grey water from the streets and experimented on that wastewater through electrocoagulation to remove COD and BOD so that their streets can be made safer as this particular wastewater can contaminate drinking water resources, and it is also very harmful for agricultural and industrial resources. The parameters that were studied were COD initial concentration, BOD initial concentration, pH of the wastewater, voltage applied to the system and the operating time. Final COD and BOD levels were measured through spectrophotometer. They also studied the effects of contact time of electrodes to the wastewater, initial Ph of wastewater, electric potential applied across the electrodes and voltage levels on the removal efficiencies of COD and BOD levels. The statistical analysis was done through SPSS 16 (Mohammadi et al., 2017).

The study concluded that Electrocoagulation process application is vast and can be used for other types of wastewater, not only industrial or textile wastewater.

Chapter 3

Methodology

In order to optimize the system for textile wastewater, the parameters were chosen on the basis of their utmost importance as well as according to the waste water characteristics. The selected parameters were then optimized with reference of their effect on chemical oxygen demand (COD) reduction percentage. The parameters used for the optimization of the system are:

1) Voltage.
2) pH
3) Temperature.

The samples were collected from two different textile industries, Kohinoor Textile Mills and Kay & Emms, in order to get the representative sample of textile wastewater.

3.1 Voltage

Electrocoagulation is a two-stage process i.e. destabilization and aggregation of colloidal particles. The second stage is usually more time consuming as compared to the first stage. It can be reduced by increasing the voltage. Because retention time and voltage applied both are relative parameters, changing the voltage changes the retention time or time required for the system to reach equilibrium stage.

More the voltage is applied more is the percentage removal. However, it does not mean voltage can be increased up-to any extent to achieve the required removal efficiency in less time. Because at higher voltage electrodes tends to degrade faster and it only increases the power consumption. Which is why voltage had to be optimized on the first priority in order to find out the optimal voltage.

In order to optimize voltage, several experiments were conducted at voltage range 8 to 14 volts. All of the experiments were conducted for the same interval of time, i.e. 15 minutes, and their respective COD percentage removal was calculated.

3.2 pH

After the optimization of voltage, our second parameter was the optimization of the retention time with respect to pH. As due to number of different process in the textile industry, different chemicals are used as required at different times, which changes the pH of the effluent wastewater. Hence, pH of the wastewater is not constant throughout the day and it varies accordingly (Savin and Butnaru, 2008). And the literature review suggest that the efficiency of the electrocoagulation varies with pH which is why the effect of pH on the removal efficiency had to be examined in order to alter the retention time accordingly (Naje et al., 2015).

3.3 Temperature

The third and last parameter in our study was the effect of temperature on the removal efficiency. Textile industry discharges wastewater mainly around 40^{o}C. That's why in order to decide whether would it be viable to treat wastewater directly as it discharges or wait for it to cool down and then treat it.

3.4 Experimental setups

Initially a lab scale setup was used to optimize voltage, pH and temperature. The sample taken for each and every experiment was constantly 800 ml and the duration of all the experiments was 15 minutes each. The beaker used for the lab scale experiment is present in the figure 3.1 below.

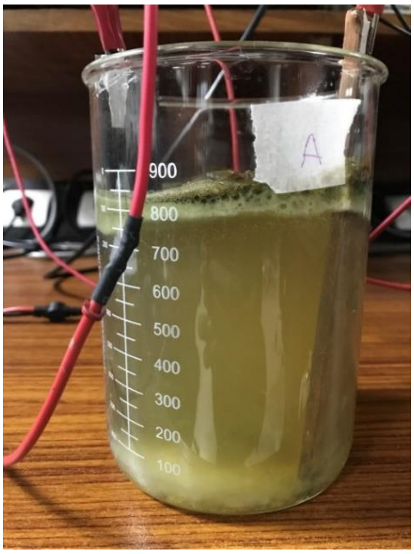

Figure 3.1: Result after electrocoagulation of an 800 mL sample of textile wastewater

Before every experiment beaker was rinsed with tap water and afterwards with distilled water and then the sample was collected in it. A pair of electrode, Copper cathode and iron anode, were used for every experiment. After each experiment COD removal percentage was calculated in order to find out the optimal values.

3.5 Power Supply

DC voltage was supplied using DC power supply. The DC power supply can provide the maximum voltage of 35 volts. Also, it has an in-built circuit breaker that breaks when the short circuit occurs. The power supply used can be seen from figure 3.2.

Figure 3.2: Power supply that was used to provide voltage to the electrodes

3.6 Batch system

The results obtained from lab scale setup were used in an upgraded lab scale project which had a capacity to treat 6 liters of water. The purpose of conducting batch experiment was to determine the retention time for calculating the flow rate of continuous system. This was done by taking samples after regular intervals and measuring percentage removal.

A total of three pair of electrodes, three iron anodes and three copper cathodes, were used for up graded lab-scale batch system. All of the electrodes were kept 4 cm apart using the side brackets of the reactor and all of them were connected in a parallel manner in order to ensure equal voltage supplied. The reactor had a capacity to treat 6 liters of water. The experimental setup of the batch system can be seen from figure 3.3.

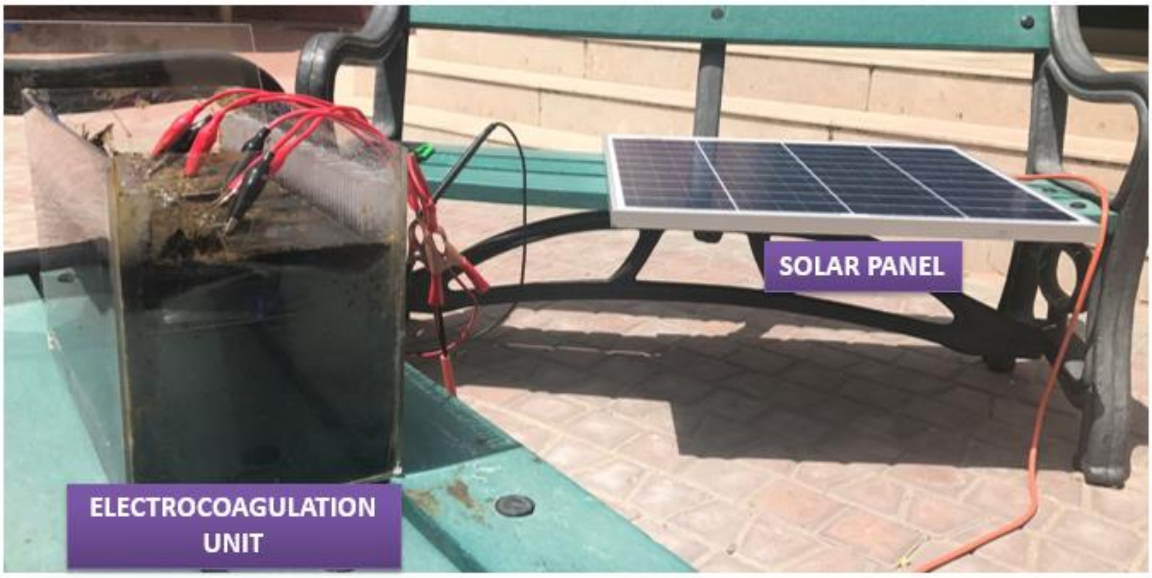

Figure 3.3: Batch system running at 12V with 3 pairs of iron anode and copper cathode placed parallel to each other

3.7 Continuous system

Using the experimental results of batch reaction, operating conditions for continuous system was set. Electrocoagulation unit was sealed properly in order to ensure there is no leakage of gas, using silicon. During electrocoagulation gas is produced at the cathode which helps in agitating the colloidal particles and also to bring froth to the top. This gas was collected in the gas sampling bag in order to examine either the gas produced is hydrogen or not. The experimental setup of the continuous system can be seen from figure 3.4.

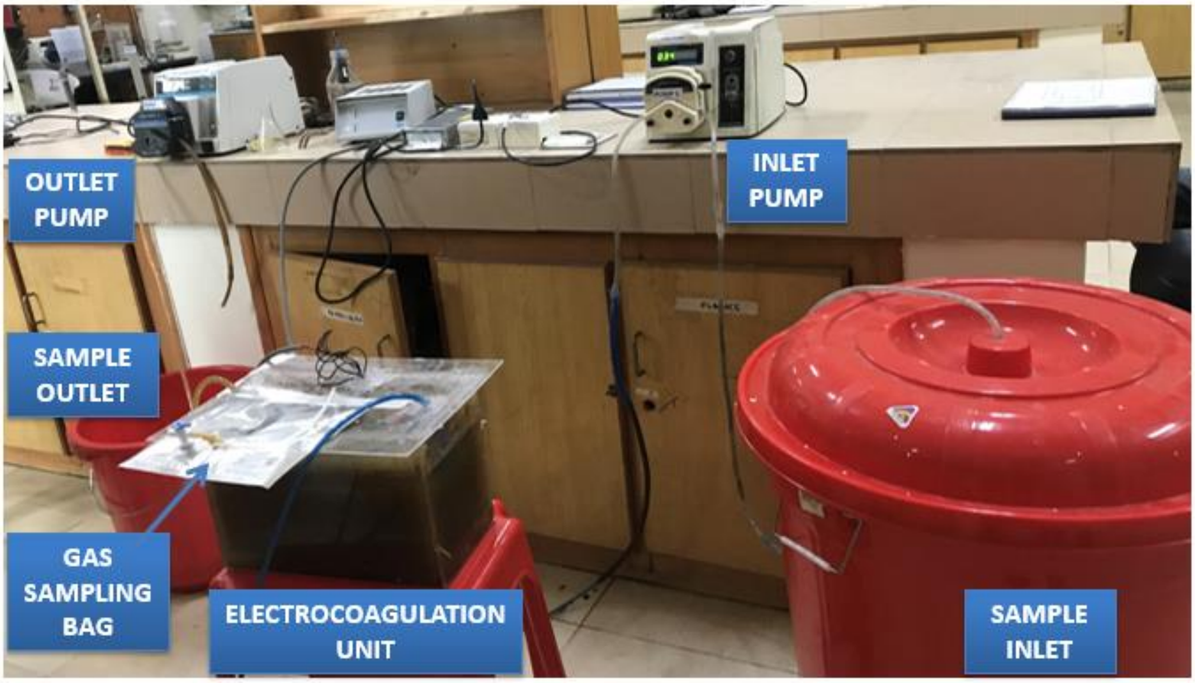

Figure 3.4: Continuous system with an electrocoagulation unit, a gas sampling bag, two pumps and two buckets

There was just one outlet left for the gas exit and gas collection bag was connected to it to store the gas produced. The gas sampling bag used can be seen from figure 3.5.

Figure 3.5: Gas sampling bag was used to collect the hydrogen gas produced from electrocoagulation

Two peristaltic pumps were used. One of the pumps was used for the inlet and the other pump was to pump the effluent out of the system. Both pumps were operated at same flow rate. The type of pump used during the continuous system can be seen from figure 3.6.

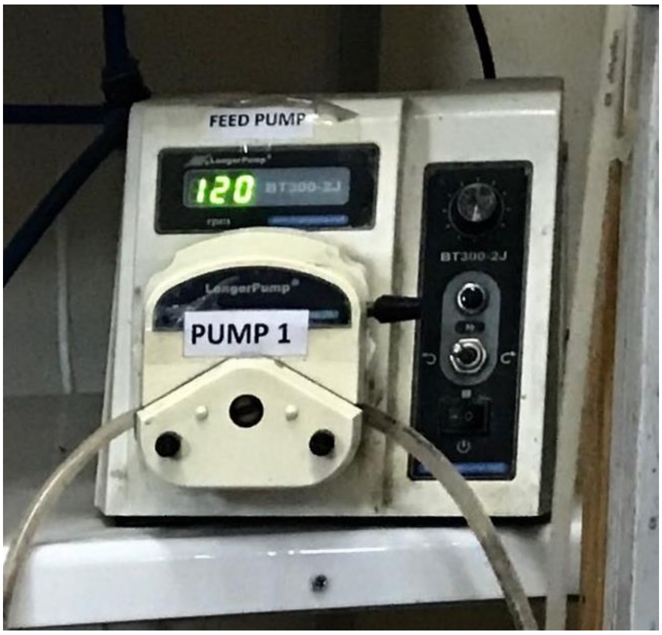

Figure 3.6: Pump that was used in the continuous system

3.8 Chemical Oxygen Demand

Chemical Oxygen Demand (COD) is a measure of amount of impurities present in wastewater which is determined by determining the amount of oxygen required in order to decompose organic matter and oxidized inorganic chemicals i.e. Ammonia and Nitrate.

A COD vial is first rinsed with tap water and then from distilled water. After that filtered 2.5 ml of sample, 1.5 ml potassium dichromate and 3.5 ml of H_2SO_4 is added in the vial. Using the same method, a 'blank' vial is also prepared to use as a reference. Both vials are then digested in the COD reactor at 150°C for 2 hours.

After that COD vial is titrated with FAS using ferroin (ortho phenanthroline) indicator. Using the equation 4 COD value is find out.

$$COD\ (mg/L) = \frac{(A-B)*N*8000}{Volume\ of\ sample} \quad \text{(eq. 4)}$$

A = Volume of FAS used to titrate blank sample (mL) N = Normality of FAS (N)

B = Volume of FAS used to titrate wastewater sample (mL)

Chapter 4

Results and Discussion

4.1 Lab Scale Experiments

This study is mainly focused on the treatment of textile wastewater for determining effects of the basic operating parameters on system performance. The parameters under study were the voltage provided to the system, the initial pH of the wastewater and the initial temperature of the wastewater that enters the system. The results obtained from the voltage experiment are mentioned below in table 4.1. The increasing trend from figure 4.1 states that with an increase in voltage, an increase in COD removal efficiency was seen. Maximum COD removal efficiency of 82% was achieved at 14V at a running time of 12 minutes. The reason we didn't precede any further than 12 minutes was because we encountered a problem of short circuiting at 14V. Thus we decided to optimize our system at 12V where a removal efficiency of 75% was observed. Initial COD of the sample in this case was 1440 mg/L

Table 4.1: The effect of voltage on the percentage removal efficiency with a running time of 15 minutes

Voltage (V)	COD (mg/L)	COD Percentage removal (%)
8	400	71
10	400	71
12	360	75
14	240	82

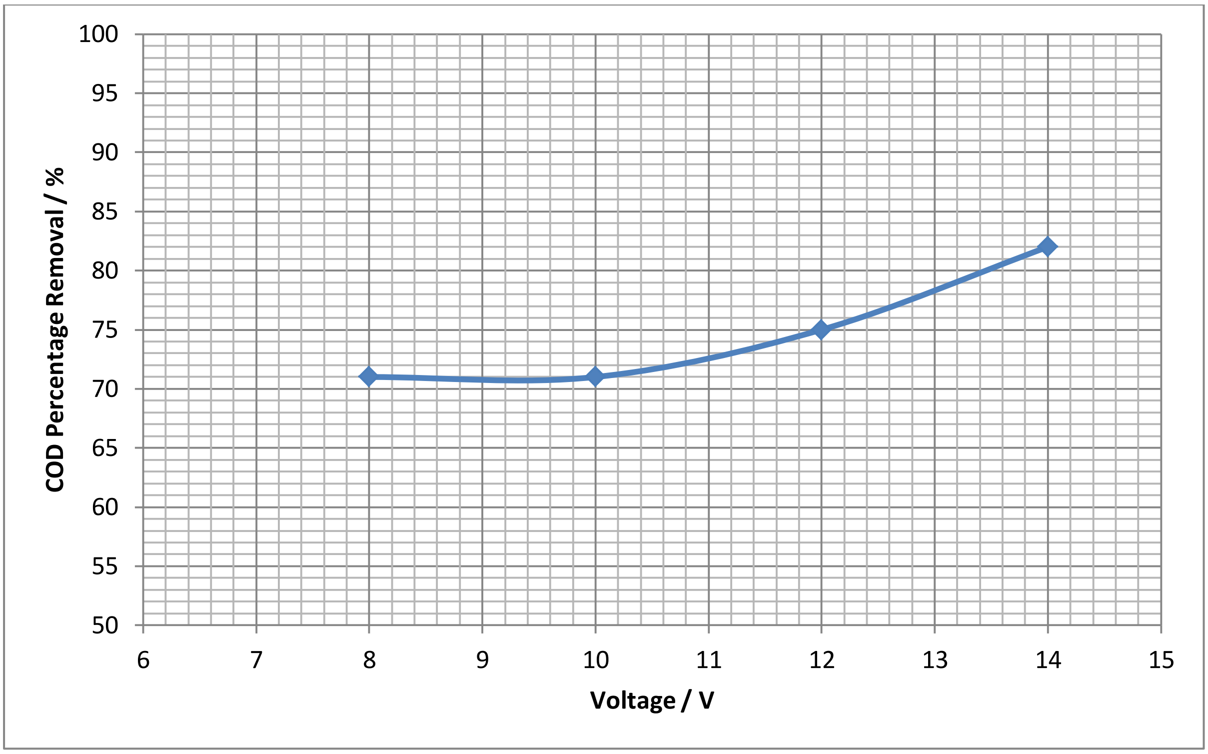

Figure 4.1: The effect of voltage on the COD percentage removal with a running time of 15 minutes

Since industries have a pH range from 6 to 10 thereby a test run was performed at the same range. The results obtained from the voltage experiment are mentioned below in table 4.2. Initial COD of the sample in this case was 1120 mg/L. It can be seen from figure 4.2 that maximum removal efficiency of 85.7% was obtained at a pH of 10 (basic). At an acidic pH (pH 6), the COD removal efficiency was found out to be minimum. This higher value of removal efficiency at basic pH is due to the formation of ferric hydroxide, and this compound maybe responsible for the removal of the major part of the impurities in textile wastewater.

Table 4.2: The effect of pH on the percentage removal efficiency with a running time of 15 minutes

pH	COD (mg/L)	COD Percentage removal (%)
6	800	28.6
7	560	50.0
8	320	71.4
9	240	78.6
10	160	85.7

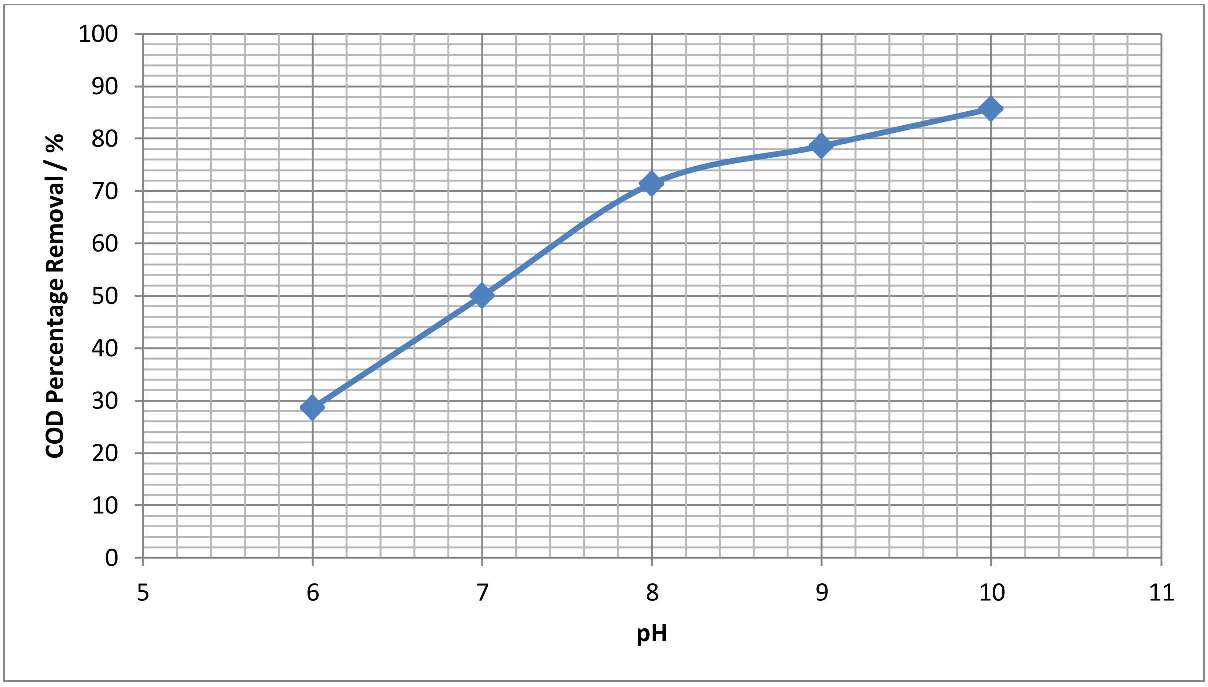

Figure 4.2: The effect of pH on the COD percentage removal with a running time of 15 minutes

Furthermore, when the final samples of pH 6 and pH 10 were later observed after their settling had taken place. It was observed that the acidic sample had more scum than the basic sample at the top. It was also observed that the sludge settled at the bottom of the beaker was more in the case of basic pH than in the acidic pH. Both of these observations can be observed from figure 4.3 and 4.4.

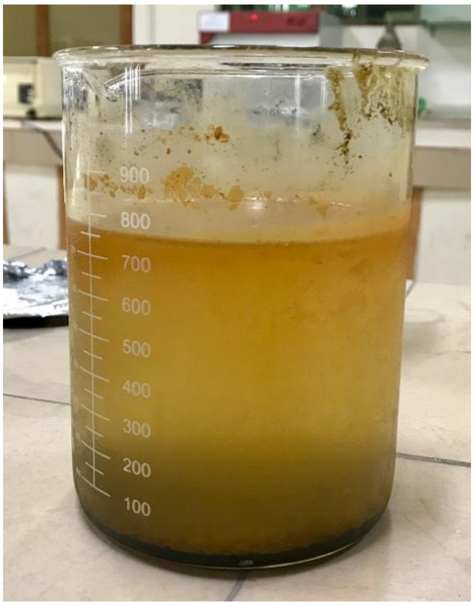

Figure 4.3: Final sample at pH 6 after settling

Figure 4.4: Final sample at pH 10 after settling

The results obtained from the voltage experiment are mentioned below in table 4.3. A decreasing trend can be observed from figure 4.5. Initial COD of the sample in this case was 1400 mg/L. There was not much of a difference in COD percentage removal observed at room temperature (22°C) and at 40°C but still a decrease from 73.2% to 71.4% was seen. As soon as the temperature was raised to 60°C the COD percentage removal dropped relatively more to 48.6%. Thus after this experiment we decided to run our batch system at the following operating conditions:

- A voltage supply of 12 volts
- Wastewater of basic pH (our sample had a pH of 8)
- Room temperature

Table 4.3: The effect of temperature on the percentage removal efficiency with a running time of 15 minutes

Temperature (°C)	COD (mg/L)	COD Percentage removal (%)
22	320	73.2
40	400	71.4
60	720	48.6

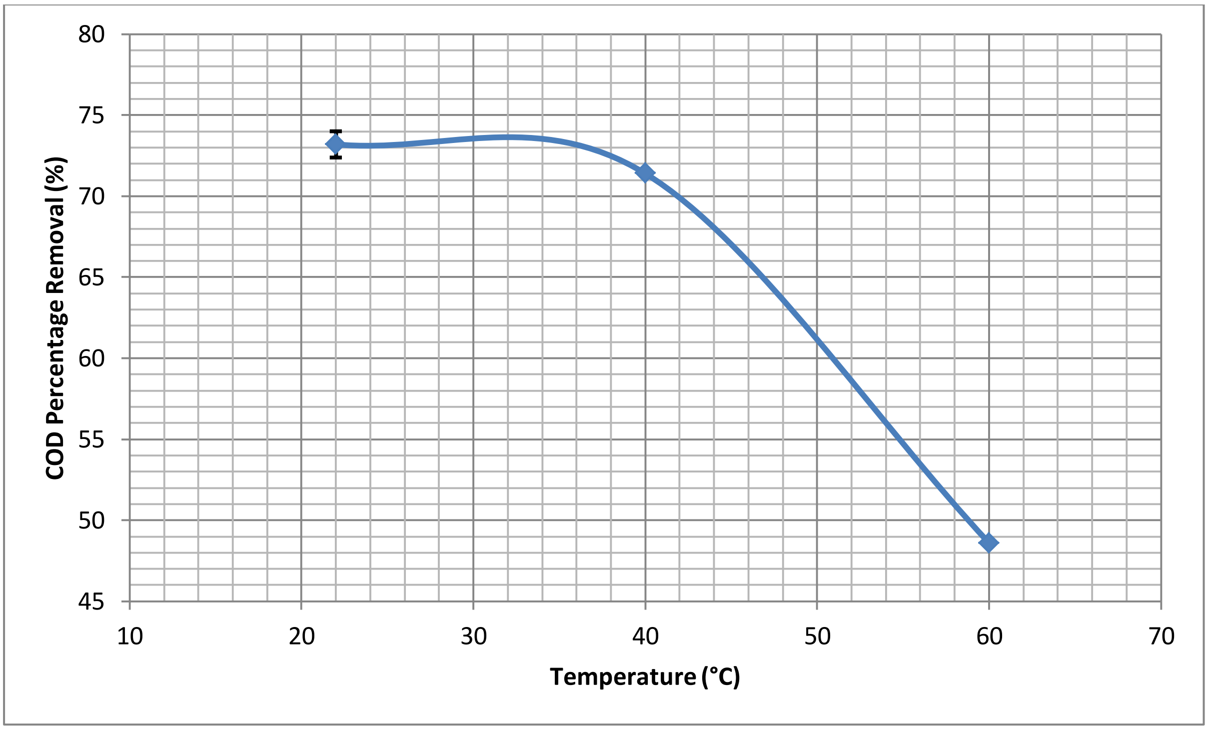

Figure 4.5: The effect of temperature on the COD percentage removal with a running time of 15 minutes

4.2 Batch System

A total of 6 samples were drawn at different time intervals as the reaction continued and this can be seen from figure 4.6.

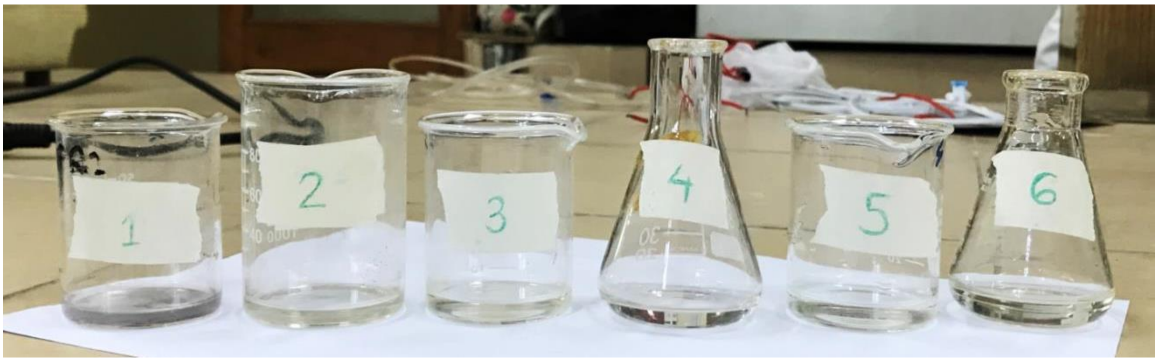

Figure 4.6: Samples drawn at different time intervals from the batch system at 12V, pH 8 and room temperature

The results obtained from the batch system can be seen from table 4.4 and figure 4.7. A COD removal percentage of 88.6% was achieved at one hour and forty-seven minutes. The chemical oxygen demand attained at one hour and forty-seven minutes was of 160 mg/L. The conclusion drawn from the results is that with an increase in treatment time, the COD removal percentage also increased.

Table 4.4: The effect of treatment on the percentage removal efficiency with a running time of 1 hour and 47 minutes

Sr. No.	Time (min)	COD (mg/L)	COD Percentage Removal (%)
0	0	1400 (initial)	0
1	15	1216	13.1
2	30	896	36.0
3	50	512	63.4
4	70	416	70.3
5	90	320	77.1
6	107	160	88.6

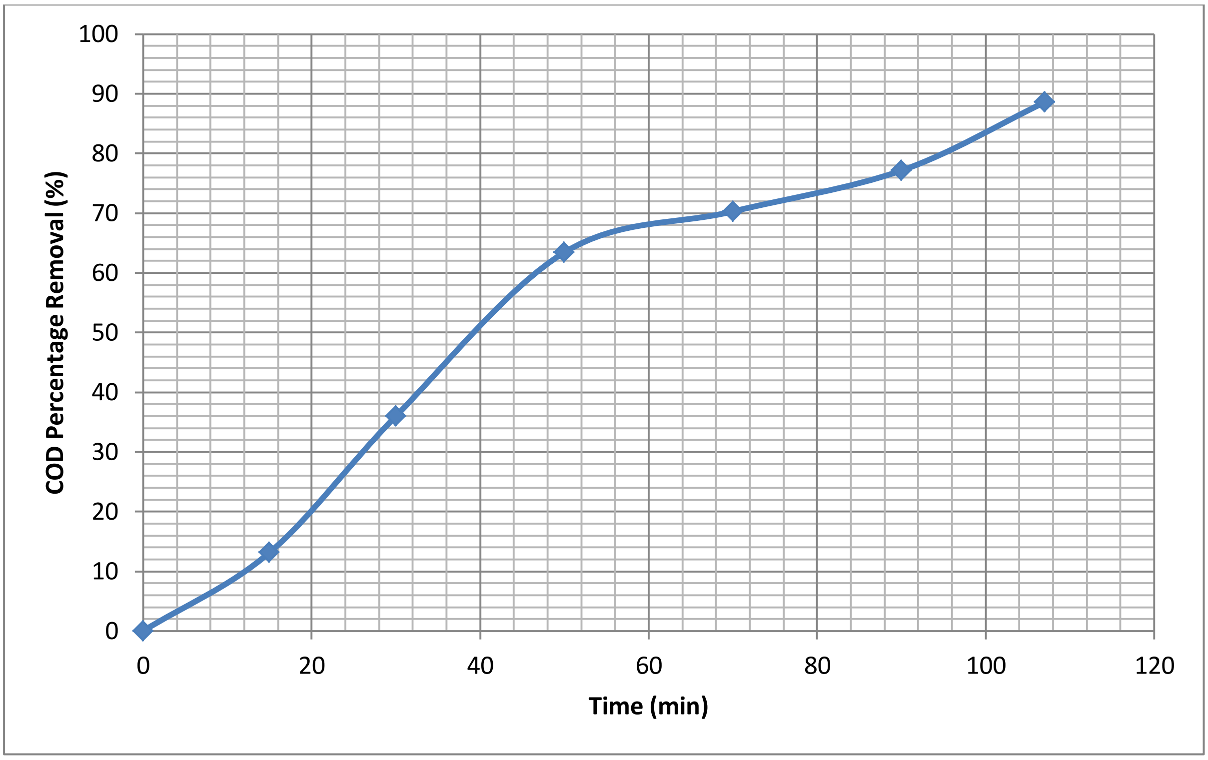

Figure 4.7: The effect treatment time on the COD percentage removal with a running time of 1 hour and 47 minutes

Figure 4.8 shows the initial color of the sample of the textile wastewater from Kohinoor Textile Mills Ltd. Figure 4.9 shows the color change as the electrocoagulation of the wastewater preceded. Finally figure 4.10 shows the final color of the wastewater sample at one hour and forty-seven minutes. Furthermore, spectroscopy was performed of the initial and final sample collected from the batch system. The initial sample had an absorbance of 1.377 and the final sample had an absorbance of 0.132.

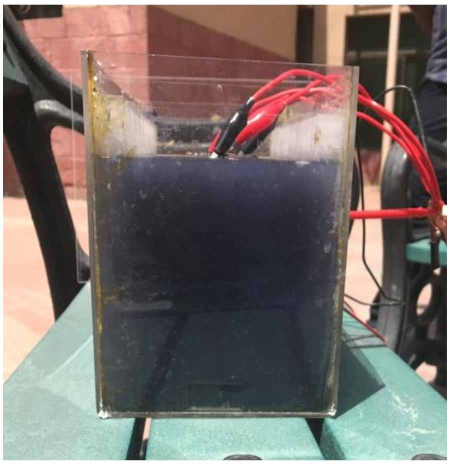

Figure 4.8: Initial color of the wastewater sample before electrocoagulation

Figure 4.9: Color of the wastewater sample during electrocoagulation

Figure 4.10: Final color of the wastewater sample after electrocoagulation

4.3 Continuous System

The last and final step of our study was the continuous system through which we collected the gas produced. The gas produced at the copper cathode due to electrocoagulation was collected in a gas sampling bag. The initial and final COD was found to be 1400 mg/L and 224 mg/L and this resulted in the COD removal percentage of 84% as presented in table 4.5. The gas collected in the gas sampling bag was further analyzed using gas chromatography. The results from gas chromatography confirmed that hydrogen gas is produced in electrocoagulation. The peak of hydrogen appears at a range of 1.5 to 1.8 minutes residence time. Hydrogen gas in our case was shown as a peak at 1.7 minutes residence time with a comparatively small peak of methane as well and this can be seen from figure 4.11.

Table 4.5: Results after running a continuous system at a flow rate of 3.36 L/h

Flow Rate (L/h)	COD (mg/L)	COD Percentage removal (%)
3.36	1400 (initial)	0
	224 (final)	84

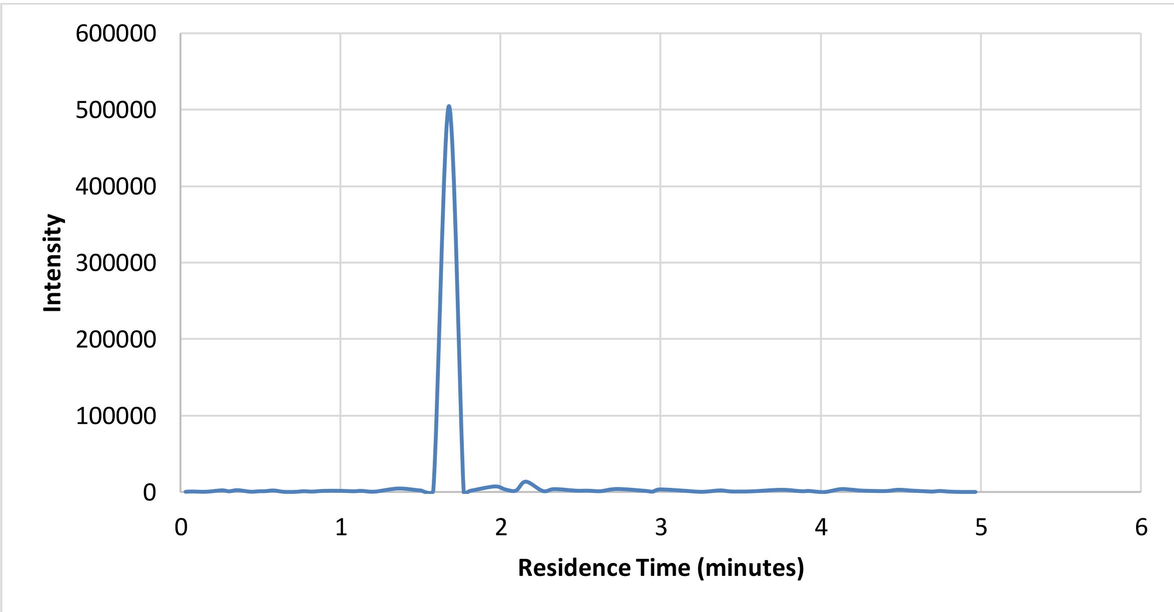

Figure 4.11: Peak of hydrogen obtained at 1.7 minutes residence time using gas chromatograph

Chapter 5

Cost Estimation

5.1 Cost Comparison between Conventional, Modified Conventional and Electrocoagulation Treatment Methods

Although conventional and modified conventional treatment methods for wastewater are proven and effective as evident from past studies, there is still a need of a different revolutionary treatment method which is effective and also economical. Electrocoagulation serves both of these completely. The following table 5.1 and 5.2 are conclusive of the study done in 2008 by Pablo et al. (Pablo et al., 2009) to investigate the economic reasons to opt for electrocoagulation and it can be seen that electrocoagulation is very economical as compared to conventional and modified conventional treatment methods to treat per cubic meter volume of raw wastewater.

Table 5.1: Total Cost comparison between different treatment methods (Pablo et al., 2009)

Treatment Method/ Cost	High Cost	Moderate Cost	Low Cost
Conventional	✓		
Modified Conventional		✓	
Electrocoagulation			✓

Table 5.2: Operating Cost comparison between different treatment methods (Pablo et al., 2009)

Treatment Method/ Cost	High Cost	Moderate Cost	Low Cost
Conventional	✓		
Modified Conventional	✓		
Electrocoagulation			✓

Electrocoagulation has very low operating costs when influent wastewater has high conductivity because of less operating time of the system to destabilize the charged particles. Moreover, when hydrogen gas is collected from the system, it can serve for energy purposes. So, the EC system, when powered through solar panels and added modification of hydrogen gas collection, is a viable, most cost-effective and energy-efficient system for treating wastewater purposes.

The table below shows the breakdown of EC system design parameters used in this study. Both Iron anodes and copper cathodes had same dimensions of 0.152m x 0.305m x 0.191m and an area of 0.014m^2. The volume of each electrode was 0.00885m^3. Each electrode was dipped about 0.127m of its own length into the wastewater. The volume of wastewater treated in batch test in the system was 6 L. The design parameters can be seen from table 5.3 below.

Table 5.3: Design parameters of the electrocoagulation system

Area of Electrode	0.014m^2
Length of Electrode	0.305m
Width of Electrode	0.152m
Height of Electrode	0.191m
Volume of Electrode	0.00885m^3
Each electrode dipped	0.127m
Volume of wastewater treated	6 Liters

5.2 Capital Cost Analysis

The following table breaks down the capital cost for establishing the electrocoagulation system used in this study for batch and continuous runs. Total of six electrodes were used for all experimental runs. Each electrode's cost was Rs.1000. So, total cost for electrodes came out to be Rs.6000 which is about 51.93$. Only one solar panel was enough to run the reactor for batch experiments. The cost of solar panel was Rs.3000 which is 25.96$ which gives 50W power output. The 12V Adapter was used to run the system for batch experiments in beakers whose cost was Rs.250. The EC unit was borrowed from graduate level in which the electrodes were fixed through silicone adhesive and cut up acrylic sheets. The price of EC unit was Rs.2000. Two buckets were used to set up the continuous system. In one bucket, influent wastewater was present and in second bucket, treated wastewater was collected from which samples were collected to conduct COD experiments. The cost of buckets was Rs. 800. Miscellaneous items were bought for Rs.500 from local electric and hardware stores. The total capital cost of whole project came out to be Rs.12550 which is almost 106$. This cost is to treat 6 liters of wastewater. The cost breakdown can be seen from the table 5.4 below.

Table 5.4: Capital cost breakdown

Cost of Electrodes	Rs. 6000
Solar panel	Rs. 3000
12V Adapter	Rs. 250
EC Unit	Rs. 2000
Buckets	Rs. 800
Misc. (Wires, glue etc.)	Rs. 500
Capital Cost	**Rs. 12550**

5.3 Operating Cost Estimate

For all the batch and continuous experimental runs conducted in this study, Voltage of 12 volts was applied at each electrode through crocodile wires and adapter for batch and continuous runs without solar panel. The current always varied because of distribution of current in electrodes but it was continuously noted down at different intervals and the average came out to be 0.49 Amperes. The power applied to the system was 5.88 Watts but these values can change when the system is upgraded to pilot scale or industrial scale.

The continuous experiments were run for 107 minutes and hence it is called hydraulic retention time (HRT). Industrial cost of electricity per unit (kWh) in Pakistan is 12 Rs. The total units used for one batch run were 0.0105 units. This number was found by using the equation 5 mentioned below.

$\text{Units Used} = \text{Power Input} * \text{HRT(hours)}$ ………………………………………………………………….(eq 5)

The total electricity cost for treating 6 liters of wastewater in one batch run was calculated using the equation 6 mentioned below.

$\text{Electricity Cost} = \text{Cost of one Unit} * \text{Units used}$ ……..……………………………………………….(eq 6)

The total electricity cost of treating wastewater came out to be Rs. 013 which was then divided by 6 to find the cost of treating one liter of wastewater which was Rs.0.02 (approximately 0.0002$).

The summary of all operating costs is given below in table 5.5.

Table 5.5: Operating cost breakdown

Voltage	12V
Current	0.49 A
Power	5.88 W
HRT	107 minutes
Cost of Electricity per unit (Industrial)	Rs.12
Units used	0.0105kWh
Electricity Cost (for 6 Liters)	Rs. 0.13
Electricity Cost (per Liter)	**Rs. 0.02**

The cost estimation of industrial scale EC unit is as follows:

The pilot scale EC system which will be able to treat 4680m^3 of wastewater volume per month will consume 7020kW of power input. When the cost is calculated by using the previous formulas, the industrial cost comes out to be Rs. 84,240 per month (approx. $729) when the renewable energy source like solar cells are not used. When solar cells will be used, the cost will reduce to about Rs. 49,140 which is almost half of the previous mentioned cost. The solar panels can only be used for 10 hours daily because of average effective solar intensity time, so a backup energy source is recommended for pilot-scale model.

Chapter 6

Conclusions

6.1 Effect of varying voltage on removal efficiency

In the first stage of study, it was concluded that an increase in voltage results in an increase in COD removal efficiency but, the main obstacle in doing that is the short circuiting which starts to occur at 14 volts when treating 6 liters of sample. With the highly inflammable hydrogen gas producing in the system, it is not safe to run the experiments at 14 volts. So, the system was optimized at 12 volts and the removal efficiency achieved at this input was 75%.

6.2 Effect of varying pH on removal efficiency

In the next stage of the study, voltage of 12 Volts was applied and pH was varied to study its impact on removal efficiency. From the literature review, it was found out that most textile industries release effluent in pH range of 6 to 10, so experiments were run in this range to find the optimum pH value. This study also concluded that optimum range of pH is basic as removal efficiency of textile wastewater is high in this range. This trend can be attributed to the production of ferrous hydroxide ions being generated by the reactions occurring at electrodes and this compound maybe the reason of removal of many impurities from sample.

6.3 Effect of varying temperature on removal efficiency

After optimization of voltage at 12 Volts and pH at basic range, experiments were conducted with varying temperature to find the optimized value of temperature to run EC system. The study found that when temperature increases from room temperature to 40 degrees Celsius, very little difference in removal efficiency was observed. However, when the experiments were run at 60 degrees Celsius, the removal efficiency decreased. So, the temperature was optimized at room temperature and it was concluded that effect of temperature on wastewater is dependent on characteristics of wastewater sample under study.

6.4 Effect of operating time on removal efficiency

In fourth stage of study, effect of operating time on removal efficiency was investigated. It was found that as treatment time increases, COD removal efficiency increases. The main constraint in this stage is energy load. After a certain time period, the energy load starts increasing with operating time which results in increase in operating cost of the system. This is because more voltage and power input will be required by the system to remove COD.

6.5 Experimental Runs on optimized EC system and Hydrogen Recovery

After optimization of decided parameters, the study continued to run experiments on optimized EC system in both batch and continuous modes. The results showed that at optimized parameters, the system ran effectively and removed 88% COD from the wastewater sample at running time of 107 minutes. The solar panel was also used to reduce operating cost of system and make the system more energy-efficient. The color removal from the experiments was also satisfactory.

The gas sampling bags were used to collect gas generated at the cathode and the collected gas was analyzed through Gas Chromatography to prove the production of hydrogen gas. This hydrogen gas, when collected in the industrial scale EC unit, can be used to make hydrogen fuel cells which are also an emerging renewable energy source.

6.6 Electrocoagulation- A cost-effective and energy-efficient technique

The total operating cost for treatment of 6 L wastewater was Rs. 0.02 which is comparatively really low as compared to other conventional methods and hence this study proved that EC is definitely a viable, economically sound and energy-efficient treatment technique for removing COD from textile wastewaters.

More research is still needed for studying the efficiency of removal of other impurities through EC and also its viability for other types of wastewater.

Chapter 7

Future Recommendations

The lab scale project shall be upgraded to pilot scale to simulate the efficiency of the system in order to fully analyze the selective parameters to get an idea of the system at industrial scale. The proposal is that it should be able to treat 8 to 10 m^3/hour. The pH of the inlet wastewater should be measured after regular intervals and the flow rate should be adjusted accordingly to get the maximum efficiency out of it.

In our lab scale project, we have removed the sludge that forms at the surface of water, manually. Skimmers should be used to collect the sludge that forms during the process. These skimmers will be operated with the help of motors. This sludge can be removed from the top of the tank and then deposited in the compartment at the left and this can be seen from figure 7.1. The purpose of doing this is to avoid the drop in voltage and the problem of short circuiting due to the accumulation of scum (Mollah et al., 2004).

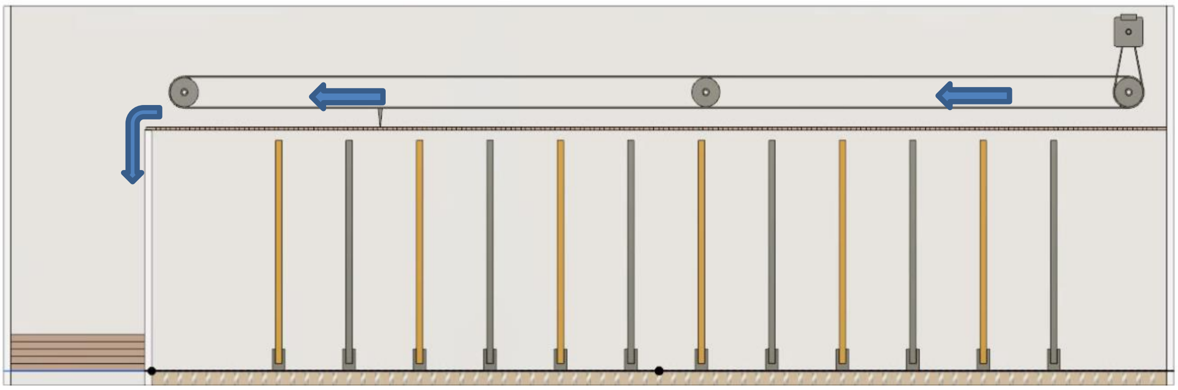

Figure 7.1: A two dimensional representation of a skimmer

7.1 Resource recovery from skimmed sludge

The skimmed sludge can be processed to extract alcohols and ketones from it. It can be done by using zirconia supported iron oxide catalyst. Zirconia decomposes water molecules, present in the skimmed organic froth, into hydrogen and oxygen. These oxygen species spill over to the surface of iron oxide and react with hydrocarbons to produce oxygen-containing organic chemicals such as ketones (Fumoto et al., 2006).

The produced ketones can be converted into alcohols by hydration. $LiAlH_4$ or $NaBH_4$ can be used as reducing agents reaction as shown in figure 7.2, which gives hydride ion.

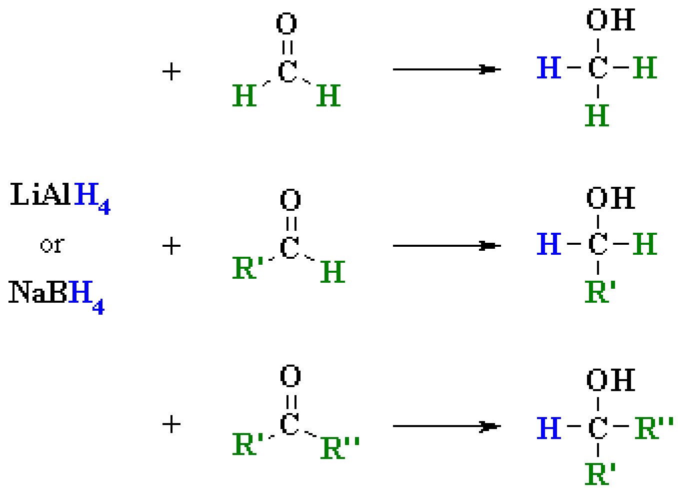

Figure 7.2: Aldehydes and ketones converted to alcohols using reducing agents

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