TREATMENT OF BREWERY WASTEWATER BY ELECTROCOAGULATION

A Thesis

submitted in partial fulfilment of the requirements for the award of the degree of

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IN

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With specialization in

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by

SAHIL KUMAR

(152762)

under the supervision of

Mr. ANIRBAN DHULIA

(Assistant Professor)

to

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY

WAKNAGHAT, SOLAN – 173234, HIMACHAL PRADESH, INDIA

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CERTIFICATE

This is to certify that the work which is being presented in the thesis titled **"TREATMENT OF BREWERY WASTEWASTER BY ELECTROCOAGULATION"** in partial fulfilment of the requirements for the award of the degree of Master of Technology in Civil Engineering with specialization in "**ENVIRONMENTAL ENGINEERING"** and submitted to the Civil Engineering Department, Jaypee University of Information Technology, Waknaghat is an authentic record of work carried out By **SAHIL KUMAR (Enrolment No. 152762)** during a period from July 2016 to December 2017 under the supervision of **Mr. ANIRBAN DHULIA (Assistant Professor, Civil Engineering Department**, Jaypee University of Information Technology, Waknaghat**)**.

The above statement made is correct to the best of our knowledge.

Date: - ………………………

Dr. Ashok Kumar Gupta	Mr. Anirban Dhulia	External Examiner
Professor & Head of Department	Assistant Professor	
Department of Civil	Department of Civil Engineering	
JUIT Waknaghat	JUIT Waknaghat	

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ABSTRACT

Electrocoagulation has been known for more than a century for the treatment of contaminated waters. This process has been applied to treat various kinds of industrial wastewaters, domestic wastewaters, sewage and ground water. The aim of this study is to investigate the treatment of the brewery wastewater using electrocoagulation and to examine the effect of operational parameters of electrocoagulation such as electrode material, inter electrode distance and initial wastewater temperature on the removal of Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Turbidity, Conductivity and pH. Three electrode materials i.e. aluminium, iron and stainless steel have been used as anodes and cathodes in different combinations and are connected in mono polar parallel mode. To check the effect of electrode spacing, three distances have been selected 0.5 cm, 1 cm and 1.5 cm. To check the effect of temperature, 20 ˚C, 30 ˚C and 40 ˚C were chosen as variable temperature. A total number of 81 electrocoagulation experimental runs were performed using 8 electrodes. Removal of selected parameters were checked after 15 minutes and 30 minutes of treatment times. The results showed that the maximum removal of contaminants were achieved using aluminium as anode and cathode. The optimum temperature value was found to be 30 ˚C. At this temperature, maximum removal of COD, TSS and turbidity were found. The optimum value for electrode spacing was 0.5 cm. The maximum COD, turbidity and TSS removals were found to be around 81.5 % with aluminium as anode and cathode, 85.8 % with aluminium as anode and iron as cathode and 89.6 % with aluminium anode and stainless steel as cathode at the temperature of 30 ˚C and with electrode spacing of 0.5 cm. The results showed that electrocoagulation is an effective process for treating brewery wastewater.

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ABBREVATIONS

COD – Chemical Oxygen Demand

TSS – Total Suspended Solids

Al – Aluminium

SS – Stainless Steel

Fe – Iron

CHAPTER 1: INTRODUCTION

1.1 General

Today in 21st century one of the major global problem we are facing is the lack of availability of quality drinking water for the fast growing population of the world. Also, contamination of natural water resources by human activities i.e. discharge of untreated or less treated wastewater (domestic, sewage and industrial) into natural water resources is causing health hazards to all the living beings. To tackle this issue, strict regulations have been made worldwide regarding the wastewater discharges into the water streams. Therefore, there is a necessity to develop effective, power efficient and eco-friendly water treatment technologies to treat wastewaters and drinking water [1,11].

Electrocoagulation technology has been studied and used in US and USSR since the starting of the 20th century using iron and aluminium electrodes. But it was not found feasible mainly due to high electricity consumption [8]. But during the last two or three decades' electrocoagulation has been tested and optimised for the effective and efficient treatment of various industrial, domestic wastewater and contaminated surface and groundwater. So far, electrocoagulation has been found as a complete replacement for the chemical coagulation process due to the number of advantages over chemical coagulation [17,23,25]. The main advantages are easy to operate and maintain, less sludge formation and no addition of chemicals and wide range of pH [3,17]. Also, electrocoagulation has capabilities to replace other wastewater treatment processes as it can be applied to wide range of wastewater containing heavy metals, colour, turbidity, TSS, COD, pathogens as well as organics [23].

1.2 Brewery Industries and their Wastewater

The brewery industries use a very large volume of water for the production. About four to ten litres of wastewater is generated in the production of single litre of final product. The brewery wastewater contains a large amount of fats, solids, protein, carbohydrates and ethanol which is formed during the fermentation processes. The main source of wastewater in a brewery industry is cleaning and washing of containers, floors and brew houses. The brewery wastewater has a very high Chemical Oxygen Demand, high turbidity, high Total Solids concentration and has an orange-brown colour. So, its discharge to the environment without treatment can pollute the surface and ground waters, and can adversely affect the environment.

Also, the huge water demands of such industries can be fulfilled by treating and reusing the wastewater. General characteristics of the brewery wastewater are given in **Table 1.1** [2,9].

Table 1.1 General characteristics of the brewery wastewater

Parameter	Value
COD(mg/L)	2000-100000
TS(mg/L)	1000-5000
pH	4-12
BOD_5(mg/L)	500-50000
Temperature(˚C)	15-40

1.3 Treatment of Brewery Wastewater

There are many treatment processes which are used for the treatment of brewery wastewater. Microbial Fuel Cells, Reverse Osmosis, Upflow Anaerobic Sludge Blanket, Nanofiltration are few processes which are generally used worldwide for treatment of such wastewaters. The selection of the process to be used depends on the strength of the wastewater to be treated, construction and operation cost of the treatment unit etc. The conventional coagulation process is not effective for such wastewaters due the high concentrations of pollutants. Electrocoagulation process(EC) has many advantages like no addition of any chemicals that will not lead to high sludge volumes and secondary pollution. Additionally, EC units are easy to operate and maintain. EC is a cost effective process, as it requires sacrificial metal plates as anodes which dissolute and form on-site coagulants as metal hydroxides [2,9].

1.4 Objectives of Study

- To study the effects of operational parameters of electrocoagulation on the removal of pollutants from brewery wastewater.
- To optimize the operational parameters for efficient removal of selected pollutants by electrocoagulation process.

1.5 Need of the Study

To tackle the major issue of water shortage and contamination of surface waters due to the discharge of untreated industrial effluents into the surface streams, we need effective, feasible, time saving and cost efficient water treatment processes. Electrocoagulation is one the emerging technologies which uses direct current, a very less labour and less treatment time. There are several parameters that control the process efficiency and final treating cost. So it is necessary to optimize various parameters of this process. This research includes the optimization of certain parameters such as electrode material, electrode spacing and initial temperature of wastewater.

1.6 Scope of Study

This research will characterize the properties of a brewery indusrty's wastewater and will optimize some important parameters of electrocoagulation for its treatment. The results of this research will be helpful for the future study of this process for the treatment of brewery wastewaters of similar characteristics as of the wastewater used in this study.

CHAPTER 2: ELECTROCOAGULATION

2.1 History

The electrocoagulation process was firstly used in early 20th century and further studies were done during the whole century in United States as well as Russia [1]. But electrocoagulation did not gather much interest at that time because of the use of electricity in the process. The high costs of electricity directly gave this process a little disadvantage in comparison to the other conventional treatment processes. At the end of the 20th century and in the first two decades of 21st century, electrocoagulation again came into picture and became an interesting topic of research among all researchers all over the world. The main reason behind this was the decrease in electricity costs because cost effectiveness is one of the major factor which influences the selection of water treatment process [1,3]. In the last two decades electrocoagulation has been tested and optimized in order to reduce treatment cost and to increase the performance of the process. Other processes like pretreatment with calcium oxide and Moving Bed Biofilm Reactor have also been investigated in combination with the electrocoagulation in the recent years [17,13].

2.2 Process Description

The process of electrocoagulation includes some physical and chemical phenomena for the treatment of water. Firstly, electro dissolution of metal anode occurs when we apply a direct current to the electrodes. Corresponding metal ions are generated near the anode(Eq.1) which reacts with the water molecules and forms various polymeric and monomeric metal hydroxide species at different pH ranges. For aluminium material used as electrode, the pH range of four to nine is considered suitable. Whereas, for using iron and stainless steel as electrodes, the neutral pH range is considered suitable. These hydroxide species are very good coagulants and have high adsorption capabilities. The degree of metal hydroxide formation is dependent on the metal concentration, pH of the solution and quantity of other species existing in the water. The coagulation takes place when these cations combines to the anionic particles in the water due to the electrophoretic motion. Further, flocculation occurs and polymeric metal hydroxide species entraps the organics and other neutral suspensions in the water. As a whole, the contaminants are removed by the following mechanisms:

- Neutralisation of charged pollutants by monomeric metal hydroxides formed

- Binding of neutral pollutants with polymeric metal hydroxide species
- Adsorption of pollutants to the growing metal hydroxide precipitates

Simultaneously electrolysis of water also causes the formation of oxygen gas at anode(Eq.2) and hydrogen gas at the cathode(Eq.4,5). These gases cause bubble formation and leads to the flotation of the flocculated sludge blanket.

Reduction of metal ions at the cathode also takes place(Eq.3) which causes passivation of cathode i.e. formation of a layer on cathode which reduces the performance of the process. Regular cleaning of the electrodes is suggested after each cycle of use to counter the negative effect of passivation. Addition of anions such as Cl^-, Br^-, I^-, F^-, ClO_4^- reduces the passivation effect, Cl^- being most effective. Reversal of the polarity of electrodes can also be used to decrease the passivation effect and to increase the performance of the system [3,13,20,23]. The schematic diagram of typical electrocoagulation process is given in Fig **2.1**.

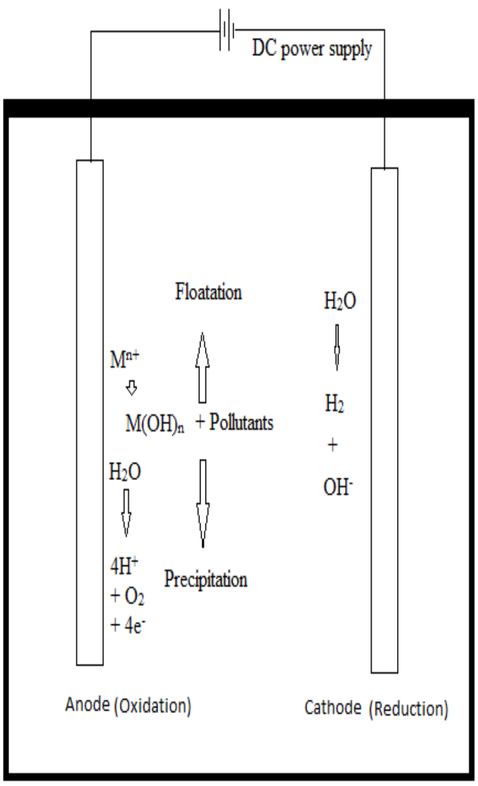

Fig. 2.1 Schematic diagram of a typical electrocoagulation process with two electrodes and DC power supply

Reactions: -

At anode: - [oxidation]

$M_{(s)} \rightarrow M_{(aq)}^{n+} + ne^-$ (1)

$2H_2O \rightarrow 4H^+_{(aq)} + O_{2(aq)} + 4e^-$ (2)

At cathode: - [reduction]

$M_{(aq)}^{n+} + ne^- \rightarrow M_{(s)}$ (3)

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

$2H^+_{(aq)} + 2e^- \rightarrow H_{2(g)}$ (5)

Electrocoagulation is also very effective for the removals of heavy metals. Arsenic is one of the metals which contaminates ground waters. Its removal using electrocoagulation has been found very effective as As(III) ions are converted to As(V) up to some extent. The metal hydroxides and oxyhydroxide formed during the process provide a quite large surface area for the adsorption of arsenic by slowing down the crystalline development of iron oxides. The removal of Cu^{2+}, Zn^{2+} and Cr(VI) is also very effective using electrocoagulation. The coprecipitation of $Cu(OH)_2$ and $Zn(OH)_2$ is the removal mechanism for these metals and has been found about five times faster than the removal of Cr(VI). Cr(VI) is first reduced to Cr(III) and then precipitation to $Cr(OH)_3$ has been found the removal mechanism using electrocoagulation with aluminium anodes [20].

2.3 Factors Affecting Electrocoagulation

1. Current Density:
   Current density is the most important factor because it determines the quantity of metal ions released by the anode i.e. coagulant dosage. The operation time of the process and the removal rate of pollutants are affected by the current supplied. This parameter is controlled directly. The bubble generation rate due to the formation of gases is also affected by the current density [3,20].

The relation between amount of metal eroded and the current density is derived from Faraday's law: -

$$w = \frac{itM}{zF}$$

here,

w = quantity of electrode material dissolved (gm/cm^2)

i = current density (A.cm^{-2})

t = time of electrolysis (seconds)

M = molar mass of the electrode material

z = number of electrons in oxidation or reduction reaction

F = Farraday's constant (96500 C.mol^{-1})

2. pH of Wastewater:

   The pH of the wastewater plays a very big role in chemical as well as electrocoagulation. A number of polymeric compounds at different pH values are formed due to the hydrolysis and polymerisation reactions of metal dissolved. For the pH range of four to nine, $Al(OH)^{2+}$, $Al(OH)_3$, $Al(OH)_2^+$, $Al(OH)_2^{4+}$, $Al(OH)_{32}^{7+}$ can be formed if aluminium is used as sacrificial anode. For the pH values greater than 10, the coagulant effect decreases because $Al(OH)_4^-$ is ascendant in this range. Similarly, for other anode metals various metal hydroxide species are formed depending on the pH of the wastewater. For iron as anode, at neutral pH, 90 % conversion is achieved and $Fe(OH)_3$ is formed.

   Also, if the initial pH of the wastewater is in range 4 to 9, the pH of the treated wastewater water will increase due to the formation of hydroxide ions near cathode. And if the initial pH is greater than 9, the pH of treated wastewater will decrease. Therefore, electrocoagulation has the tendency to neutralise the pH of the wastewater up to some limit [3,18,20].

3. Inter Electrode Distance:

   The inter electrode distance has also a direct influence on the removal of the pollutants. With the decrease in inter electrode distance, the resistance between the electrodes decreases and current passed increases. This increase in current increases the metal ions dissolution and metal hydroxide formation, thus increase in removal rate of pollutants [14,16,21].

4. Electrode Material:

The type of metal used as electrodes defines the electrochemical reactions occurring in electrocoagulation reactor. Generally, electrodes of aluminium and iron are used in the process. Aluminium dissolutes as Al^{3+} and iron dissolutes as Fe^{2+} which is further oxidised as Fe^{3+} by the existence of dissolved oxygen and at alkaline pH. Fe^{3+} is stronger coagulant than Fe^{2+} due to the higher positive charge on the ion. Stainless steel, mild steel and other alloys of iron and aluminium are also used and they show comparative results in removal of pollutants [3,18,20,27].

5. Conductivity:

As we know that electric current needs a conductive medium to travel. The increase in the conductivity of the wastewater increases the current efficiency. If the conductivity is low, it will lead to the decrease in the current efficiency because a high potential will be required which causes the passivation of electrodes and will ultimately increase the treatment cost. The conductivity in electrocoagulation experiments is generally increased by adding sodium chloride salt [3,16,20].

6. Temperature of Wastewater:

The wastewater temperature also effects the electrocoagulation process. Many researches concluded that for aluminium anodes, the aluminium current efficiency will keep increasing briskly with the increase in the initial temperature of wastewater from 2˚C to 30˚C. The destruction reaction of oxide membrane will increase with increase in temperature which results in the increment of current efficiency. And for wastewater temperature of more than 60˚C, the current efficiency starts falling [3,16,20].

7. Electrode Arrangement:

The electrodes can be connected in parallel connection or in series connection to the power supply. The electrodes connected in parallel connection needs less potential difference than in series because the current is divided to all electrodes relative to each cell's resistance. So a parallel connection is mostly used to face less final treatment costs. Mono-polar and bipolar electrodes are used in series or parallel connection in the electrocoagulation cells [3,7,20,27]. There are three types of arrangements used in electrocoagulation described below: -

a) Mono-polar parallel arrangement:

In this arrangement, mono polar electrodes are connected in such a manner that the current is divided to the all electrodes. Various researches show that this arrangement is the most cost efficient one [7,27]. The arrangement is shown in Fig. **2.2.**

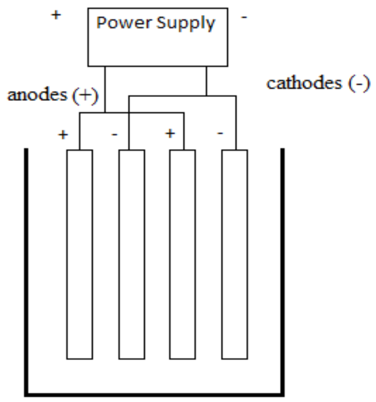

Fig. 2.2 Schematic diagram of an electrocoagulation reactor with mono polar parallel arrangement

b) Mono-polar serial arrangement: -

In this arrangement, mono polar electrodes are connected in such a manner that all electrode pairs are connected to each other internally. This results in the summing up of individual potentials of all cells and therefore higher potential difference is needed. This arrangement is shown in **Fig. 2.3.**

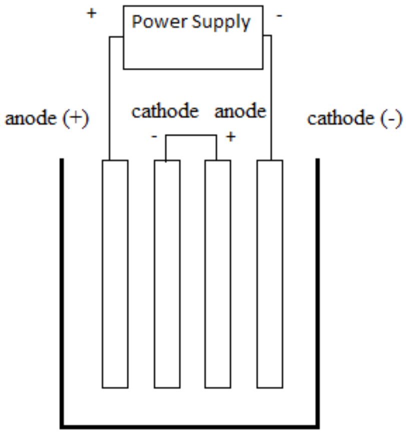

Fig. 2.3 Schematic diagram of an electrocoagulation reactor with mono polar serial arrangement

c) Bipolar serial arrangement: -

In this arrangement, only the outer electrodes are connected to the power supply and are mono-polar in nature. The inner electrodes are the bipolar electrodes and are not connected to each other. This arrangement is attributed with the low cost maintenance during the operation. This arrangement is shown in **Fig. 2.4**

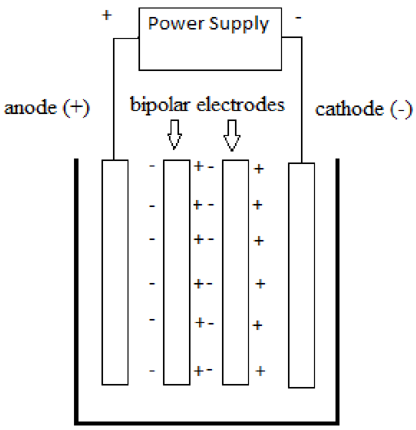

Fig. 2.4 Schematic diagram of electrocoagulation reactor with bipolar serial arrangement

CHAPTER 3: LITERATURE REVIEW

3.1 General

This section includes some important studies already done in the same field and are important for the present study:

Eyvaz, M. (2016). [2] The objective of the study was to evaluate technical and economic viability of the electrocoagulation for the brewery wastewater. The reactor had four electrodes of either aluminium or iron connected in mono-polar parallel mode with inter electrode distance of 2 cm. The reactor dimensions were 13 cm ×13 cm × 12 cm. DC power supply having adjustable time relay feature was connected to provide alternating pulse current. pH, electrolysis time, material of electrode and current density were studied with removal efficiency. The results showed that aluminium electrodes were more cost efficient than iron electrodes because of more electrode consumption of iron electrodes. Also, the alternating pulse current showed faster removals than direct current.

Dia, O., Drogui, P., Buelna, G., Dube, R., Ihsen, B.S. (2016). **[5]** In this study electrocoagulation was used to treat the residual organic matter from a landfill leachate after it was treated with an aerated bio filter. Humic substances (humic acids and fulvic acids) were contributing to the 90 % of the Total Organic Carbon. The effect of type of material used as anode (iron or aluminium) and the current density were examined. The COD removal was found 70 % with aluminium and 65 % with iron as anode, and with the range between 8 to 10 mA/cm^2 with an electrolysis time of 20 minutes. The results showed that humic acids were completely removed but fulvic acids and hydrophilic compounds were removed around 60 % and 45 % respectively. Both the materials used as anode showed approximately same results. The reactor used in this research had a cylindrical shape. The cathode was the hollow cylinder made of stainless steel and anode was a cylindrical rod.

Demirci, y., Pekel, L.C., Alpbaz, M. (2015). [7] This study presented the results of treating textile wastewater using electrocoagulation. Mono-polar-parallel, mono-polar-series and bipolar-parallel modes of connection using aluminium and iron electrodes were examined. Four electrodes were used with spacing of 0.8 cm. The results showed that the mono-polar parallel connection was the most cost efficient for both type of electrodes. Also, it was found that aluminium was better than iron in removing COD, colour and turbidity. The reactor used in the study was made of plexiglass and having 1 L capacity with four electrodes of dimensions 6 cm × 6 cm × 3 cm. The electrodes were connected in mono-polar parallel mode.

Mahmad, M.K.N, Rozainy, M.R.M.A.Z., Abustan, I., Baharun, N. (2015) [8] In this research, landfill leachate was treated with electrocoagulation and the removal of Total Chromium, Turbidity and Colour were investigated. Aluminium and stainless steel materials were used as electrodes. A pH range of 3 to 7 were applied and voltages of 1.5V, 2V and 2.5V were applied. At the end of the treatment time, the concentration of heavy metals using Atomic Absorption Spectroscopy was determined, turbidity and colour were also checked. Stainless steel was found more effective for the removal of total chromium and aluminium was more effective in removing turbidity and colour. The reactor used in this study had a total volume of 150 mL and 100 mL sample was used in each experiment.

Maneti, D.R., Modenes, A.N., Soares, P.A., Boaventura, R.A.R., Palacio, S.M., Borba, F.H., Quinones, F.R.E., Bergamasco, R., Vilar, V.J.P. (2014). [10] In this study electrocoagulation of textile wastewater with the use of iron electrodes was examined. And its comparison with the biological processes was done. The wastewater collected had COD=1257 mg/L, temperature= 20.5 ˚C, conductivity= 19.2 mS/cm and BOD_5= 200 mg/L. The optimal values for pH, time and current density were obtained. The values were found to be pH=7 and current density= 14.3 mA/cm^2. The reactor designed was cylindrical of capacity 1.5 L and dimensions (diameter= 11.6 cm and height=14.4 cm). Eight electrode plates were used of dimensions (5 cm × 11 cm × 0.15 cm) and having 0.5 cm spacing. A magnetic stirrer and a DC power supply (20 A, 30V) were used. The results illustrated that 45 min of electrolysis time was sufficient for the 70% removal of COD with the optimum values of pH and current density for the wastewater treated.

Kuokkanen, V., Kuokkanen, T., Ramo, J., Lassi, U. (2013) [11] In this review, various studies (2008-2011) on the treatment of wastewaters of different industries (food, tannery, textile, oily wastewater etc.) by electrocoagulation were reviewed. Also, a review on the optimum values of pH, treatment time and current density was given. The values found were 10-150 A/m^2 for current density, pH=7 and electrolysis time 5 to 60 minutes.

Mondal, B., Srivastava, V.C., Mall, I.D. (2012) [14] This study aimed at the maximum removal of COD and colour with minimum power consumption of the dye-bath effluent by electrocoagulation. The effects of pH, inter electrode distance, current density and treatment time were investigated. At the optimum conditions, COD and colour removal were 91.7 % and 99.8 % respectively. And the energy consumed was 7.71 kWh/kg of COD removal. The electrocoagulation reactor was made of Perspex material with dimensions 13cm×13cm×21cm and had a capacity of 2 litres. Two pairs of stainless steel electrodes of dimensions 11 cm × 8.5 cm × 0.3cm were installed and were varied with 0.5 to2.5 cm gap to find out the effect of inter electrode distance. A DC power supply with capacity 20V and 5A was connected to the cell. The optimum inter electrode distance was 1.5 cm and optimum pH was 7.

Dalvand, A., Gholami, M., Joneidi, A., Mahmood, N.M. (2010) [21] In this study, aluminium electrodes were used to examine the performance of electrocoagulation for the treatment of synthetic wastewater having reactive Red198 in it. The effects of electrolyte concentration, electrode spacing, initial dye concentration, voltage, electrodes arrangement and electrolysis time were examined. It was investigated that the highest dye and COD removals were 98.5 % and 84 %. Also, electrode usage was 0.052 kg/m^3, energy usage was 1.303 kWh/m^3 and operating cost was 0.256 US$/$m^3$. The reactor dimensions were 14 cm × 12 cm × 14 cm with a volume of 2 litres. Four electrodes of aluminium were installed with the dimensions of 11.2 cm × 10.8 cm × 0.2 cm in mono polar or bipolar mode. A DC power supply of 40 V and 5 A was connected. Mono polar parallel arrangement of electrodes was found most efficient and the removal efficiency decreased with increasing inter electrode distance. Optimum pH was in the range of 5 to 6 and the removal efficiency decreased with the increase in initial dye concentration.

Akbal, F., Camci, S. (2010) [22] In this research, the removals of nickel, chromium and copper by chemical coagulation and electrocoagulation were examined and compared. Chemical coagulants used were ferric chloride and aluminium sulphate. And electrocoagulation was done with aluminium and iron electrodes. The electrode dimensions were 4.5 cm × 7.5 cm × 0.3 cm and were having 1 cm of spacing and connected to a DC power supply. The wastewater was stirred at 200 rpm. Results showed that around 99 % removals were obtained from both types of coagulation. In case of electrocoagulation, iron electrodes were found more efficient with 10 mA/cm^2 current density, pH 3 and treatment time of 20 minutes. The removal efficiency increased with the increase in number of electrodes.

Kobya, M., Bayramoglu, M., Eyvaz, M. (2007) [27] In this research, the treatment of textile wastewater using electrocoagulation in three different electrode arrangements i.e. mono polar parallel, mono polar series and bipolar series was presented. The batch reactor had dimensions 12 cm × 11 cm × 11 cm. Four electrodes of iron and aluminium were used with a spacing of 2 cm, and had dimensions of 4.5 cm × 5.3 cm × 0.3 cm. The results showed that for COD removal acidic pH is more suitable for both electrode materials. Acidic pH for aluminium and neutral for iron were suitable for turbidity removal. Mono polar parallel mode was found most cost efficient for both materials. Results showed that in comparison with chemical coagulation, electrocoagulation consumed lesser material and produced lesser sludge.

CHAPTER 4: MATERIALS AND METHODS

4.1 Wastewater Samples

The wastewater samples were collected from a brewery industry named "Green Valley Cider Private limited" situated at Shoghi, Shimla, Himachal Pradesh, India. This industry produces wine, cider and vinegar from apples. Wine, cider and vinegar production needs controlled fermentation of the apple fruits. So, the wastewater of such industries generally have high COD, turbidity and total solids. Wastewater in this industry is generated from washing and cleaning of the large vessels used for various processes and washing of the brew house.

The wastewater was collected in plastic containers of capacity 5 litres from the equalisation tank just before the Effluent Treatment Plant of the industry. The wastewater was then immediately stored in the cold room of temperature less than 4˚C. The stored wastewater was not used after the duration of 72 hours from storing. The wastewater was collected for a period of about 5 months for experimentation purpose. The wastewater was checked for pH, COD, total solids, conductivity and turbidity.

4.2 Electrocoagulation Reactor

The reactor used for the treatment was made up of acrylic sheets of thickness 0.5 cm. The reactor was rectangular in shape with the outer dimensions of 20 cm × 15 cm × 8 cm and had a maximum capacity of about 2 litres. Inlet valve at 2 cm below the top of reactor and outlet valve at 2 cm above the bottom of reactor were installed. Eight number of electrode sheets were used with dimensions of 9 cm × 5 cm and 0.3 cm in thickness. Three electrode materials were examined as anodes and cathodes: Aluminium, Iron and Stainless Steel. And were connected in mono-polar parallel mode. The inter electrode distance was adjustable up to least distance of 0.5 cm. A DC power supply was connected to the electrocoagulation system of capacity 0-5 A and 0-20 V.

4.3. Selection of Parameters

There are several parameters that affect the performance of electrocoagulation process as we have discussed in CHAPTER 2. Among all current density is the most effective parameter as it controls the removal rate directly due to its effect on the rate of coagulants generated in the process. Also, it directly controls the operation cost because of the use of electricity. So an optimal value of 25 mA/cm^2 was chosen for the experimentation based on the various literatures reviewed in the CHAPTER 3. The analysis of the brewery wastewater used in the study showed that the pH was between 7 to 8 which was between optimal value range for pH according to the past literatures. The parameter electrode material was then selected because different materials generate different types of coagulants and have different passivation capacities. Temperature was also selected because its effect has not been much studied in the past literatures and has a much effect on the performance of process as we have discussed in CHAPTER 2. Another parameter i.e. electrode spacing (inter electrode distance) was selected because it has a direct effect on the Internal Resistance of the cell.

4.4 Experimental Procedure

In the present research, the effect of operating parameters such as inter electrode distance, temperature of wastewater and electrode material were investigated on the removal of COD, turbidity, conductivity, total solids and effects on pH were investigated with treatment time of 30 minutes. For this purpose, an experimental plan was designed which is shown in **Table 4.1**. For checking the effect of electrode spacing, distances of 0.5 cm, 1 cm, and 1.5 cm were chosen. And to check the effect of temperature of wastewater, 20 ˚C, 30 ˚C and 40 ˚C temperatures of initial wastewater were selected.

Table 4.1 Experimental Plan

Electrode Material	Inter-electrode Distance	Temperature	Time Intervals
4 anodes – 4 cathodes	Cm	˚C	Minutes
Al-Al	0.5, 1, 1.5	20, 30, 40	0, 15, 30
Al-SS	0.5, 1, 1.5	20, 30, 40	0, 15, 30
Al-Fe	0.5, 1, 1.5	20, 30, 40	0, 15, 30
SS-SS	0.5, 1, 1.5	20, 30, 40	0, 15, 30
SS-Al	0.5, 1, 1.5	20, 30, 40	0, 15, 30
SS-Fe	0.5, 1, 1.5	20, 30, 40	0, 15, 30
Fe-Fe	0.5, 1, 1.5	20, 30, 40	0, 15, 30

Fe-SS	0.5, 1, 1.5	20, 30, 40	0, 15, 30
Fe-Al	0.5, 1, 1.5	20, 30, 40	0, 15, 30

For each experiment, firstly the initial temperature of wastewater to be treated was adjusted to the desired value by heating the wastewater and was checked by thermometer. Then the required arrangement of the electrodes was set up. 1.25 L of sample was used for each experimental run. For this volume, electrodes were dipped up to 6.5 cm of their height leaving 3 cm space below the electrodes. And the effective surface area of the electrode was 65 cm^2. The current density was kept constant at 25 mA/cm^2 and 1.76 A current was required for 1.25 L of sample. After 15 minutes of electrolysis, power was turned off and reactor was left undisturbed for 10 minutes of sedimentation. After 10 minutes, a volume of 200 ml sample was drawn from the reactor from the outlet valve provided at the side bottom of reactor. This sample was then used to determine the physiochemical characteristics of the wastewater after 15 minutes of treatment time. The parameters checked were pH, COD, turbidity, conductivity and total suspended solids.

The DC power supply was again switched on to provide a constant current density of 25 mA/cm^2. But now the volume of wastewater left in the reactor was 1.05 L. For this volume, the electrodes were dipped up to the height of 4.95 cm. Corresponding wet surface area of the electrode was 49.5 cm^2. A current intensity of 1.35 A was supplied to maintain the required current density. After the completion of the whole electrolysis time i.e. 30 minutes, again the reactor was left undisturbed for 10 minutes of sedimentation time. Then, again a sample of 200 ml was withdrawn from the reactor for its analysis. The remaining treated wastewater and the sludge generated was disposed of carefully.

After every experimental run, the reactor was cleaned using distilled water. And the electrodes were dipped in 1 N H_2SO_4 for few minutes and then in distilled water successively for the removal of oxide layers and scaling formed on the electrode's surface due to redox reactions occurring on their surfaces during electrocoagulation.

All the experiments were done in the same manner and order for all the experimental runs. A total number of 81 experimental runs were performed.

4.5 Analytical Methods

The wastewater samples and the treated wastewater samples were analysed for few physical and chemical analysis. The parameters chosen were: -

- pH
- Turbidity
- Total Suspended Solids (TSS)
- Conductivity
- Chemical oxygen demand (COD)

The TSS and COD were measured as per Standard Methods (APHA, 2005). The pH was measured using a pH paper. Turbidity was measured using a Turbidity Meter (LABTRONICS MODEL NO. 33). Conductivity was measured using a Deluxe Conductivity Meter (MODEL LT-26).

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Physio-chemical characteristics of Wastewater

The wastewater for the experimentation was collected regularly from the brewery industry which produces cider, wine and vinegar from apples. The physiochemical properties of all the grab samples varied a little in every sample collected. This was because of the different capacities of the batch production of the industry. The characterisation of the wastewater was done every time a new grab sample was collected. The results showed that turbidity and the concentrations of COD, total suspended solids were much higher than the effluent discharge limits. The pH of the wastewater was almost around neutral value. The results showed that the wastewater generated in this industry needs a treatment before its discharge to the environment. The ranges of the physiochemical parameters of the wastewater are shown in the **Table 5.1.**

Table 5.1 Physio-chemical characteristics of wastewater

Parameter	Value range
Chemical Oxygen Demand (mg/L)	11520 – 13440
Total Suspended Solids (mg/L)	678 – 765
Turbidity (NTU)	160 – 195
pH	7 - 8
Conductivity (m.mho/cm)	1.128 – 1.576

5.2 Results of Electrocoagulation Experiments

In the research, eighty-one number of experiments were done in different configurations that we have discussed in Chapter 4. Since the aim of this study was to examine the effects of electrode material, initial temperature of wastewater and inter electrode distance, a constant current density of 25 mA/cm^2 was chosen. Removal efficiencies of COD, turbidity and total suspended solids were chosen as the criteria for determining the effects of these operational parameters of electrocoagulation. The results showed that for all the materials, the maximum removal efficiencies were achieved at the inter electrode distance of 0.5 cm and at the temperature of 30 ˚C. All the experimental results are given in **APPENDIX B**.

5.2.1 Effect of Electrode Material

In this research, the materials chosen to be used as electrodes were Aluminium, Iron and stainless steel. The results showed that for 0.5 cm of inter electrode distance and 30 ˚C of initial wastewater temperature, the maximum COD removal i.e. 81.5 % was obtained after 30 minutes of electrocoagulation time by having aluminium as both anode and cathode. The turbidity and TSS removals at these conditions were 89.28 % and 85.5 % respectively. Another combination i.e. aluminium as anode and stainless steel as cathode with same electrode spacing and temperature gave the maximum total suspended solids removal of 89.67 % and a second highest removal of COD as 79.05 %. Hence, comparisons between all electrode materials (anode and cathode) for the % COD, % turbidity and % total suspended solids removal at electrode spacing of 0.5 cm and temperature of 30 ˚C has been shown in **Fig. 5.1, 5.2 and 5.3.**

The maximum turbidity removal was achieved by using aluminium as anode and iron as cathode after 30 minutes. And the maximum TSS removal was achieved by using aluminium as anode and stainless steel as cathode. For all the combinations of anode and cathode the COD, turbidity and TSS removals were between 73 – 81.5 %, 82 – 85.5 % and 85.5 – 89.6 % respectively. Among all, the combination of aluminium anodes and cathodes showed the best results in performance criteria. So, aluminium has been found as the most effective material as electrode.

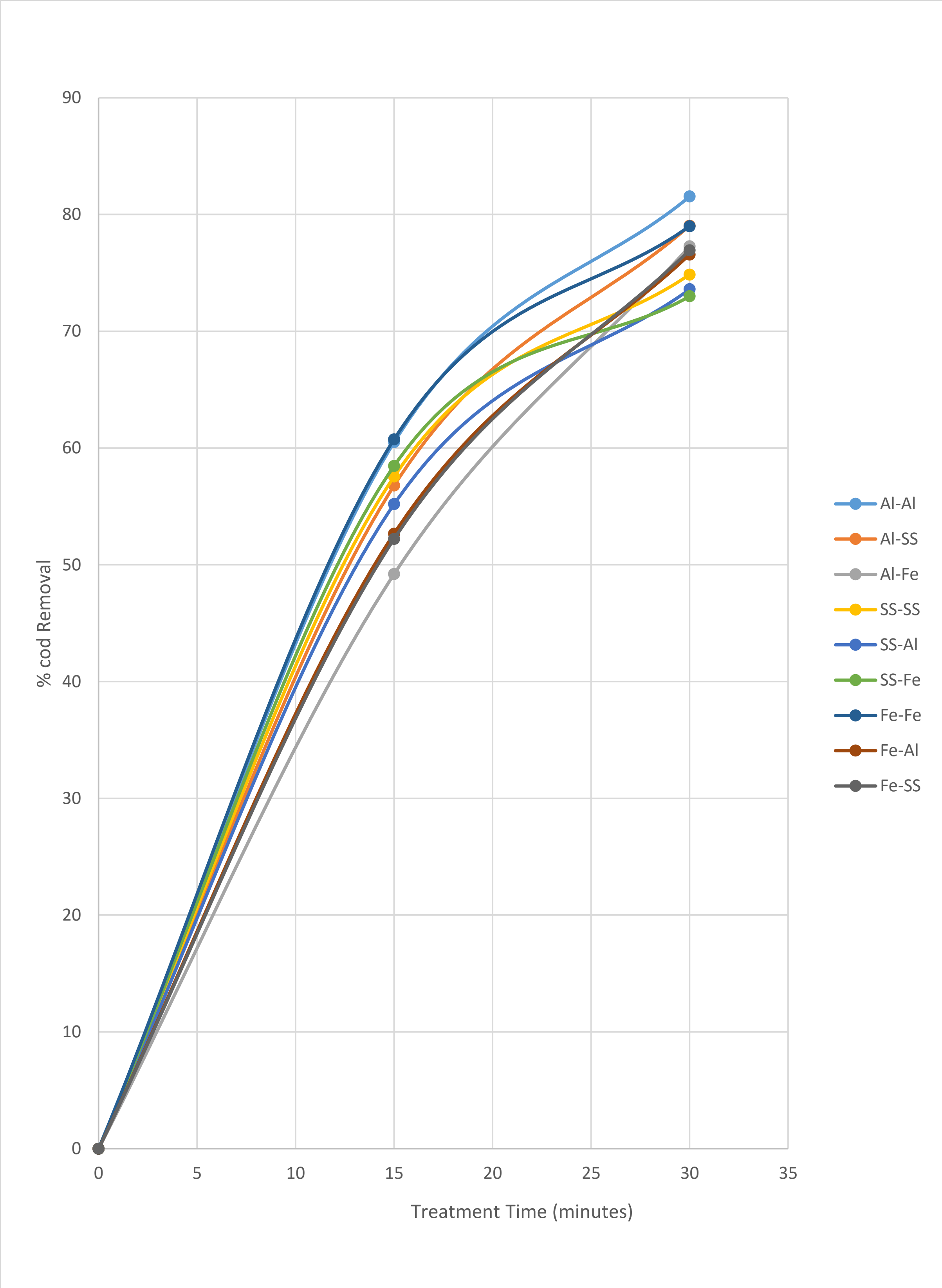

Fig. 5.1. Comparison of different electrode materials on COD removal with 0.5 cm spacing and 30 ˚C initial wastewater temperature.

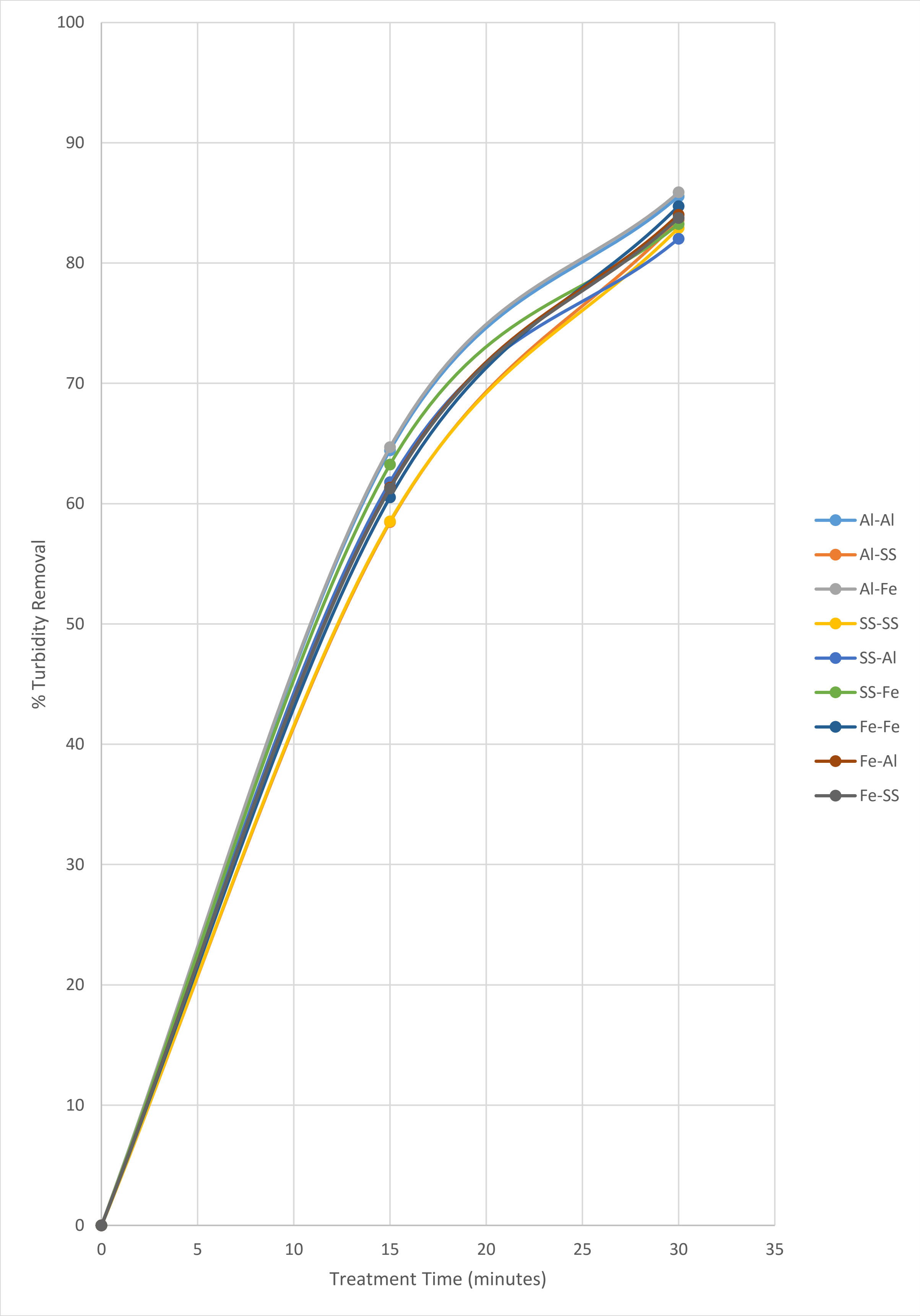

Fig. 5.2. Comparison of different electrode materials on turbidity removal with 0.5 cm spacing and 30 ˚C initial wastewater temperature.

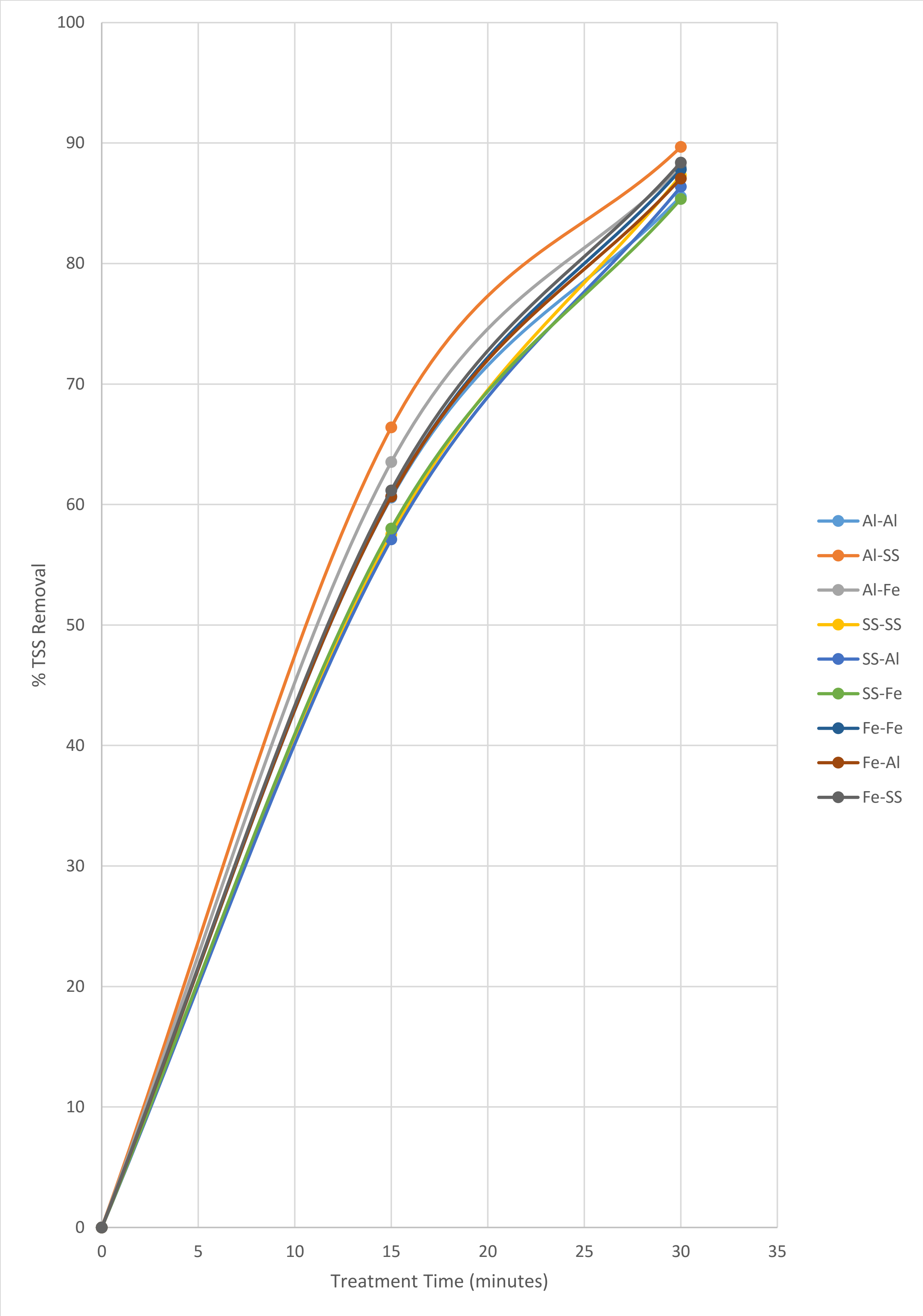

Fig. 5.3. Comparison of different electrode materials on TSS removal with 0.5 cm spacing and 30 ˚C initial wastewater temperature.

5.2.2 Effect of Temperature

The initial wastewater temperature values chosen for the experimentation were 20 ˚C, 30 ˚C and 40 ˚C. For aluminium electrodes and inter electrode distance of 0.5 cm, at 20 ˚C the COD, turbidity and TSS removals were 78.18 %, 79.44 %, 83.28 % respectively. At 30 ˚C, COD = 81.5 %, turbidity = 85.5 % and TSS = 83.28 % were removed. At temperature of 40 ˚C, COD = 78.96 %, turbidity = 82.2 % and TSS = 84.28 % were removed. We can see that, when temperature increase from 20 ˚C to 30 ˚C, the removal rates increased. And when temperature was raised to 40 ˚C, the removal rates again decreased. For all the electrode materials the effect of temperature was observed the same.

A comparison on COD removal using Al-Al (anode and cathode) electrodes with 0.5 cm of spacing at different temperatures is shown in **Fig. 5.4**. Comparison on removal of turbidity using Aluminium-Iron (anode-cathode) electrodes with 0.5 cm of spacing at different temperatures is shown in **Fig. 5.5**. And a comparison on total suspended solids removal using Aluminium-Stainless steel (anode and cathode) electrodes with 0.5 cm of spacing at different temperatures is shown in **Fig. 5.6.** These electrode materials for comparisons has been chosen because these combinations were most effective in removing the respective parameter from wastewater.

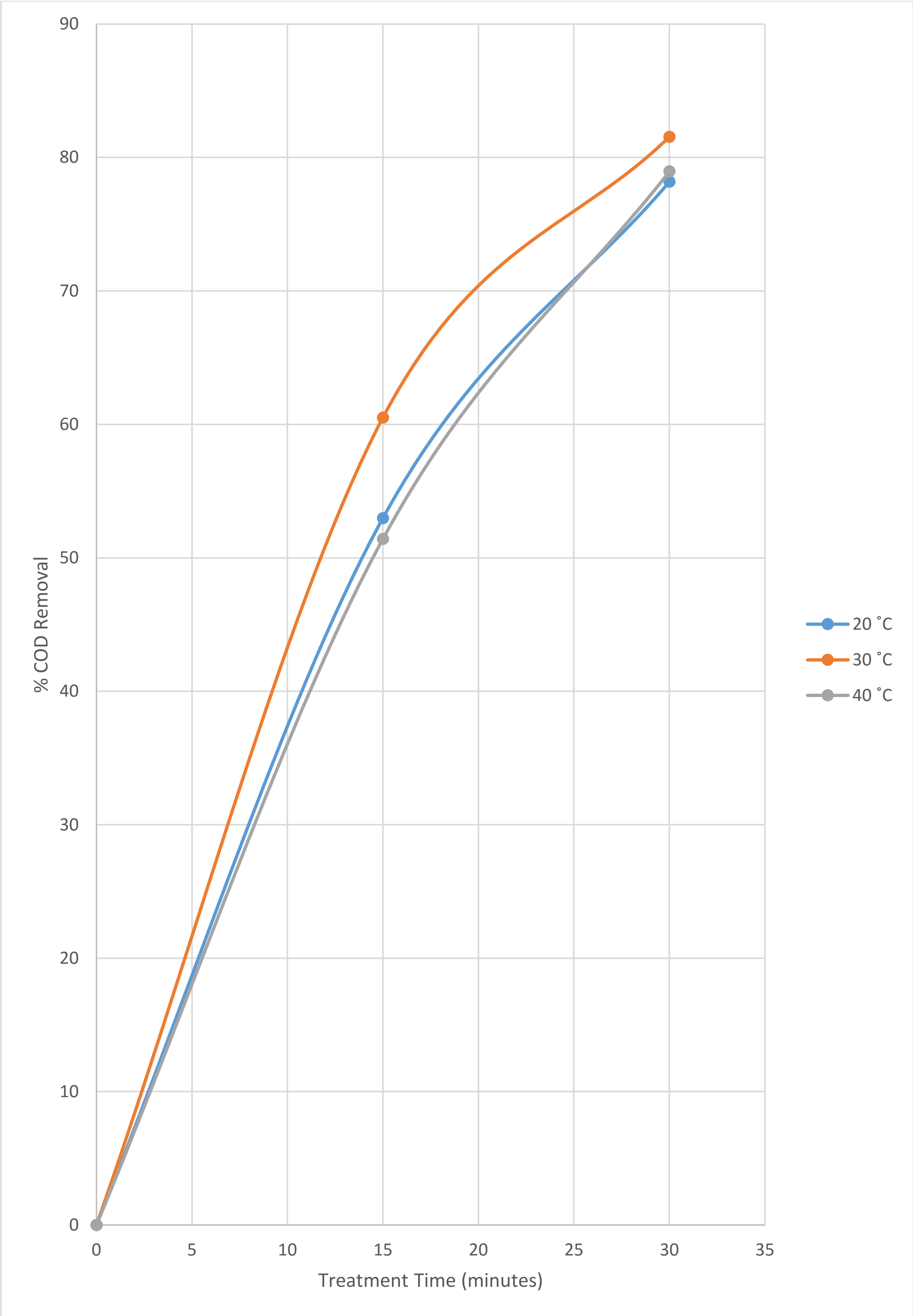

Fig. 5.4. Comparison of different wastewater temperatures on COD removal using Al-Al electrodes (anode-cathode) with 0.5 cm spacing.

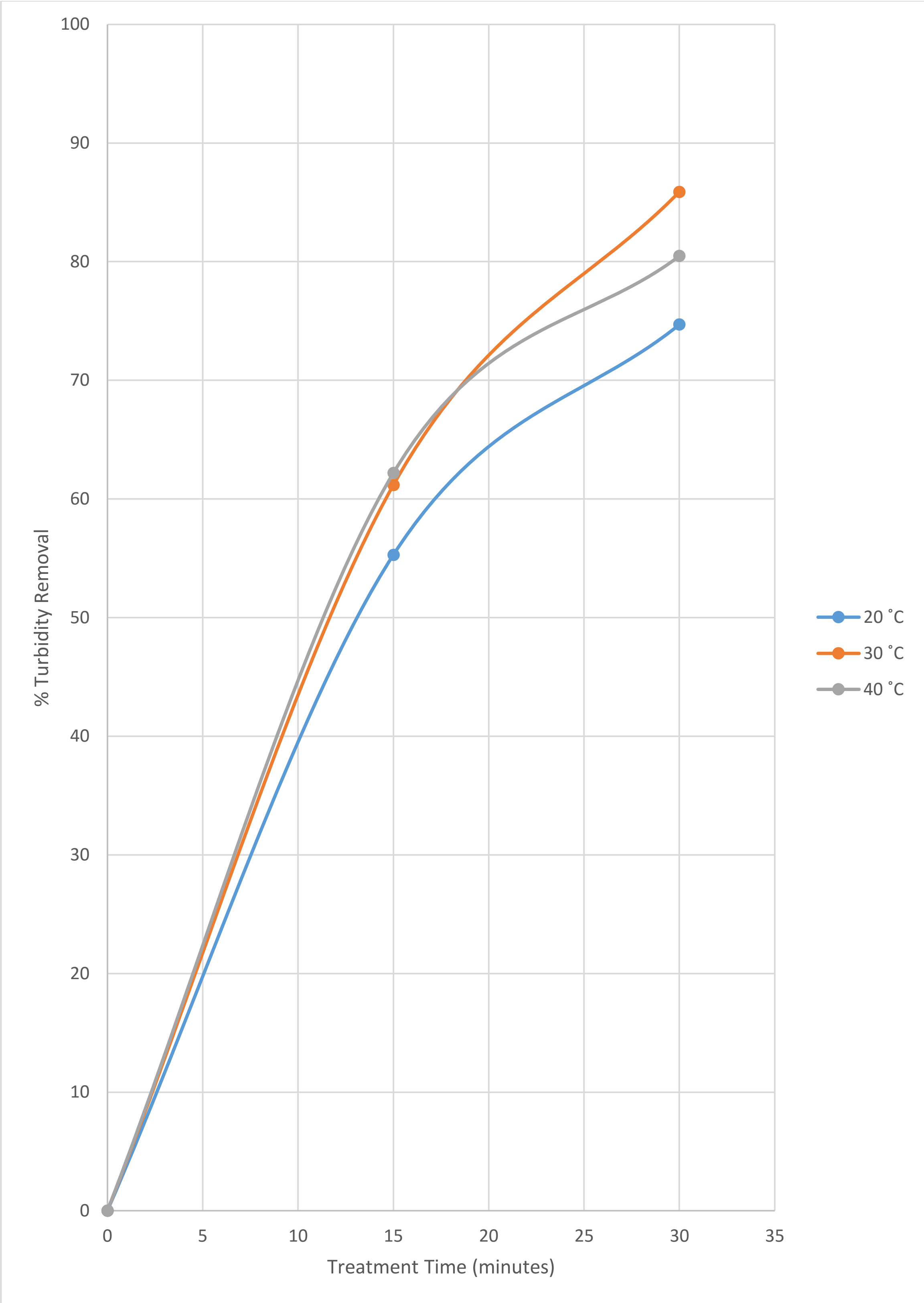

Fig. 5.5. Comparison of different wastewater temperatures on turbidity removal using Al-Fe electrodes (anode-cathode) with 0.5 cm spacing.

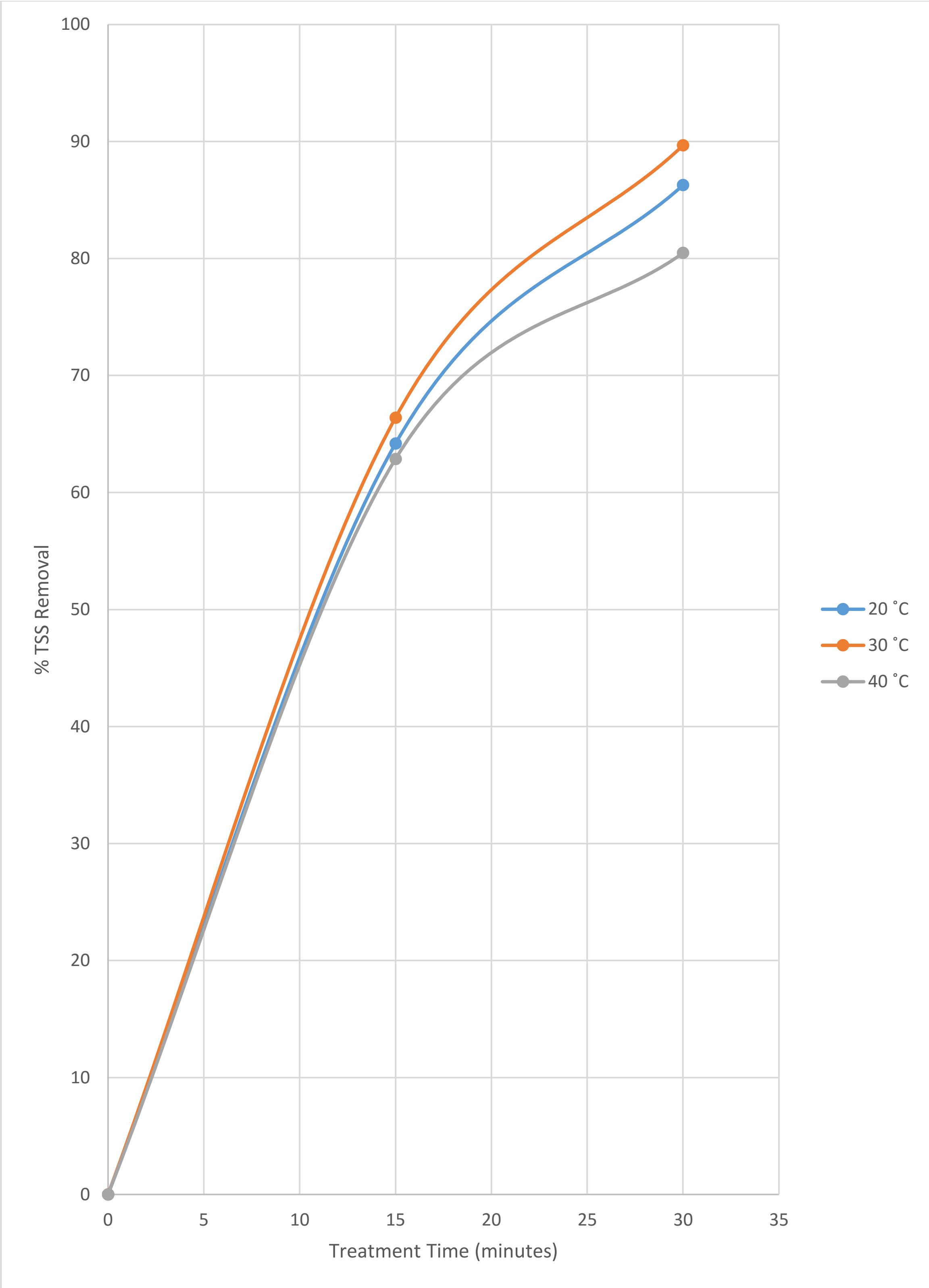

Fig. 5.6. Comparison of different wastewater temperatures on TSS removal using Al-SS electrodes (anode-cathode) with 0.5 cm spacing.

5.2.3 Effect of Inter Electrode Distance

The inter electrode spacing of 0.5 cm, 1 cm and 1.5 cm were selected to observe its effect on the removal of COD, turbidity and TSS. For aluminium material used for both anode and cathode at 30 ˚C temperature of wastewater, the COD removals were found to be 81.5 %, 76.6 % and 70.12 % for electrode spacing of 0.5 cm, 1 cm, 1.5 cm respectively. Results clearly show that this decrease of removals rates occurred in almost all experimental runs. This effect is because of the internal resistance of the cell. As we decrease the electrodes spacing, the internal resistance of the cell starts decreasing which results in more passing of current through the electrodes and results in more coagulant generation and hence increases removal rates.

The comparisons of removals of COD, turbidity and total suspended solids using Aluminium-Aluminium, Aluminium-Iron and Aluminium-Stainless steel electrodes (anode-cathode) respectively at 30 ˚C wastewater temperature with different electrode spacing is shown in **Fig. 5.7, 5.8 and 5.9**.

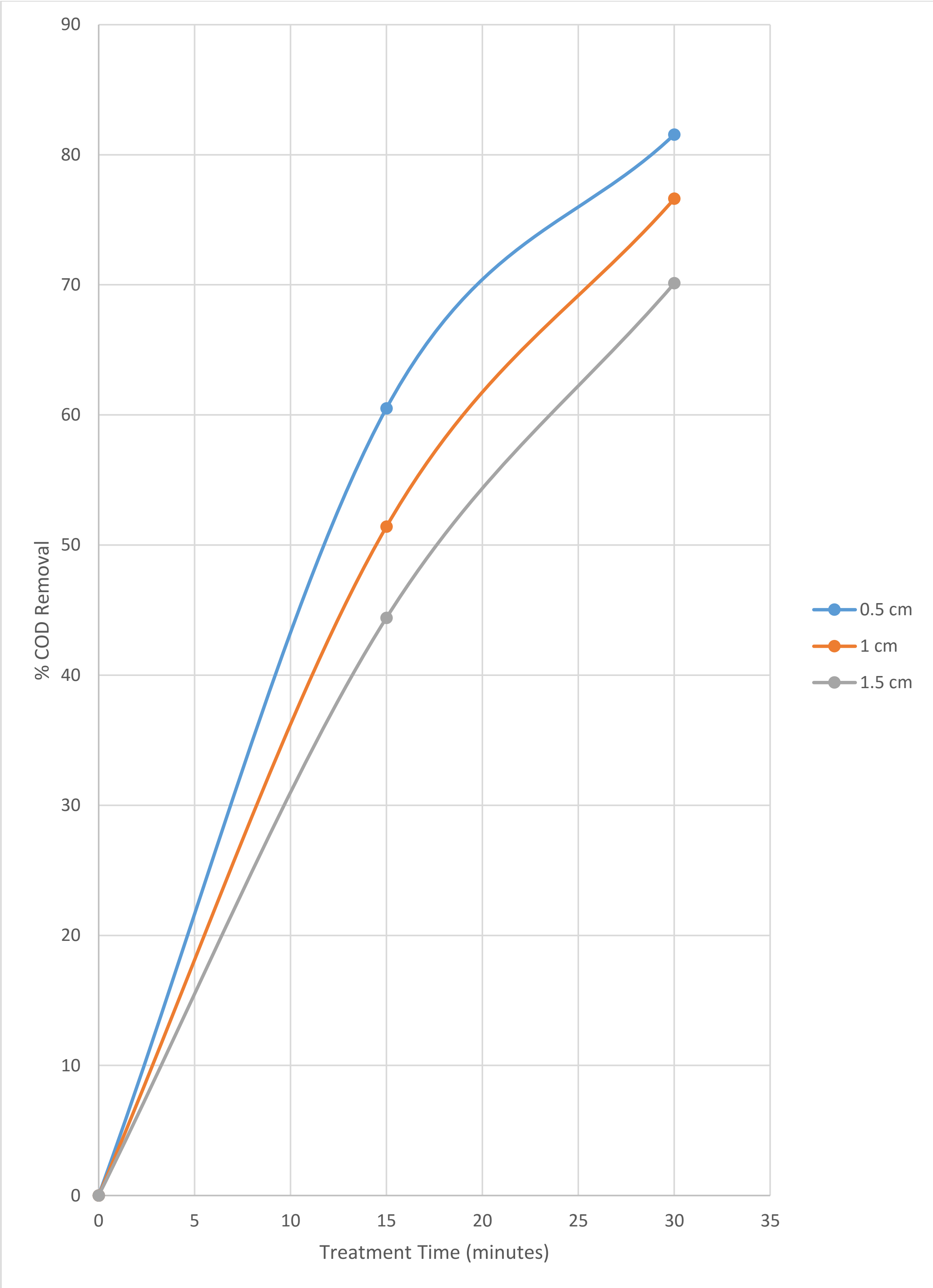

Fig. 5.7. Comparison of different electrode spacing on COD removal using Al-Al electrodes (anode-cathode) with initial wastewater temperature of 30 ˚C.

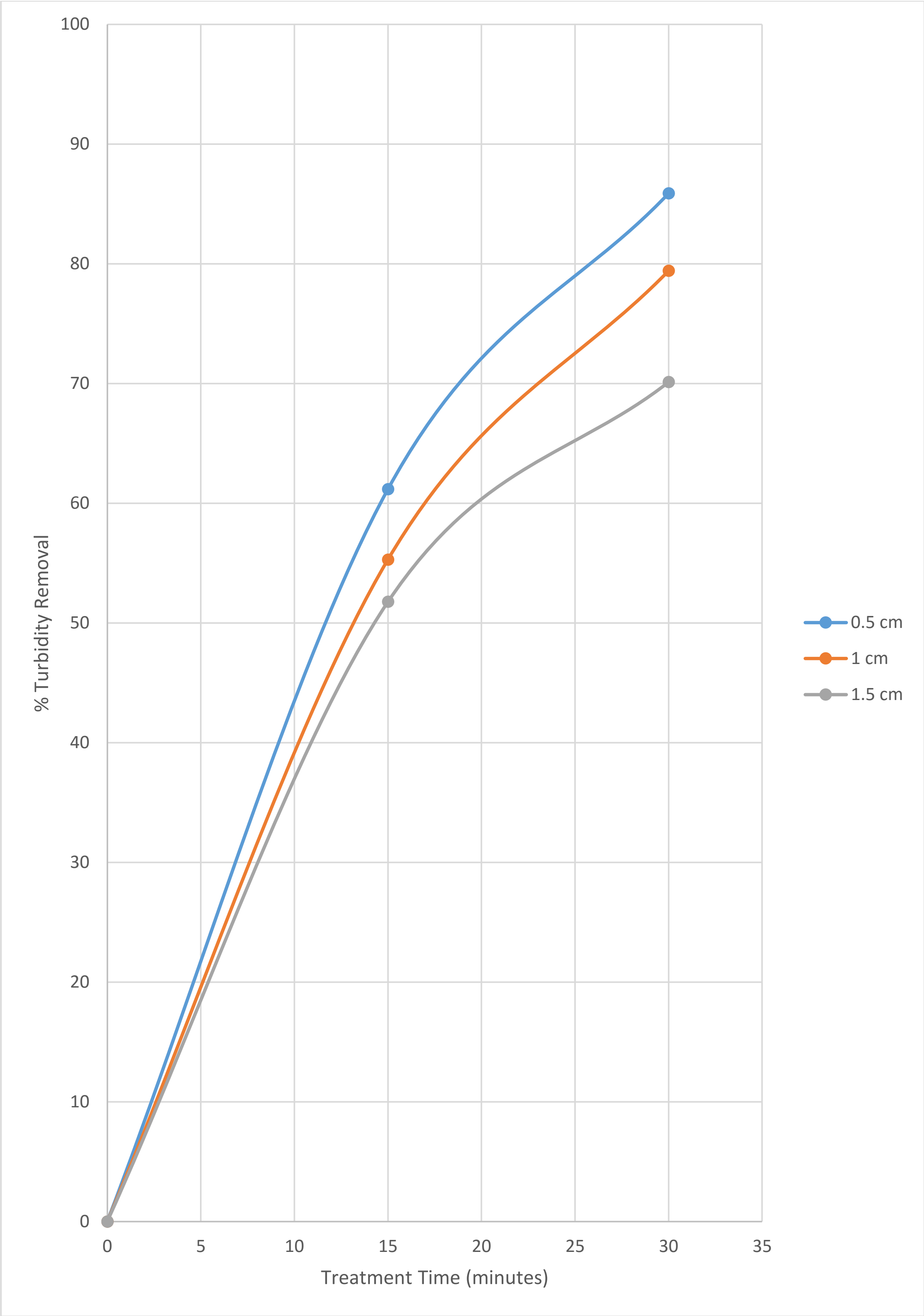

Fig. 5.8. Comparison of different electrode spacing on turbidity removal using Al-Fe electrodes (anode-cathode) with initial wastewater temperature of 30 ˚C.

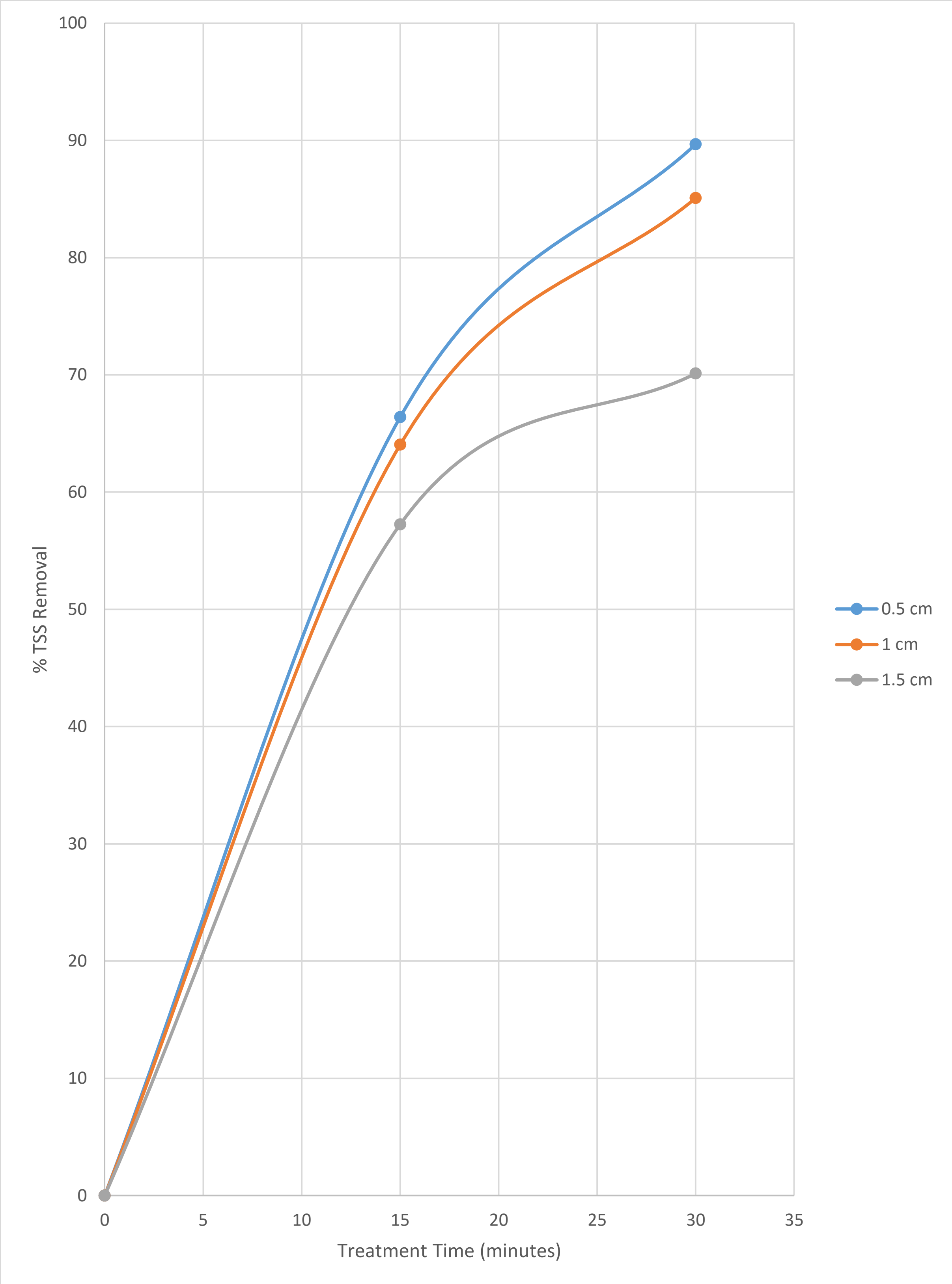

Fig. 5.9. Comparison of different electrode spacing on TSS removal using Al-SS electrodes (anode-cathode) with initial wastewater temperature of 30 ˚C.

CHAPTER 6: CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1 Conclusions

The main focus of the present study was to explore the feasibility of electrocoagulation reactor for the treatment of Brewery Wastewater. The present study involved the operation of electrocoagulation reactor in monopolar parallel mode.

On the basis of the results presented following conclusions could be made from the present study:

- Among all the materials used as electrodes, aluminium is the most effective material in the removals of pollutants. Iron also showed effective results in removals but a little less in comparison to the aluminium.
- Stainless steel also showed effective results when used as cathode in combination with aluminium or iron anode. The maximum of 79.05 % COD removal, 89.67 % TSS removal with aluminium anode, 83.75 % Turbidity removal with iron as anode were observed.
- The removals increased with the decrease in inter electrode distance. The optimum value of electrode spacing was found to be 0.5 cm in comparison to the 1 cm and 1.5 cm spacing.
- The initial temperature of wastewater also had an effect on the process. The removals increased when the temperature increased from 20 ˚C to 30 ˚C and decreased at temperature of 40 ˚C.
- Electrocoagulation is an effective wastewater treatment process and showed highest of 81.55 % removal of COD, 85.55 % turbidity removal and 89.67 % of total suspended solids reduction.
- The present study shows that the operation of electrocoagulation reactor for the treatment of the Brewery wastewater could be feasible, though further study is needed to assess variations in performance parameters.

6.2 Suggestions for future work

In the present study, a sedimentation time was provided before taking the samples from the reactor for the analysis. A constant agitation mechanism was not used in the present study. However, agitation can provide well mixing of coagulants in the electrocoagulation reactor as it does in the conventional chemical coagulation and flocculator systems.

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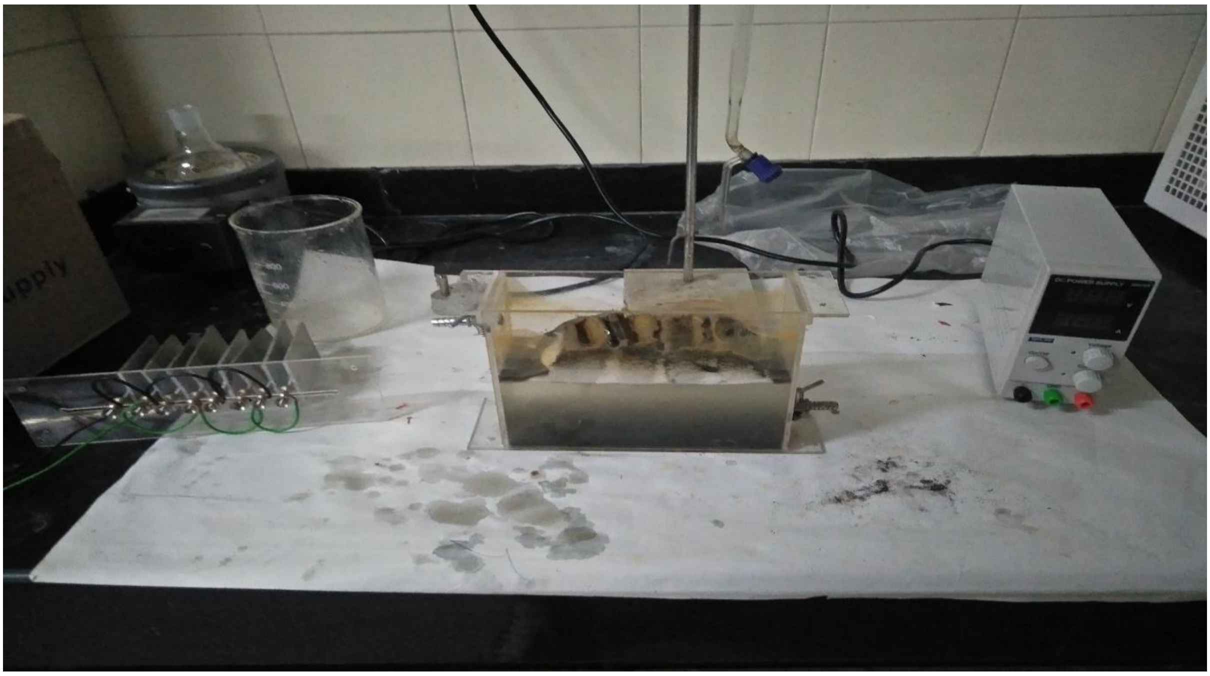
APPENDIX A

PHOTOGRAPHS

Photograph A.1. Electrocoagulation Reactor

Photograph A.2. Electrocoagulation reactor with DC power supply



APPENDIX B
TABLES OF RESULTS

Table B.1. Aluminium as both anode and cathode

Anode-Cathode	Temperature (˚C)	Electrodes spacing (cm)	Time (minutes)	pH	COD (mg/L)	Conductivity (m.mho/cm)	Turbidity (NTU)	TSS (mg/L)
Al-Al	**20**	**0.5**	**0**	7	12320	1.278	180	700
			15	7.5	5792	1.115	81	315
			30	8.5	2688	0.975	37	117
Al-Al	**20**	**1.0**	**0**	7	12320	1.278	180	700
			15	7.5	6976	1.138	95	343
			30	8	3296	1.010	43	135
Al-Al	**20**	**1.5**	**0**	7	12320	1.278	180	700
			15	7.5	7552	1.2	113	382
			30	8	3968	1.119	45	178
Al-Al	**30**	**0.5**	**0**	7	12320	1.278	180	700
			15	8	4864	1.08	64	276
			30	9	2272	0.928	26	75
Al-Al	**30**	**1.0**	**0**	7	12320	1.278	180	700
			15	8	5984	1.149	74	301
			30	8.5	2880	0.986	38	106
Al-Al	**30**	**1.5**	**0**	7	12320	1.278	180	700
			15	7.5	6848	1.189	87	347
			30	8	3680	1.11	46	165
Al-Al	**40**	**0.5**	**0**	7	12320	1.278	180	700
			15	8	5984	1.117	75	296
			30	8.5	2592	1.04	32	110
Al-Al	**40**	**1.0**	**0**	7	12320	1.278	180	700
			15	8	6400	1.121	84	327
			30	8.5	3104	1.06	39	139
Al-Al	**40**	**1.5**	**0**	7.5	13440	1.457	195	765

			15	8	7104	1.359	113	368
Al-Al			**30**	8.5	4288	1.276	75	189

Table B.2. Aluminium as anode and Stainless Steel as cathode

Anode-Cathode	Temperature (˚C)	Electrodes spacing (cm)	Time (minutes)	pH	COD (mg/L)	Conductivity (m.mho/cm)	Turbidity (NTU)	TSS (mg/L)
Al-SS	**20**	**0.5**	**0**	7.5	13440	1.457	195	765
			15	8	6880	1.187	99	274
			30	8.5	3360	1.106	35	105
Al-SS	**20**	**1.0**	**0**	7.5	13440	1.457	195	765
			15	7.5	7680	1.335	106	301
			30	8.5	4160	1.286	43	134
Al-SS	**20**	**1.5**	**0**	7.5	13440	1.457	195	765
			15	8	8160	1.37	113	358
			30	8.5	4512	1.301	56	177
Al-SS	**30**	**0.5**	**0**	7.5	13440	1.457	195	765
			15	8.5	5672	1.258	81	257
			30	9.5	2816	1.148	32	79
Al-SS	**30**	**1.0**	**0**	7.5	13440	1.457	195	765
			15	8.5	6784	1.336	93	275
			30	9	3328	1.286	38	114
Al-SS	**30**	**1.5**	**0**	7.5	13440	1.457	195	765
			15	8	7456	1.389	102	327
			30	9	3968	1.30	46	148
Al-SS	**40**	**0.5**	**0**	7.5	13440	1.457	195	765
			15	8.5	6048	1.29	88	284
			30	9.5	3200	1.175	36	91
Al-SS	**40**	**1.0**	**0**	8	12960	1.349	170	743
			15	8.5	6848	1.301	90	297
			30	9.5	3680	1.258	42	138

Al-SS	**40**	**1.5**	**0**	8	12960	1.349	170	743
			15	8.5	7584	1.32	102	358
			30	9	4128	1.27	53	163

Table B.3. Aluminium as anode and Iron as cathode

Anode-Cathode	**Temperature (˚C)**	**Electrodes spacing (cm)**	**Time (minutes)**	**pH**	**COD (mg/L)**	**Conductivity (m.mho/cm)**	**Turbidity (NTU)**	**TSS (mg/L)**
Al-Fe	**20**	**0.5**	**0**	8	12960	1.349	170	743
			15	8.5	6656	1.357	76	308
			30	9.5	3392	1.12	43	115
Al-Fe	**20**	**1.0**	**0**	8	12960	1.349	170	743
			15	8.5	6976	1.31	81	336
			30	9	3648	1.23	58	138
Al-Fe	**20**	**1.5**	**0**	8	12960	1.349	170	743
			15	8.5	7520	1.29	94	372
			30	9	4224	1.258	62	154
Al-Fe	**30**	**0.5**	**0**	8	12960	1.349	170	743
			15	9	6080	1.190	66	271
			30	10	2944	0.975	24	89
Al-Fe	**30**	**1.0**	**0**	8	12960	1.349	170	743
			15	9	6752	1.26	76	298
			30	9.5	3488	1.18	35	126
Al-Fe	**30**	**1.5**	**0**	8	12960	1.349	170	743
			15	8.5	7104	1.281	82	341
			30	9	4032	1.21	48	142
Al-Fe	**40**	**0.5**	**0**	7.5	11840	1.128	164	678
			15	8.5	6304	0.986	62	286
			30	10	3264	0.783	32	98
Al-Fe	**40**	**1.0**	**0**	7.5	11840	1.128	164	678
			15	8.5	7008	1.134	75	323

			30	9.5	3744	0.865	40	149
Al-Fe	**40**	**1.5**	**0**	7.5	11840	1.128	164	678
			15	8.5	7392	1.006	79	348
			30	9	4384	0.937	46	175

Table B.4. Stainless Steel as both anode and cathode

Anode-Cathode	**Temperature (˚C)**	**Electrodes spacing (cm)**	**Time (minutes)**	**pH**	**COD (mg/L)**	**Conductivity (m.mho/cm)**	**Turbidity (NTU)**	**TSS (mg/L)**
SS-SS	**20**	**0.5**	**0**	7.5	11840	1.128	164	678
			15	8.5	5408	1.11	77	315
			30	9.5	3328	1.067	35	97
SS-SS	**20**	**1.0**	**0**	7.5	11840	1.128	164	678
			15	8.5	6016	1.12	84	348
			30	9	3872	1.09	39	110
SS-SS	**20**	**1.5**	**0**	7.5	11840	1.128	164	678
			15	8	6656	1.12	92	372
			30	8.5	4352	1.095	46	128
SS-SS	**30**	**0.5**	**0**	7.5	11840	1.128	164	678
			15	8.5	5024	0.936	68	288
			30	10	2976	0.876	28	86
SS-SS	**30**	**1.0**	**0**	7.5	11840	1.128	164	678
			15	8.5	5600	0.964	76	323
			30	9.5	3520	1.11	37	102
SS-SS	**30**	**1.5**	**0**	7.5	12000	1.202	178	690
			15	8.5	6368	1.143	87	351
			30	9	4000	0.99	48	116
SS-SS	**40**	**0.5**	**0**	7.5	12000	1.202	178	690
			15	8.5	5248	1.19	74	304

			30	9.5	3232	0.998	36	101
SS-SS	**40**	**1.0**	**0**	7.5	12000	1.202	178	690
			15	8.5	5824	1.183	83	345
			30	9.0	3744	1.148	43	136
SS-SS	**40**	**1.5**	**0**	7.5	12000	1.202	178	690
			15	8.5	6560	1.19	90	371
			30	9	4352	1.168	49	155

Table B.5. Stainless Steel as anode and Aluminium as cathode

Anode-Cathode	**Temperature (˚C)**	**Electrodes spacing (cm)**	**Time (minutes)**	**pH**	**COD (mg/L)**	**Conductivity (m.mho/cm)**	**Turbidity (NTU)**	**TSS (mg/L)**
SS-Al	**20**	**0.5**	**0**	7.5	12000	1.202	178	690
			15	9	5728	1.024	72	326
			30	10	3392	0.823	31	118
SS-Al	**20**	**1.0**	**0**	7.5	12000	1.202	178	690
			15	8.5	6144	1.09	79	349
			30	9	3744	0.892	38	135
SS-Al	**20**	**1.5**	**0**	7.5	12000	1.202	178	690
			15	8.5	6688	1.138	86	374
			30	9	4192	0.962	47	170
SS-Al	**30**	**0.5**	**0**	7.5	12000	1.202	178	690
			15	9	5376	1.008	68	296
			30	10	3166	0.764	32	94
SS-Al	**30**	**1.0**	**0**	7	12320	1.474	182	715
			15	8.5	5952	1.265	76	321
			30	9.5	3456	1.128	42	123
SS-Al	**30**	**1.5**	**0**	7	12320	1.474	182	715
			15	8.5	6432	1.315	85	356
			30	9	4064	1.226	51	156
SS-Al	**40**	**0.5**	**0**	7	12320	1.474	182	715

			15	8.5	5600	1.146	74	312
			30	9.5	3328	0.884	40	120
SS-Al	**40**	**1.0**	**0**	7	12320	1.474	182	715
			15	8	6272	1.2	84	347
			30	9	3648	1.15	50	145
SS-Al	**40**	**1.5**	**0**	7	12320	1.474	182	715
			15	8	6784	1.347	90	382
			30	8.5	4256	1.248	58	171

Table B.6. Stainless Steel as anode and Iron as cathode

Anode-Cathode	**Temperature (˚C)**	**Electrodes spacing (cm)**	**Time (minutes)**	**pH**	**COD (mg/L)**	**Conductivity (m.mho/cm)**	**Turbidity (NTU)**	**TSS (mg/L)**
SS-Fe	**20**	**0.5**	**0**	7	12320	1.474	182	715
			15	8.5	5728	1.253	76	328
			30	9.5	3712	1.134	38	125
SS-Fe	**20**	**1.0**	**0**	7	12320	1.474	182	715
			15	8.5	5920	1.311	85	346
			30	9	4288	1.236	45	150
SS-Fe	**20**	**1.5**	**0**	7	12320	1.474	182	715
			15	8	6368	1.362	92	381
			30	9	4704	1.301	54	167
SS-Fe	**30**	**0.5**	**0**	7	12640	1.576	185	724
			15	8.5	5248	1.287	68	304
			30	10	3412	0.964	31	106
SS-Fe	**30**	**1.0**	**0**	7	12640	1.576	185	724
			15	8	5536	1.358	76	321
			30	9	4064	1.12	39	134
SS-Fe	**30**	**1.5**	**0**	7	12640	1.576	185	724
			15	8	6080	1.235	82	358
			30	8.5	4448	1.23	45	143

SS-Fe	**40**	**0.5**	**0**	7	12640	1.576	185	724
			15	8.5	5472	1.32	70	339
			30	10	3808	1.119	34	131
SS-Fe	**40**	**1.0**	**0**	7	12640	1.576	185	724
			15	8	5728	1.39	77	356
			30	9	4160	1.164	39	145
SS-Fe	**40**	**1.5**	**0**	7	12640	1.576	185	724
			15	8	6208	1.353	83	374
			30	8.5	4640	1.297	44	162

Table B.7. Iron as both anode and cathode

Anode-Cathode	**Temperature (˚C)**	**Electrodes spacing (cm)**	**Time (minutes)**	**pH**	**COD (mg/L)**	**Conductivity (m.mho/cm)**	**Turbidity (NTU)**	**TSS (mg/L)**
Fe-Fe	**20**	**0.5**	**0**	7	12640	1.576	185	724
			15	8.5	5312	1.136	82	306
			30	9.5	3008	0.973	37	107
Fe-Fe	**20**	**1.0**	**0**	7	12640	1.576	185	724
			15	8.5	5536	1.245	96	332
			30	9	3584	1.139	48	131
Fe-Fe	**20**	**1.5**	**0**	7.5	12800	1.368	190	730
			15	8.5	5888	1.294	113	374
			30	9	3904	1.28	59	167
Fe-Fe	**30**	**0.5**	**0**	7.5	12800	1.368	190	730
			15	9	5024	1.10	75	287
			30	10	2688	0.924	29	89
Fe-Fe	**30**	**1.0**	**0**	7.5	12800	1.368	190	730
			15	8.5	5216	1.212	82	311
			30	9.5	3296	1.045	38	117
Fe-Fe	**30**	**1.5**	**0**	7.5	12800	1.368	190	730
			15	8.5	5504	1.21	91	342

			30	9	3520	1.153	45	145
Fe-Fe	**40**	**0.5**	**0**	7.5	12800	1.368	190	730
			15	9	5280	1.149	79	313
			30	10	2976	1.038	34	115
Fe-Fe	**40**	**1.0**	**0**	7.5	12800	1.368	190	730
			15	8.5	5472	1.259	88	335
			30	9.5	3392	1.094	42	143
Fe-Fe	**40**	**1.5**	**0**	7.5	12800	1.368	190	730
			15	8.5	5760	1.242	95	379
			30	9	4128	1.185	51	168

Table B.8. Iron as anode and Aluminium as cathode

Anode-Cathode	**Temperature (˚C)**	**Electrodes spacing (cm)**	**Time (minutes)**	**pH**	**COD (mg/L)**	**Conductivity (m.mho/cm)**	**Turbidity (NTU)**	**TSS (mg/L)**
Fe-Al	**20**	**0.5**	**0**	7.5	12800	1.368	190	730
			15	9	6528	1.156	85	314
			30	10	3328	1.004	40	119
Fe-Al	**20**	**1.0**	**0**	7	13120	1.522	194	750
			15	8	6848	1.182	98	348
			30	8.5	3584	1.11	47	142
Fe-Al	**20**	**1.5**	**0**	7	13120	1.522	194	750
			15	8	7040	1.267	106	370
			30	9	3904	1.145	58	164
Fe-Al	**30**	**0.5**	**0**	7	13120	1.522	194	750
			15	8.5	6208	1.321	75	295
			30	10	3072	1.135	31	97
Fe-Al	**30**	**1.0**	**0**	7	13120	1.522	194	750
			15	8	6528	1.27	83	321
			30	9	3488	1.158	38	120
Fe-Al	**30**	**1.5**	**0**	7	13120	1.522	194	750

			15	8	6880	1.15	94	341
			30	8.5	3840	1.041	47	133
Fe-Al	**40**	**0.5**	**0**	7	13120	1.522	194	750
			15	8.5	6496	1.382	79	330
			30	9	3200	1.218	35	130
Fe-Al	**40**	**1.0**	**0**	7	13120	1.522	194	750
			15	8.5	6816	1.312	85	348
			30	9	3680	1.21	41	142
Fe-Al	**40**	**1.5**	**0**	7	13120	1.522	194	750
			15	8	7136	1.258	94	366
			30	8.5	4064	1.104	50	158

Table B.4. Iron as anode and Stainless Steel as cathode

Anode-Cathode	Temperature (˚C)	Electrodes spacing (cm)	Time (minutes)	pH	COD (mg/L)	Conductivity (m.mho/cm)	Turbidity (NTU)	TSS (mg/L)
Fe-SS	**20**	**0.5**	**0**	7.5	11520	1.39	160	680
			15	8	5824	1.178	70	293
			30	9	2976	0.98	35	99
Fe-SS	**20**	**1.0**	**0**	7.5	11520	1.39	160	680
			15	8.5	6080	1.262	81	326
			30	9.5	3168	1.11	43	127
Fe-SS	**20**	**1.5**	**0**	7.5	11520	1.39	160	680
			15	8.5	6368	1.292	93	360
			30	9	3488	1.168	52	149
Fe-SS	**30**	**0.5**	**0**	7.5	11520	1.39	160	680
			15	9	5504	1.18	62	264
			30	10	2656	0.9447	26	79
Fe-SS	**30**	**1.0**	**0**	7.5	11520	1.39	160	680
			15	8.5	5760	1.205	72	301
			30	9.5	3008	1.124	35	110

Fe-SS	**30**	**1.5**	**0**	7.5	11520	1.39	160	680
			15	8.5	6112	1.228	86	335
			30	9	3232	1.1	47	135
Fe-SS	**40**	**0.5**	**0**	7.5	11520	1.39	160	680
			15	8.5	5728	1.195	68	296
			30	9.5	2784	0.982	32	87
Fe-SS	**40**	**1.0**	**0**	7.5	11520	1.39	160	680
			15	8.5	5984	1.248	74	329
			30	9	3328	1.174	40	133
Fe-SS	**40**	**1.5**	**0**	7.5	11520	1.39	160	680
			15	8	6432	1.25	88	362
			30	8.5	3776	1.156	49	177