

Combined electrooxidation and electrocoagulation processes for the treatment of municipal wastewater

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Abstract

A study was conducted to investigate the effectiveness of combined processes of electrooxidation and electrocoagulation using stainless steel electrodes for the removal of BOD, ammonia, coliform, turbidity and total suspended solids. In addition to total organics, removal of soluble and particulate organics was also investigated. Experiments were also conducted with filtered samples to study the effect of suspended solids on the electrooxidation of soluble BOD and ammonia. Comparative jar test experiments were conducted with FeCl_3 coagulant, to compare the sludge production by electrocoagulation with chemical addition process.

Combined processes were proved effective for the removal of BOD. Most of the removal of BOD was contributed by the removal of particulate organics by electrocoagulation. Significant effect of current and contact time was observed on the removal of the above contaminants. BOD removal increased with the increase in current and contact time up to 0.2 A, beyond which, further increase in current (i.e. at 0.4 and 0.8 A) resulted in the decrease in the removal efficiency. The maximum removal of 84.82% was observed at 0.2 A and 50 minutes contact time. Ammonia removal on stainless steel electrodes was not efficient. Maximum removal of only 18.13% was observed at 0.2 A and 50 minutes contact time. Coliform removal was observed to be directly dependent on applied current and contact time. Maximum removal of 5.05 log scale removal was observed at 0.8 A and 30 minutes contact time. High removal of turbidity and total suspended solids (93.33 and 95.38%) was achieved by the combined processes. Experiments with filtered samples resulted in the increase in the removal of soluble BOD and ammonia thus shows that there is an effect of suspended solids on the electrooxidation of contaminants. Sludge production by electrochemical process was observed to be 2.45 less than the conventional coagulation process. However, when the sample pH was altered from 7.07 to 9.11, marked decrease in the optimum dosage was observed, and the sludge production was observed to be 2.95 times less than the electrocoagulation process.

Dedicated to
My Beloved Parents
Brothers and Sister

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THESIS ABSTRACT

NAME	Mohammed Sajeed Farooqui
TITLE OF STUDY	Combined Electrooxidation and Electrocoagulation Processes for the Treatment of Municipal Wastewater
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A study was conducted to investigate the effectiveness of combined processes of electrooxidation and electrocoagulation using stainless steel electrodes for the removal of BOD, ammonia, coliform, turbidity and total suspended solids. In addition to total organics, removal of soluble and particulate organics was also investigated. Experiments were also conducted with filtered samples to study the effect of suspended solids on the electrooxidation of soluble BOD and ammonia. Comparative jar test experiments were conducted with FeCl_3 coagulant, to compare the sludge production by electrocoagulation with chemical addition process.

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ملخص الرسالة

الاسم: محمد سجاد فاروقى

عنوان الرسالة: استخدام طرق التخثر والاكسدة الكهربائيه فى عمليات معالجة مياه الصرف الصحى

التخصص: الهندسه المدنيه

تاريخ التخرج: ديسمبر 2004 م

يهدف هذا البحث الى دراسه مدى فاعليه طرق الاكسدة والتخثر الكهربى باستخدام اقطاب من الحديد الغير قابل للصدأ وذلك لازاله الاكسجين الحيوى والنشادر والبكتيريا والتعكر بالاضافه الى المواد الصلبه العالقه كما يدرس البحث ايضا ازاله المواد العضويه الذائبه. وقد اجريت بعض التجارب على عينات تم ترشيحها مسبقا بهدف دراسه تاثير المواد الصلبه العالقه على طريقه الاكسدة الكهربائيه على نسبة الاكسجين الحيوى الذائبه. وقد عمل تجارب باستخدام اختبار الرج النسبى فى وجود كلوريد الحديد ($FeCl_3$) كماده متخثره وذلك لمقارنه كميته الرواسب المتبقية بعد المعالجه باستخدام طريقه التخثر الكهربى مع اضافات كيميائيه.

ولقد وجد ان تطبيق عمليتي الاكسدة والتخثر الكهربى معا يعطى فاعليه اكثر لازاله الاكسجين الحيوى حيث انه ادى الى زياده معدل الازاله عند تيار كهربى 0.2 امبير ولكن عند زياده التيار الكهربى الى قيم اعلى (0.4 و 0.8 امبير) ادى الى نقص فى الكفاءه. تم الحصول على اعلى قيمه كفاءه وهى 84.82 % عند تيار 0.2 امبير وذلك عند زمن توصيل مقداره 50 دقيقه. ومن ناحيه اخرى وجد ان ازاله النشادر باستخدام اقطاب من الحديد الغير قابل للصدأ غير فعاله حيث ان اكبر كفاءه تم الحصول عليها كانت 18.13 % عند تيار 0.2 امبير وزمن 50 دقيقه. اما عن ازاله بكتيريا الكوليفورم فلقد وجد انها تتناسب طرديا مع التيار الكهربى المستخدم وزمن التوصيل حيث كانت اقصى ازاله ممكنه هى 5.05 على مقياس لوغارىثمى وذلك عند تيار 0.8 امبير وزمن توصيل مقداره 30 دقيقه. وكانت اقصى كفاءه لازاله المواد الصلبه العالقه والتعكر هى 93.33 و 95.38 % على التوالى.

ولقد وجد ان تطبيق طريقتى المعالجه معا على عينات سبق ترشيحها يعطى زياده فى الكفاءه مما يشير الى وجود علاقه بين كميته المواد الصلبه العالقه وكفاءه طرق الازاله المستخدمه. ولوحظ ان تكون الرواسب الطينيه باستخدام العمليات الكهروكيميائيه اقل بمقدار 2.45 عن عمليات التخثر التقليديه المعروفه , ولكن عند زياده رقم الاس الحمضى للعينه من 7.07 الى 9.11 ادى الى نقص ملحوظ فى الكميته المترسبه بفارق 2.95 عن طريقه التخثر الكهربى.

درجه الماجستير

جامعه الملك فهد للبترول والمعادن

الظهران- المملكه العربيه السعوديه

CHAPTER 1

INTRODUCTION

Municipal wastewater is the mixture of domestic wastewater, (the basic component), small amounts of industrial and agro-zootechnical wastewater, storm water, drain water, surface infiltration, and ground water (Barlett, 1990). It usually consists of a number of contaminants, such as suspended solids, biodegradable organics, pathogens, nutrients, refractory organics, heavy metals and dissolved inorganics. Direct discharge of untreated wastewater into the natural water bodies is not desirable, as the decomposition of the organic waste would seriously deteriorate the water quality. In addition, communicable diseases can be transmitted by the pathogenic microorganisms. Nutrients such as nitrogen and phosphorous, along with organic material, when discharged to the aquatic environment can also lead to excessive growth of undesirable aquatic life. When discharged in excessive amounts on land, can also lead to the pollution of groundwater. It was estimated that nearly half a million organic compounds have been synthesized and some 10,000 new compounds are added each year. As a result, many of these compounds are now found in the wastewater from municipalities and communities (Metcalf and eddy, 1991). For these reasons, treatment of wastewater has become necessary for the protection

of the environment keeping in view public health, economic, social, and political concerns.

Biological processes are the most common methods, which are usually employed for the treatment of municipal wastewater (Iniesta et al., 2002). However, due to the long detention time and large treatment system, it results in higher treatment cost. Due to the reason, location of biological treatment utilities has become a big problem in the areas, where there is a scarcity of land and has high land value. In addition to that, biological processes are also susceptible to the changes of influent characteristics, and require highly skilled labor. Therefore there is a need for new and novel processes that could efficiently treat municipal wastewaters at relatively low operating cost. Research shows that electrochemical processes have the potential to be developed as a robust process, which can completely convert organic pollutants into gases such as N_2 and CO_2 (Feng et al., 2003). Electrochemical processes proved to be simple, and are relatively economical (Feng et al., 2003).

Municipal wastewaters usually contain very high suspended solids and, most of the BOD is contributed by the suspended particulate matter that is present in it. Therefore, effective removal of particulate organic matter would result in relatively higher reduction of BOD in the effluent. When used prior to the biological treatment, it would also result in high reduction of the BOD loading to the biological treatment. Now a day's, electrocoagulation is gaining more attention for the removal of suspended solids, in which the chemical coagulants are not directly added. Instead, coagulants are produced insitu in the reactor by using reactive electrodes of stainless steel and aluminum. Electrooxidation

has also been found to be promising in oxidizing the soluble organic matter that is present in wastewater by direct and indirect oxidation. So, by combining electrocoagulation for the removal of particulate organic matter and electro-oxidation for oxidizing the soluble organic matter, better treatment efficiencies may be achieved in terms of BOD removal.

According to our knowledge, although extensive research has been done by many researchers in the treatment of municipal wastewaters, but still a detailed study about the combined removal of particulate BOD₅ and Soluble BOD₅ has not been given much attention yet. In addition to that so far, ammonia oxidation has been investigated only on the non-reactive electrodes, such as graphite (Poon and Brueckner, 1975, Lin and Wu, 1996, Lin and Wu, 1997), dimensionally stable anode electrodes (Lee et al, 2002), (titanium (Feng et al, 2003), platinum (Marincic and Leitz, 1978, Feng et al, 2003), titanium coated with Ti/RuO₂-TiO₂ electrodes (Feng et al, 2003) etc. A study on oxidation of ammonia on the reactive electrodes such as iron and aluminum has not been reported yet.

The main objective of the research is to investigate the effectiveness of the combined processes of electro-oxidation and electro-coagulation using stainless steel electrodes in the removal of BOD, ammonia, coliform, turbidity and suspended particulate matter from municipal wastewater.

CHAPTER 2

LITERATURE REVIEW

2.1 The Electrochemical Processes

Using electricity to treat water was first proposed in UK in 1889 (Strokach, 1975). The electro coagulation of drinking water was first applied on a large scale in the US in 1946 (Stuart, 1946, Bonilla, 1947). Because of the relatively large capital investment and the expensive electricity supply, electrochemical treatment of water or wastewater technologies did not find wide application worldwide then (Koby et al, 2003). However due to extensive research in US and USSR during the following half century, the process has gained large amount of knowledge. With the ever-increasing stringent environmental regulations regarding the wastewater discharge, electrochemical technologies have regained their importance worldwide during the past two decades. (Chen et al, 2000, Lin et al, 1998). Now a day, electrochemical technologies have reached a state that they are not only comparable with other technologies in terms of cost but also potentially more

efficient, and for some situations, electrochemical technologies may be the indispensable step in treating wastewaters containing refractory pollutants (Chen, 2003). Electrochemical technologies offer various treatment processes such as electro oxidation, electro coagulation, electro disinfection, and electro deposition.

An extensive research has been done by many researchers in treating various wastewaters by using electrochemical technologies. Abuzaid et al., 1998 had studied nitrite removal from aqueous solution by electrochemical process using stainless steel electrodes. Complete removal of nitrite was achieved at 2 A after a duration of ten minutes, when treating a total sample of 4.4 liter using six electrodes of 50 cm² each. The study also dealt with the effect of various parameters like, current input, volume of the solution, initial pH, and number of electrodes on removal of nitrite at a concentration typical to aquaculture system effluent. In addition to that a first order reaction model was developed to predict the effect of current on nitrite removal.

Bejankiwar et al., 2003 treated the wastewater from color photograph processing unit by electrochemical process using cast iron electrode. It was reported that cast iron was efficient in removing both chemical oxygen demand and biochemical oxygen demand to the levels that meet the standards for discharge to surface water and public sewers. The energy consumption to meet the standards for sewer disposal was observed to be less than that of surface water disposal, and concluded that, on the basis of energy consumption, the wastewater could be partially treated (pretreatment) electrochemically to meet the standard for sewer disposal rather than that of surface water disposal.

Kim et al., 2002 combined the electrochemical process with fluidized biofilm process and chemical coagulation for the treatment of textile wastewater. In the pilot scale study,

fluidized biofilm process was used prior to chemical coagulation and electrochemical oxidation processes. Effective COD and color removals of 95.4 % and 98.5 % were achieved by overall combined processes.

Ge et al., 2004 developed a new bipolar electrocoagulation and electroflotation process to treat laundry wastewater. In the study, electrocoagulation and electroflotation were carried out in single reactor. The operating parameters such as initial pH, hydraulic residence time, and current density were investigated. The process successfully removed turbidity, COD, phosphate and MBAS simultaneously in the pH range of 5-9. The laboratory results showed that the removal of COD was greater than 70 %, and the removal efficiencies of MBAS, turbidity and P-phosphate was above 90 %.

Kumar et al., 2004 treated the arsenite and arsenate containing water by electrocoagulation. Laboratory scale experiments were conducted with three electrode materials, iron, aluminum and titanium to assess their efficiency for arsenic removal. Efficiencies with different electrode materials followed the sequence: iron > titanium > aluminum. The process was able to remove more than 99 % of arsenic from an As-contaminated water and met the drinking water standard of $10 \mu\text{g}^{-1}$ with iron electrode. As(III) was more efficiently removed in electrocoagulation than chemical coagulation, whereas, As(V) removal performance of both electrocoagulation and chemical coagulation was reported to be nearly same.

Lai and Lin., 2004 investigated the treatment of copper chemical mechanical polishing wastewater from a semi conductor plant by electrocoagulation. In the study, electrocoagulation was employed to treat the CMP wastewater with an attempt to simultaneously lower its turbidity, copper and COD concentrations. The test results

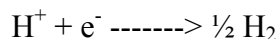
indicated that electrocoagulation with Al/Fe electrode pair was efficient and able to achieve 99 % copper ion and 96.5 % turbidity removal in less than 30 minutes. The COD removal was more than 85 %, with an effluent COD below 100 mg/l. The effluent wastewater was reported to be very clear, and its quality met the direct discharge standard. Bejankiwar, 2002 investigated the feasibility of treatment of cigarette industry wastewater by using electrochemical process. The treatment efficiency was monitored in terms of COD, BOD and suspended solids concentration. About 56 % of COD and 84 % removal of BOD removal were observed at 3.5 A current for 5 h of electrolysis using cast iron electrodes. The treated effluent by electrochemical process was subjected to chemical coagulation using Ca(OH)_2 as coagulant. With the combined processes, overall removal efficiency of 71.01 %, 89.62 % and 80.59 % of COD, BOD, and TSS was reported. The final treated effluent confirms to the stipulated standards for safe disposal into surface water bodies (Indian standards).

2.2 The Nature of Electrochemical Processes

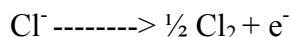
A typical electrochemical treatment process consists of electrolytic cell, which uses electrical energy to affect a chemical change. In simplest forms, we can say that, an electrolytic cell consists of two electrodes, anode and cathode, immersed in an electrical conducting solution (the electrolyte), and are connected together, external to the solution, via an electrical circuit which includes a current source and control device. The chemical processes occurring in such cells are oxidation and reduction, taking place at the

electrode/electrolyte interface. The electrode at which reduction occurs is referred to as the cathode and conversely, the anode is the electrode at which oxidation processes occur.

The current flow in an electrochemical cell is maintained by the flow of electrons resulting from the driving force of the electrical source. In order to allow the current to flow, there must be an electrolyte, which facilitate the flow of current by the motion of its ionic charged species. Type of electrolyte has significant effect on the process in the formation of oxidizing species during the process. For example, if HCL is used as the electrolyte, H^+ moves toward the negatively charged electrode (cathode) in order to accept electrons and get reduced to hydrogen according to the following reaction.



At the same time, Cl^- moves toward the positively charged electrode (anode) to discharge electrons and gets oxidized to chlorine as the following:



The species H^+ and Cl^- in this example are called the principal charged species, which are responsible for current flow in the solutions.

High conductivity is an added advantage to the process, which reduces the electrical resistance of the solution. On other hand, it also significantly reduces the adverse effects of HCO_3^- , SO_4^- . As the existence of the carbonate or sulfate ions would lead to the

precipitation of Ca^{2+} or Mg^{2+} ions that form an insulating layer on the surface of the electrodes, which would further hinder the oxidation and reduction process (Chen, 2003).

2.3 Electro oxidation of soluble organic matter

Electro oxidation of organic and inorganic compounds takes place via two principle pathways direct oxidation and indirect oxidation. The direct oxidation occurs at the anode electrode in which the pollutants discharge its electron to the anode electrode in order to maintain the flow of current in the bulk solution. The indirect oxidation occurs as a result of the production of powerful oxidizing agents in the bulk solution such as chlorine, hydrogen peroxide and ozone. Short-lived intermediates, such as $\text{OH}\cdot$, $\text{O}_2\cdot$ and $\text{HO}_2\cdot$ also form during the electrooxidation and could effectively destroy the organic and inorganic pollutants.

An extensive research has been going on for the treatment of municipal wastewater using electrochemical process on various electrodes. Poon and Bruekner, 1975 investigated the treatment of screened raw domestic wastewater by mixing it with seawater by electrolysis. They used a graphite anode and an iron cathode. Their results showed that with a wastewater: seawater ratio of 9:1 and a power supply of 0.33 amp /hr/l, the process was able to remove 85 % BOD and on an average 90 % ammonia nitrogen. Vlyssides et al, 2002 have also studied the electrochemical treatment in relation to the pH of domestic wastewater using Ti/Pt (titanium alloy covered by platinum alloy foil) as anode and stainless steel 304 cylinder as cathode electrode by adding 0.8 % (W/v)

sodium chloride as electrolyte. They found the process to be more advantageous compared to conventional biological treatment and achieved almost 99.5, 99.5 and 100 % removal of COD, Volatile suspended solids and ammonia nitrogen, respectively, working at 15 V and 100 A with a detention time of 120 minutes. The energy demand was also calculated, which was ten times less than the aerobic biological processes. Formation of strong oxidants such as Cl_2 , O_3 , H_2O_2 and other short-lived oxygen, hydroxyl radicals in the reactor was reported. However Bukhari et al, 1999 had investigated the treatment of domestic wastewater without mixing any seawater or external source of electrolyte. As the mixing of seawater is a draw back that would result in the increase of quantity and salinity of the effluent. They used stainless steel electrodes, and a total anodic active surface area of 150 cm^2 to treat a wastewater sample of 5 liters. The process was found to be effective in the removal of soluble organics, and achieved 59.4 % removal of total organic removal working at 0.4 A with a contact time of 10 minutes.

Feng et al, 2003 may have been the only researchers who conducted lab experiments by using the combined approach of electro oxidation and electro coagulation processes to treat domestic wastewater. They used separate electrooxidation and electrocoagulation units, which consisted of flat plates $\text{Ti/RuO}_2 - \text{TiO}_2$ anode and stainless steel cathode in the electro oxidation unit, and the stainless steel anode and cathode in electrocoagulation unit. Both the units were followed by sedimentation tanks. The wastewater was transferred to electro oxidation unit for 15 minutes at a current density of 3 mA/cm^2 and a pulse voltage of 500V with a frequency of 25 kHz. After a detention time of 15 minutes, it was transferred to a sedimentation tank for 1 hour, and subsequently the effluent was allowed to flow to the electro coagulation unit for another 15 minutes treatment and then

finally to a sedimentation tank for 1 hour. With the combined approach of electro oxidation and electro coagulation, they achieved approximately 90 % removal of COD, ammonia and 97.05 % of TSS. However, the study did not deal with the removal of the particulate organic matter, which would have revealed the clear picture of the removal of particulate organic matter by electro coagulation and soluble organics by electro-oxidation process.

Electro oxidation process has also been successfully used to oxidize the ammonia that is present in the wastewater on various electrodes. Lin and Wu, 1996 investigated oxidation of ammonia in synthetically prepared ammonia solution on high purity graphite anode with a total active surface area of 22.6 cm^2 . Maximum removal efficiency of 61 % of ammonia was achieved at pH 9, at a current of 2.5 A and a detention time of 50 minutes. Lee et al, 2002 conducted experiments on electrooxidation of ammonia in artificial seawater using dimensionally stable electrodes of width 3 cm and depth 10 cm. It was observed that ammonia concentration to be exponentially decreasing with the increase of current density and the hydraulic residence time. Maximum ammonia removal efficiency of 80 % was observed at 66 A/m^2 and a hydraulic residence time of 90 minutes. Lin and Wu, 1997 also, studied the electrooxidation of ammonia using graphite rod anode and titanium cathode situated approximately 1.5 cm apart to each other. The removal efficiency was found to be increasing with the increase of current density and the complete removal was observed at 34.2 mA/cm^2 current density and a contact time of just 10 minutes.

2.4 Electrocoagulation

Electro coagulation technology offers an alternative to conventional coagulation process, where the metal salts or polymers are added to break the stable suspensions of the colloidal particles. In electro coagulation, coagulants are produced in situ within the reactor without direct addition of any chemicals. Coagulants are produced by the electrolytic oxidation of appropriate anode materials, such as stainless steel and aluminum electrodes, which result in formation of highly charged polymeric metal hydroxyl species. These species neutralize the electrostatic charges on the suspended solids and facilitate agglomeration resulting in separation from the aqueous phase. The technology removes metals, colloids particles, and soluble organics pollutants from aqueous media by introducing highly charged polymeric hydroxide species. The treatment prompts the precipitation of certain metals and salts (Mollah et al, 2001).

The various advantages of electro coagulation process, compared to the traditional conventional coagulation process, have been reported by Mollah et al., 2001.

- Process avoids the use of chemicals, and there is no problem of neutralizing excess chemicals and no possibility of secondary pollution.
- The equipment required for Electro coagulation process is simple and compact and is easy to operate and handle the problems encountered during running.
- Simple and compact treatment facility results in relatively low cost and there is a possibility of complete automation.

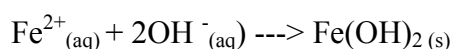
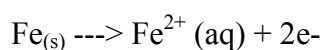
- Electro coagulation process has the advantage of removing the smallest colloidal particles because the applied electric field sets them in faster motion thereby facilitating the agglomeration.
- It is a low sludge producing process, and the sludge formed during the process tends to be readily settable and easy to dewater, as it is mainly composed of metallic oxides/hydroxides.
- The flocs formed during the electro coagulation process tends to be much larger, contains less bound, is acid resistant and more stable, therefore can be separated by filtration.
- Electro coagulation effluent can be reused with a lower water recovery cost, due to the low dissolved solids content as compared with other chemical treatment effluent.
- The gas bubbles produced during electrolysis can carry the pollutant on the top of the solution where it can be more easily concentrated, collected, and removed.
- The process has no moving parts and most of the process is controlled electrically, therefore requires less maintenance.
- The electrocoagulation technique can be conveniently used in rural areas where electricity is not available, because a solar panel attached to the unit may be sufficient to carry out the process.

The electrodes that are commonly used for the electrocoagulation process are aluminum and iron, in the form of plates or packed form of scarps such as steel turnings, millings etc. Usually, electrodes of iron for wastewater treatment and aluminum for water treatment are used, because iron is relatively cheaper (Shen et al., 2003).

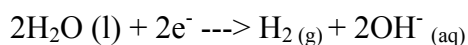
When stainless steel is used as an anode, upon oxidation in an electrolytic system, it produces iron hydroxide, Fe(OH)_n , where $n=2$ or 3 . Two mechanisms have been proposed for the production of Fe(OH)_n .

Mechanism 1

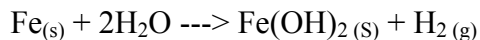
Anode:



Cathode:

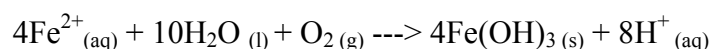
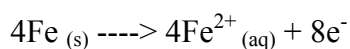


Overall:

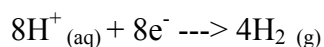


Mechanism 2

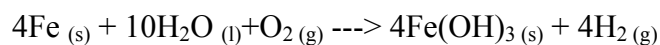
Anode:



Cathode:



Overall:



In addition to the above hydroxyle species, electro generated ferric ions form monomeric, ferric hydroxo complexes with hydroxide ions and polymeric species, depending on the

pH range. These are FeOH^{2+} , Fe(OH)_2^+ , $\text{Fe}_2(\text{OH})_2^{4+}$, Fe(OH)_4^- , $\text{Fe(H}_2\text{O)}_2^+$, $\text{Fe(H}_2\text{O)}_5\text{OH}^{2+}$, $\text{Fe(H}_2\text{O)}_4(\text{OH})_2^+$, $\text{Fe(H}_2\text{O)}_8(\text{OH})_2^{4+}$, $\text{Fe}_2(\text{H}_2\text{O)}_6(\text{OH})_4^{2+}$, which transform finally into Fe(OH)_3 at pH around 8 (Koby et al., 2003, Benefield et al., 1982, Rubin, 1974).

The charged hydrolyzed hydroxyl can reduce the net surface charge of the colloidal particles that are in suspension due to the reduction of repulsive potential of electrical double layer. As a result of this, the repulsive forces between the colloidal particles decrease, and brings the particles close to such an extent where the Vander Waal's forces predominates and facilitate agglomeration. Hydrolyzed metal species can be adsorbed on the colloids and creates bridges between the particles. In addition to that, the amorphous solid ferric hydroxide flocs that forms at elevated pH, settle down causing sweep flocculation. On the whole, the electrocoagulation process involves three successive stages (Mollah et al., 2001).

- (a) Formation of coagulants by electrolytic oxidation of the sacrificial anode electrodes.
- (b) Destabilization of the contaminants, particulate suspension, and breaking of emulsions.
- (c) Aggregation of the destabilized phases to form flocs.

The destabilization mechanisms of the contaminants and particulate suspensions may be summarized as follows.

1. Compression of the diffuse double layer due to the reduction of net surface charge, which is mainly due to the reduction of repulsive potential of the electric double layer by the presence of species of opposite charge species around the charged colloidal. This is

mainly achieved by the interactions of the ions generated by the dissolution of the sacrificial electrode, due to the passage of current through the solution.

2. Charge neutralization of the ionic species present in wastewater, which is caused by the counter ions produced by the electrochemical dissolution of the sacrificial electrode. These counter ions reduce the electrostatic inter particle repulsion sufficiently so that the van der Waals attraction forces predominates, thus causing coagulation. A zero net charge results in the process

3. Floc formation due the precipitation of amorphous ferric hydroxide species at elevated pH. This forms a sludge blanket that entraps and removes the colloidal suspended particles when settling down, as a result of enmeshment phenomena.

Electrocoagulation has been successfully applied on various wastewaters, and has been found to be the promising for solids/liquids separation (Vik et al., 1984 Donnini et al., 1994). Abuzaid et al, 2002 had investigated the efficiency of soluble stainless steel electrodes for the turbidity removal from groundwater. The study focused on the investigation of the effect of various parameters like, applied current, contact time, pH and conductivity of the wastewater sample on the performance of electrocoagulation removal of turbidity. The study also revealed the important aspects of various phenomena such as charge neutralization, compression of double layer and the phenomena of enmeshment that take place during the electrocoagulation process. They achieved excellent turbidity removal (95 %) working at 1A with a short detention time of 5 minute Koby et al 2003 applied electro coagulation in the removal of turbidity from the textile wastewaters, and the effects of various parameters such as wastewater conductivity, pH, current density, and operating time on the turbidity removal efficiencies have been

explored. In their study, they achieved more than 95 % removal of turbidity with stainless steel electrodes working at a current density $10\text{mA}/\text{cm}^2$ with a detention time of 10 minutes. Lai and Lin, 2004 applied the electrocoagulation process for the removal of turbidity from the chemical mechanical polishing wastewater and achieved more than 97 % removal efficiency of turbidity working at 1.86 A with a contact time of 30 minute. Chen et al, 2000 conducted the experiments on restaurant wastewater by electrocoagulation followed by sedimentation for 2 hours and achieved 96.4 % removal of suspended solids with the insitu-generated sludge. Paul, 1996 applied electrocoagulation for the treatment of turbid wastewater and achieved more than 95 % removal efficiency of turbidity. The operating cost was also calculated, which was found to be 60 % less than the conventional chemical treatment.

Adhikari et al., 1976 had applied the electrocoagulation process on the turbid river water in order to test its suitability for the treatment of municipal wastewater. In their study they added a little amount of coagulant dosage (Alum) during the electrocoagulation process and achieved a removal efficiency of 94.5, 91.75 and 97 % of total solids, total suspended solids and turbidity, respectively. However, adding a coagulant was a serious drawback, which could increase the total sludge production, and ultimately results in the increase of sludge handling cost. Pouet and Grasmick, 1995 studied the treatment of municipal wastewater by electrocoagulation in combination with dissolved air flotation process (DAF). They found the process to be effective in the removal of suspended solids and turbidity in addition to COD. They achieved nearly 85 %, 90 %, and 70 % removal of suspended solids, turbidity, and COD respectively. Although combining DAF with electrocoagulation was found to be advantageous, but it could result in uneconomical

process due to high initial capital and operating cost of DAF together with electrocoagulation. Therefore, here we attempted to treat the municipal wastewater keeping in view of the drawbacks of high sludge production and high capital and operating cost by employing a simple experimental process of electrocoagulation followed by flocculation and sedimentation, with the insitu generated coagulant without adding any chemicals.

2.5 Electro disinfection

Electro disinfection is a new emerging technology, which is gaining attention nowadays in the field of water and wastewater disinfection. The main advantage of the process is the production of strong disinfective chemicals in-situ in the treatment device thus avoiding the drawbacks of transport and storage of dangerous chlorine. (Patermarakis and Fountoukidis, 1990). It is a common practice to use chlorination, as the prevalent method of disinfection, but due to the safety serious problems associated with the use, there is a quest for the new eco friendly alternative. Methods such as ozonation, UV radiation, and ClO_2 are attractive alternatives, but they are still more expensive and less convenient than chlorination. Electrochemical disinfection has the potential to be developed as a robust, cost effective, and environmental friendly alternative for the disinfection of water and wastewater (Li., 2002, Patermarakis and Fountoukidis., 1990). Several mechanisms have been proposed that account for electrochemical disinfection, which includes the oxidative stress and cell death due to electrochemically generated oxidants, irreversible

permeabilization of cell membranes by the applied electric fields, and electro chemical oxidation of vital cellular constituents during exposure to electric currents or induced electric fields. Approximately 40 microorganism species of varying in size from viruses, bacteria, and algae to relatively large species such as *Euglena* have been successfully deactivated using the electrochemical technology (Stoner and Cahen, 1982).

Patermarakis and Fountoukidis, 1990 investigated the disinfection of natural water, highly contaminated with coliforms and faecal streptococci using electrochemical treatment with Ti electrodes. They achieved excellent disinfection efficiency and found residual disinfection efficiency in the treated electrochemical effluent. Li et al, 2002 had studied the electrochemical disinfection of various wastewater effluents, including saline primary effluent, saline secondary effluent, and freshwater secondary effluent. A killing efficiency of 99.9 % of total coliform was achieved for saline secondary effluent with a contact time of less than 10 sec. The same degree of disinfection was obtained with a contact time of less than 20 sec for a primarily treated saline effluent. They also conducted the direct chlorination experiments in order to compare the results of electrochemical process with it, and found that the main disinfection action of electrochemical process may not be only electro chlorination, other short lived, more powerful germicidal substances may exert strong killing function with in a short time. Diao et al., 2003, conducted the laboratory experiments to investigate the mechanisms of electrochemical disinfection on artificial wastewater contaminated by *E.coli* culture. Comparison disinfection of tests with chlorine, ozone and hydroxyl radicals produced by the Fenton reactions were also conducted. Electron microscopic examination suggested that the cells were likely inactivated during the electrochemical process by the chemical products with an oxidizing

power similar to that of hydroxyl radicals and much stronger than that of chlorine. The scanning electron microscopy supported the hypothesis that the predominant killing action of electrochemical disinfection is provided by high-energy intermediate electrochemical products and other short-lived free radicals. Drees et al, 2003 conducted comparative electrochemical inactivation of bacteria and bacteriophage experiments and found that the inactivation rate of bacteria is 2.1 to 4.3 times greater than that of bacteriophages, demonstrating that bacteria are more sensitive to electrochemical inactivation than bacteriophages. Bukhari et al, 1999 treated the primary domestic wastewater by electrochemical disinfection and achieved high level of disinfection of total coliform. In addition to the effect of current and detention time, disinfection due to the precipitation with the insitu generated ferric hydroxide flocs was studied.

CHAPTER 3

RESEARCH OBJECTIVES

3.1 Introduction

The main purpose of the research was to investigate the effectiveness of combined processes of electro oxidation and electro coagulation for the treatment of municipal wastewater. Although electrochemical processes have been successfully applied for the removal of total organic matter, but the detailed study dealing with the removal of particulate and soluble organics have not been studied yet. As the electro oxidation process is proved as an effective process for the oxidation of soluble organics and electrocoagulation for the removal of particulate organics, combining both the processes would give a better understanding of the removal mechanism of soluble and particulate organics in addition to the total organics.

3.2 Objectives

The main objective of the research is to investigate the effectiveness of the combined processes of electro-oxidation and electro-coagulation using stainless steel electrodes in the removal of BOD, ammonia, coliform, turbidity and particulate matter from municipal wastewater.

More specific objectives are

1. Investigation of the effect of current on the above contaminants removal.
2. Investigation of the effect of detention time on the above contaminants removal.
3. Assess the effect of electro oxidation on the raw wastewater sample for the removal of BOD and ammonia.
4. Assess the effect of electro oxidation on the filtered wastewater sample for the removal of soluble BOD and ammonia.

CHAPTER 4

MATERIALS AND METHODS

4.1 Experimental setup

The experimental set up used in this study is shown in figure 4.1 and 4.2, which mainly consisted of a beaker of 1.5 liters as a reactor to hold a sample of 1.2 liters. Two Pyrex glass strips were attached to the inner phase of the glass beaker as baffles, to create turbulence and facilitate proper mixing of the sample. A pair of stainless steel electrode plates as anode and cathode, each with an active surface area of 44 cm^2 (total active surface area of the plates is 88 cm^2), were arranged at a spacing of 3 cm, and connected to an external power source. A DC power source (Hampden, USA), a rheostat (Engield-Middle sex, UK) to keep the current invariant, an ammeter and volt meter to read the values of current and voltage, a magnetic bar stirrer to mix the solution and reduce the mass transfer limitation during the reaction were used. A switch was used to change the polarity of electrodes to reduce the passivation phenomenon that usually occurs during the process at cathode and impedes the oxidation and reduction reactions.

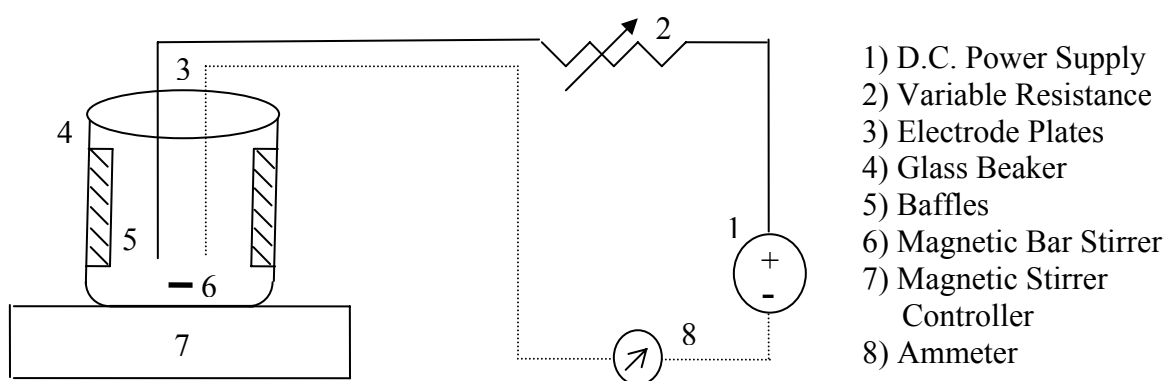


Figure 4.1: Schematic Diagram of Experimental Setup

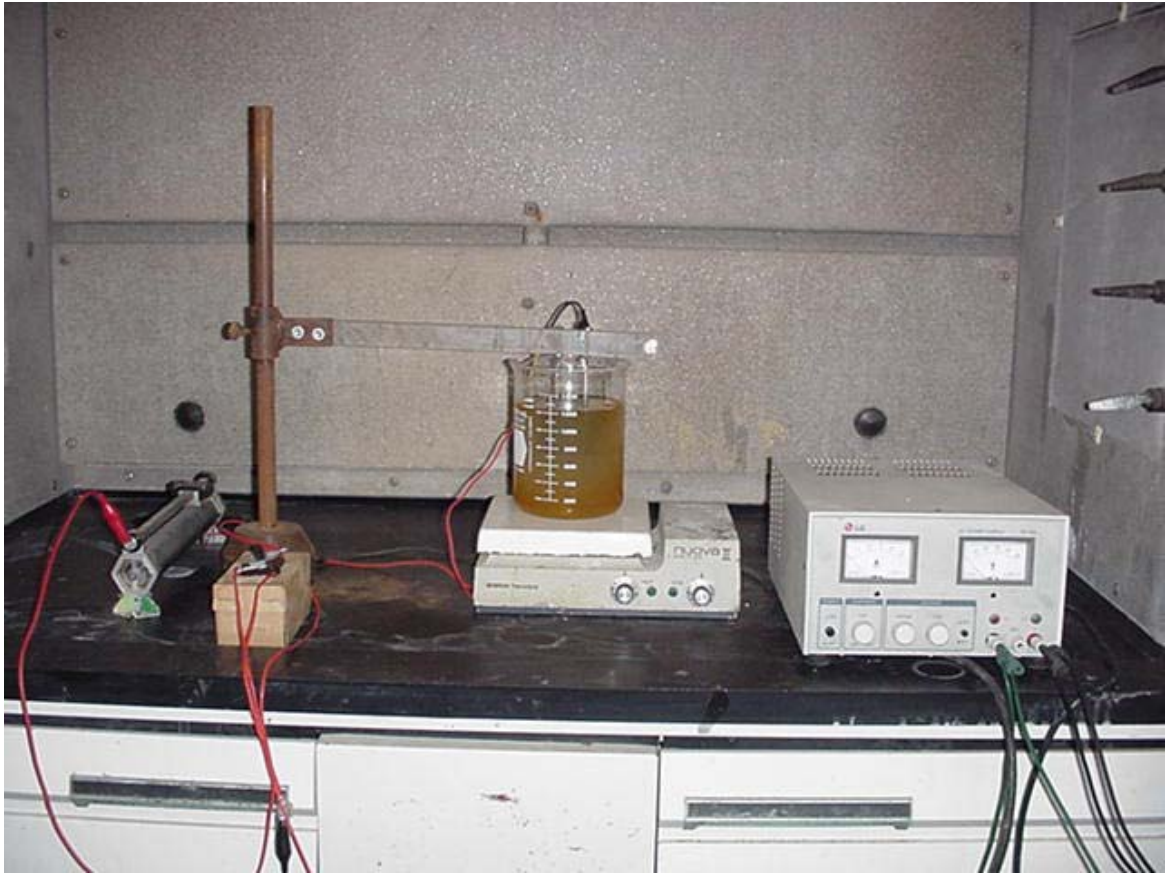


Figure 4.2: Photograph Showing the Actual Experimental Setup

4.2 Influent Wastewater Sample

For our study, sampling was done from Dhahran North Sewage Treatment Plant, which is situated near Al-Khobar highway. Raw municipal wastewater samples from the splitter box of the treatment plant after the preliminary treatment were collected.

Table 4.1. shows the characteristics of the influent raw sample used in the experiments. The influent sewage is observed to have low total BOD, which was in the range of 84-112 ppm. It is mainly due to the contribution of large amount of waters from domestic purposes. Most of the BOD, nearly 60-70 % BOD was observed to be in particulate form. The raw sewage was also observed to have high conductivity (4000 $\mu\text{mhos/cm}$), which was mainly due to the use of brackish water for many purposes in the Eastern Province. The presence of abundant chlorides and sulfate ion concentration (1238 and 393 mg/l) is also found to have an added advantage for the effective treatment process, which are beneficial for the insitu formation of agents that would result in high treatment efficiencies.

Table 4.1: Physicochemical Characteristics of the Municipal Wastewater Used in the Study

Influent Parameters	Concentration
Total BOD ₅	84-112 (mg/l)
Soluble BOD ₅	26-32 (mg/l)
Particulate BOD ₅	51-84 (mg/l)
Ammonia	14-19 (mg/l)
Coliform MPN/100 ml	$7.9 \times 10^{12} - 1.8 \times 10^{14}$ (MPN/100 ml)
Turbidity	49-53 (NTU)
TSS	126-160 (mg/l)
Chlorides (Cl ⁻)	1238 (mg/l)
Sulfate (SO ₄ ²⁻)	393 (mg/l)
pH	6.9-7.1
Conductivity	4000 μ mhos/cm

4.3 Experimental Procedure

All experiments were conducted in batches. In each experimental run, a wastewater sample of 1.2 liters was collected and placed in an electrolytic cell. The sample was rigorously stirred by a magnetic stirrer. Stainless steel electrodes were dipped into the solution up to an active surface area of 88 cm^2 , and the following currents of 0.05, 0.1, 0.2, 0.4 and 0.8 A were passed for a contact time of 5, 10, 20, 30, and 50 minutes. After passing each current for each time period (i.e., after each batch experiment), the sample was transferred into another beaker, and measured for pH. The measured sample was then taken to the jar test equipment, where it was rapidly mixed for 1 minute at 100 rpm. And, after a rapid mix for 1 minute, the sample was kept for flocculation by setting the speed of the paddles at 30 rpm for 20 minutes. Subsequently, the flocculated sample was kept undisturbed for 20 minutes, in order to allow the flocs that formed during the flocculation to settle down (Table 4.2). After a settling time of 20 minutes, 250 ml supernatant sample was collected to perform the analysis of total BOD, soluble BOD, ammonia, coliform, turbidity, and TSS etc. Similar analysis was done with the influent raw municipal wastewater samples before the start of experiment. In the analysis of total, soluble, and particulate BOD_5 , the average of two replicates was taken as the final value.

In this study, total BOD_5 of the effluent was taken as the BOD_5 of the supernatant after the settling time on 20 minutes. In order to find the soluble BOD_5 in the effluent, supernatant was filtered by using $0.45 \mu\text{m}$ filter paper, and with the filtrate, soluble BOD_5 analysis was performed. The particulate BOD_5 was calculated by subtracting the soluble

BOD₅ from total BOD₅. Similar analysis was done with the influent raw sample as in the case of effluent supernatant.

In order to achieve the objective 4, of investigating the effect of particulate matter on the electrooxidation of soluble organic matter and ammonia, the whole raw sample was filtered initially by using 0.45 μm filter paper, and then the filtrate samples of 1.2 liter were collected in the electrolytic cell. Pre-specified currents were passed for a contact time of 5, 10, 20, 30, and 50 minutes. After each batch experiment, samples were again filtered with 0.45- μm filter paper, to remove the electrically produced sludge, and then the soluble BOD₅ and ammonia analysis was done with the filtered sample. In this case, only the electrooxidation process was used, with out employing the jar test equipment.

In order to compare the sludge production during the electrochemical process with the conventional coagulant addition process, jar test experiments were conducted using $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ coagulant. In order to find the optimum coagulant dose for the turbidity removal, experiments were done with samples of different initial pH of 7.07, 8.07, 8.69, and 9.11. Subsequently, after finding the optimum dosage, the sample with optimum turbidity removal was again mixed, and a 20 ml sample was collected to perform the TSS analysis. To calculate the sludge that is produced at this dosage, TSS of the influent raw sample was calculated by subtracting the initial TSS of the raw sample from the TSS observed after the jar test experiment with optimum dosage.

Table 4.2: Experiment Designed Model

Current (A)	Current Density (mA/cm²)	Reaction Time (min)	Flocculation Time (min)	Settling Time (min)
0.05	0.56	5,10, 20, 30, 50	20	20
0.1	1.36	5,10, 20, 30, 50	20	20
0.2	2.27	5,10, 20, 30, 50	20	20
0.4	4.54	5,10, 20, 30, 50	20	20
0.8	9.09	5,10, 20, 30, 50	20	20

4.3.1 Analytical Procedures

For all experiments, the physicochemical parameters were analyzed, by the methods described in the Standard Methods for the examination of wastewater (APHA.AWWA.WEF, 1995).

4.3.1.1 Turbidity

An Orbeco-Hellige digital direct reading turbidity meter was used to determine the turbidity of samples.

4.3.1.2 pH

A pH meter manufactured by Thermo Orion of model 550A was used for the determination of pH.

4.3.1.3 Suspended Solids

TSS analysis was performed by the method described in the Standard Methods for the examination of wastewater (APHA.AWWA.WEF, 1995).

4.3.1.4 Biochemical Oxygen Demand

The BOD₅ tests were carried out on influent and effluent samples according to Standard Methods (APHA.AWWA.WEF, 1998). Winkler method was used for initial and final dissolved oxygen measurements.

4. 3. 1. 5 Total Coliform

The standard test for the coliform group was carried out by using the multiple tube fermentation technique as per the procedure mentioned in Standard Methods for the examination of wastewater (APHA. AWWA.WEF, 199 5).

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Experiments with Raw Sample

5.1.1 Soluble BOD₅

Figure 5.1 shows the relationship between the soluble BOD₅ removal efficiency and contact time for the currents of 0.05, 0.1, 0.2, 0.4, and 0.8 A. It shows that the removal efficiency of soluble BOD₅ is increasing with the increase of current from 0.05 A to 0.2 A. The contact time is found to have an effect on the removal efficiency. At 0.05 A, a removal efficiency of 5.36, 8.93, 14.29, 23.2 and 25 % at a contact time of 5, 10, 20, 30 and 50 minutes, respectively was observed. When the current was increased from 0.05 A to 0.1 A, increase in the removal efficiency from 5.36 to 16.35, 8.93 to 26.92, 14.29 to 32.69, 23.2 to 35.58 and 25 to 40.8 % was observed at various specified contact times. However, at 0.2 A, the effect of contact time was observed to be up to 30 minutes only,

beyond which the increase in the removal efficiency was found to be insignificant. Removal efficiency increased from 16.35 to 36.43, 26.92 to 56.59, 14.29 to 58.14, 23.2 to 61.24 % at 0.2 A at 5, 10, 20 and 30 minutes. The maximum removal efficiency of 61.34 % was observed at 0.2 A with a contact time of 30 minutes. It is interesting to note that further increase of current beyond 0.2 A, that is at 0.4 and 0.8 A resulted in the lower removal efficiencies than the 0.1 and 0.2 A. The removal efficiency of only 39.53 and 31.15 % was observed at 0.4 and 0.8 A. The effect of contact time is observed to be insignificant after a contact time of 5 minutes, resulted in the no change in the removal efficiencies.

As discussed earlier that the removal of organics is mainly due to direct and indirect oxidation. When sufficient voltage is developed across the electrodes, direct oxidation takes place near the anode, due to the release of electrons by the organic compounds in order to maintain the flow of current, whereas indirect oxidation occurs due to the strong oxidants that form during the reaction. Here, the Cl^- can be the principal charged species which carry the current in the solution. If Cl^- carries the current, then Cl_2 gas is produced at the anodes which rapidly hydrolyze to form hypochlorous acid, which is a strong oxidant, and has the ability to oxidize the organic compounds effectively. In addition to that, strong short lived oxidants like $\text{OH}\cdot$, O_2 and $\text{HO}_2\cdot$ may also be also formed, which are very destructive, and comparatively have very little life span.

It is observed that, most of the removal of soluble BOD_5 was taken place at a contact time of 5 minutes, after which the rate of removal declined. Tsai et al., 1997, also observed the same kind of trend in their study of electrolyzing the soluble organic matter in municipal landfill leachate. They explained the phenomenon by the fact that, as the

reaction proceeds, the organic materials with low molecular weight get degraded to CO₂ or VOC during the early stages only and larger molecules require complex processes so as to be degraded to CO₂.

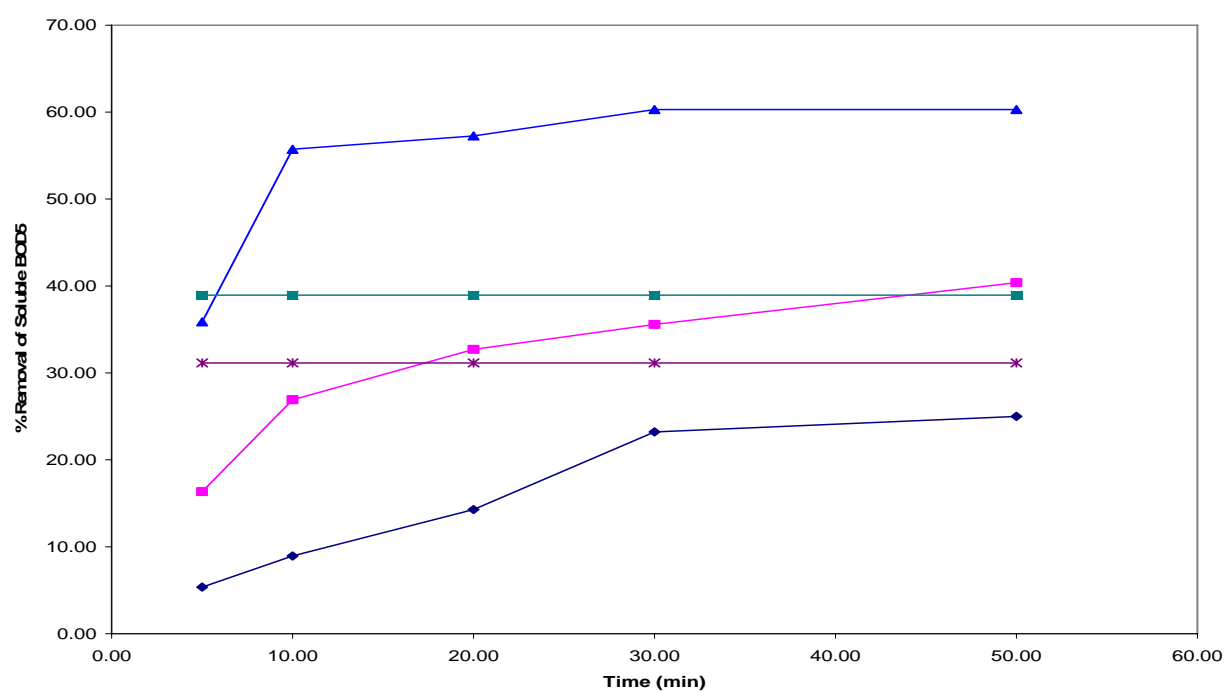


Figure 5.1: Effect of contact time on soluble BOD₅ for the range of currents used

5.1.2 Particulate BOD₅

Figure 5.2 shows the effect of current and contact time on the removal of particulate BOD₅. At 0.05 A, as the contact time increased the removal of particulate BOD₅ was also found to be continuously increasing. Removal efficiencies of 74.4, 81.5, 89.2, 91, and 92.8 % were observed at contact times of 5, 10, 20, 30, and 50 minutes, respectively. When the current was increased from 0.05 to 0.1 A, the removal efficiency increased from 74.4 to 86.82, 81.5 to 89.09, 89.2 to 94.55, 91 to 98.64 and 92.8 to 98.18 %, respectively at various specified contact times. At 0.1 A, the effect of contact time was observed only up to 30 minutes, beyond which there was no further increase in the removal efficiency. Similarly at 0.2 A, the removal efficiency of particulate BOD₅ increased, with the increase in the contact time, but the effect of contact time was observed only up to 20 minutes, beyond which there was no further increase in the removal efficiency. With the increase of current from 0.1 to 0.2 A, the removal efficiency increased from 86.82 to 92.75, 89.09 to 98.07, 94.55 to 99.52, 98.62 to 99.03, 92.8 to 99.52 % respectively at various specified contact times. When the current was further increased to 0.4 A, the maximum removal efficiency of 99.03 % was observed at a contact time of 5 minutes only, after which a slight decrease in the removal efficiency is observed, when compared to that at 0.2 A. The decrease in the removal efficiency could be due to the restabilization of colloidal particles that had taken place at 0.4 A, which is reflected in the turbidity measured during the experiments (Figure 5.11). However, when the current was increased from 0.4 to 0.8 A, resulted in the increase of the removal efficiency from 99.03 to 99.53, 97.1 to 98.6, 98.55 to 99.83, 99.03 to 99.07, and 98.55 to 99.07 %, respectively at a contact time of 5, 10, 20, 30 and 50 minutes. At this current, the effect of contact time was observed only up to 5

minutes, beyond which there was no significant increase in the removal efficiency. The maximum removal efficiency of 99.53 % of particulate BOD₅ was observed at 0.8 A with a contact time of just 5 minutes.

The increase in the removal efficiency of particulate BOD₅ with the increase of current and contact time could be explained by the fact that, as the current is passed, the anodic stainless steel electrodes gets oxidized and release ferrous ions. The amount of ferrous ions released during the process is mainly dependent on current and contact time. As per faradays law, the rate of ferrous ions released from the anode follows equation 1.

$w = itM/ZF$ -----> equation 1

w = Iron dissolving (g),

i = current (A),

t = time (s),

M = molecular weight of Fe (M = 55.85);

Z = number of electrons involved in the redox reactions (Z= 2), and

F= Faradays constant = 96500.

The released ferrous ions react with the hydroxyl ions that prevail at elevated pH to produce ferrous hydroxide, which reacts with dissolved oxygen to produce ferric hydroxide flocs. Ferric hydroxide is an excellent coagulant, and is used in solid liquid separation (Abuzaid et al, 2002). With the increase of current and contact time, the coagulant produced is also more, which might have contributed to very high removal of particulate BOD₅ at increasing currents. It can be observed in figure 5.3, which is plotted

between the calculated amount of iron electrically generated and the removal efficiencies observed at various pre specified currents and, at a detention time of 5 minutes. It clearly shows that, as the current is increased the iron that is electrically produced also increased, resulted in increase in the removal of particulate BOD₅.

The calculated dosage that was produced at 0.8 A and 5 minutes contact time was 57.88 mg/l, where the maximum removal of 99.53 % was observed. However at some currents and contact times (i.e, at 0.1 A, and 30, 50 minutes contact times), the iron dosage produced was more than 57.88 mg/l, but still the removal efficiency was lower than the maximum removal. It could be due to the sample pH, which significantly affect the formation of various ferrous monomeric and polymeric species, and the various destabilization phenomenons that takes place during the process. As discussed earlier, the dissolved ferric ions that are produced due to the electrolytic oxidation of stainless steel electrodes, hydrates, coordinating six water molecules and forming an aquometal ion, $\text{Fe}(\text{H}_2\text{O})_6^{3+}$ (Chion et al., 1983). The aquometal ion can then hydrolyze and form monomeric and polymeric ferric species, the formation of which is highly pH-dependent. The charged hydrolyzed hydroxides can neutralize the negatively charged colloidal particles, and brings the particles close together by the compression of double layer. On the other hand, these charged hydrolyzed hydroxides finally transform to amorphous solid ferric hydroxide at elevated pH near 8 (Kobya et al., 2003, Benefield et al., 1982, Rubin, 1974). Electrocoagulation has an advantage of increase in pH, due to the evolution of hydrogen gas (Abuzaid et al., 2002). As a result, the various monomeric and polymeric species that forms during the process are transformed to amorphous solid ferric hydroxide. Due to the formation of these flocs, sweep flocculation takes place, where the whole ferric hydroxide

flocs act as a blanket, and brings the suspended colloidal particles down. It can be seen in figure 5.12, which shows the pH trends that were observed at various currents and contact times. At 0.8 A, where the maximum removal of particulate BOD₅ was observed, the pH was observed to be continuously increasing from 6.91 to 7.84, due to the evolution of hydrogen gas. This increase in pH might have resulted in the formation of amorphous solid ferric hydroxide flocs, and leads to the mechanism of the sweep flocculation.

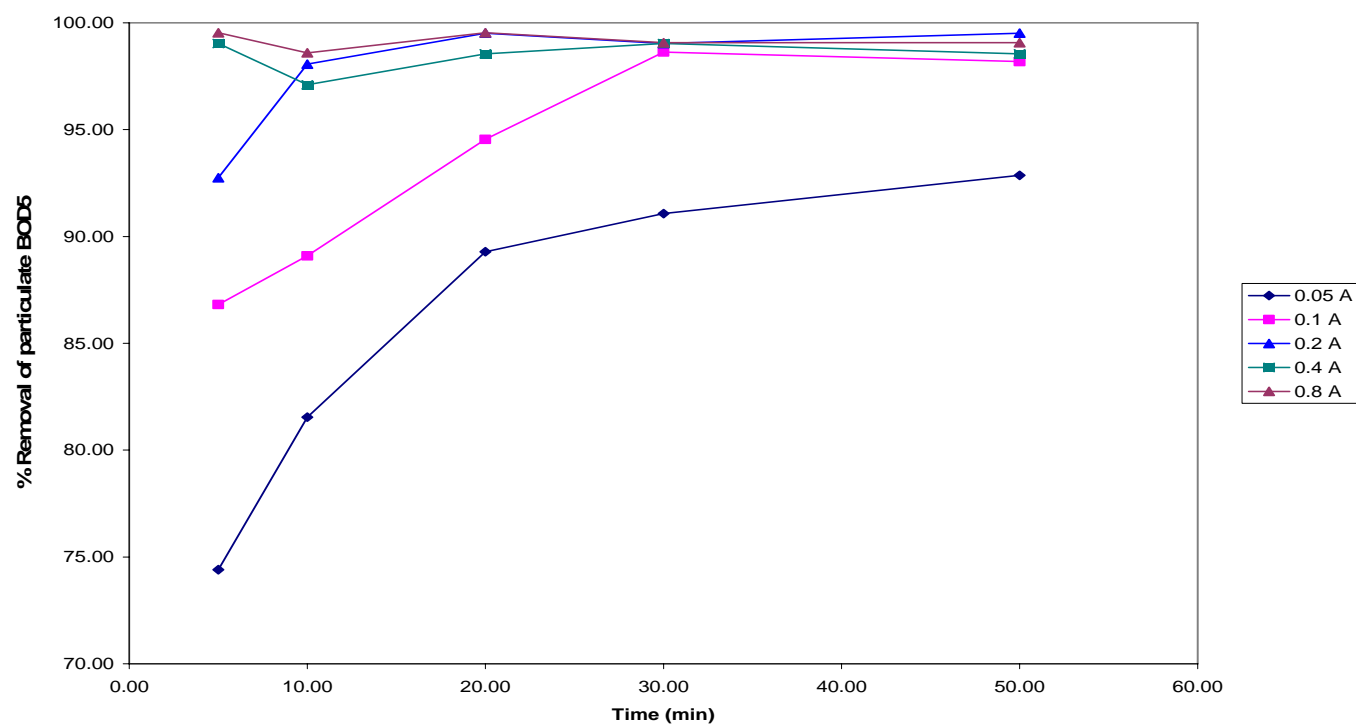


Figure 5.2: Effect of contact time on particulate BOD₅ removal efficiency for the range of currents used.

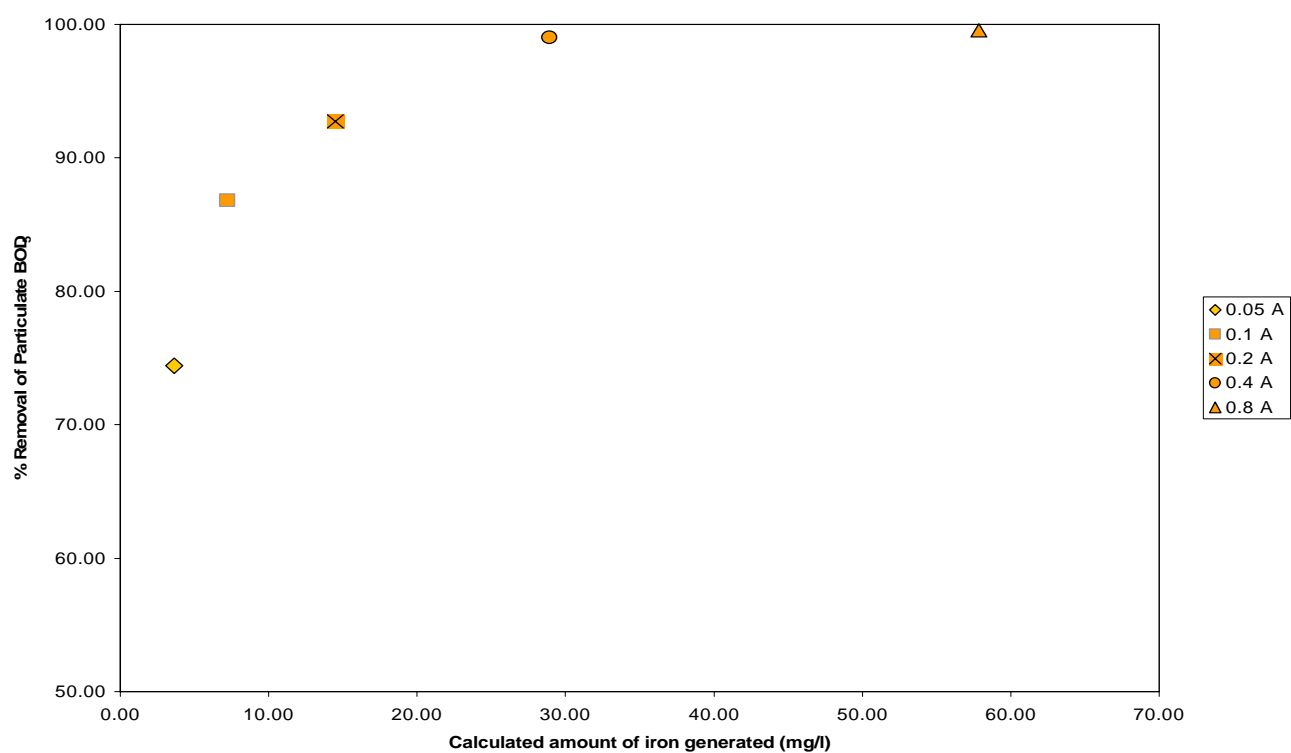


Figure 5.3: Effect of current variation on the removal of particulate BOD₅

5.1.3 Total BOD₅

Total BOD₅ is the sum of particulate and the soluble BOD₅. Figure 5.4 shows the effect of current and the contact time on the removal efficiency of total BOD₅. Total BOD₅ removal efficiency observed to be increasing with the increase of current from 0.05 to 0.2. Beyond which further increase of current to 0.4 and 0.8 A, resulted in the decrease in the removal efficiency. The effect of contact time on the removal efficiency is observed. At 0.05 A, the total BOD₅ efficiency continued to increase with the increase of contact time. The removal efficiency of 57.14, 63.39, 70.54, 74.11 and 75.89 % was observed at a 5, 10, 20, 30 and 50 minutes respectively. When the current was increased from 0.05 to 0.1 A, the removal efficiency also increased from 57.14 to 64.2, 63.39 to 69.14, 70.54 to 74.69, 74.11 to 78.4 and 75.89 to 79.63 at various specified contact times. When the current was further increased to 0.2 A, the effect of contact time was observed to be up to 30 minutes only, beyond which there was no further removal. Due to the increase of current from 0.1 to 0.2 A, the removal efficiency increased from 64.2 to 71.13 %, 69.14 to 82.14 %, 74.7 to 83.63 %, 78.4 to 84.52 % and 79.63 to 84.82 % respectively. However, further increase in the currents i.e., at 0.4 & 0.8 A resulted in very low removal efficiencies, when compared to 0.1 & 0.2 A, and the effect of contact time after 5 minutes, did not seem to be significant at these currents. Although high removal efficiency of particulate BOD₅ (98.55 and 99.53 %) was observed at 0.4 and 0.8 A, but due to the less removal of soluble BOD₅, which was only 39.53 & 31.53 %, attributed to very less total BOD₅. The maximum total BOD₅ removal of 84.42 % is observed at 0.2 A with a contact time of 50 minutes.

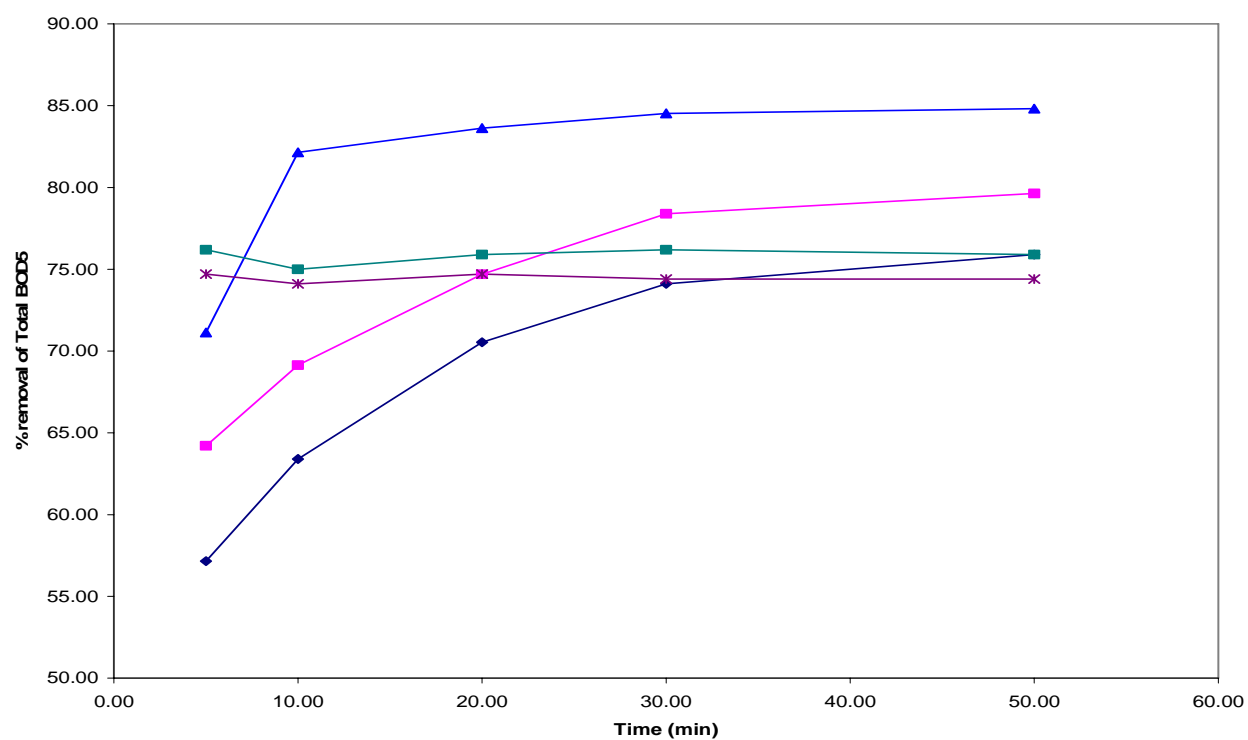
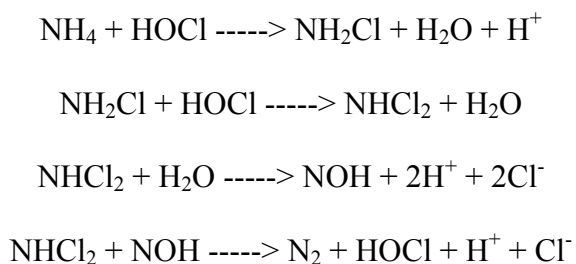


Figure 5.4: Effect of contact time on total BOD₅ removal efficiency for the range of currents used.

5.1.4 Ammonia

Figure 5.5 shows the effect of contact time on the removal efficiency of ammonia for the currents of 0.05, 0.1, 0.2, 0.4, and 0.8 A. The removal efficiency is found to follow the same trend as that of in the case of soluble BOD₅. It is observed to be increasing with the increase of current up to 0.2 A, beyond which further increase of current resulted in the decrease of removal efficiency. The maximum removal efficiency is found to be only 18.13 % at 0.2 A with a contact time of 50 minutes.

In the presence of hypochlorous acid, ammonia oxidation is reported to undergo the following complex reaction sequence (Coastaz, 1983, Krstajic and Nakic, 1987).



Lin and Wu (1996) initially conducted the experiment test runs for the removal of ammonia from the aqueous solution with the stainless steel electrodes. They also found the removal efficiency to be not more than 20 % for a 2-h test run. Because of this reason they switched to high purity graphite electrodes, where they achieved the maximum removal of almost 60 % working at a current density of 0.44 A/cm². By this, it can be concluded that ammonia oxidation on the reactive stainless steel electrodes is not so effective as in the case of non-reactive electrodes (graphite, Pt, Ti, BDD etc), which has the ability to oxidize the compounds that undergoes highly complex reactions.

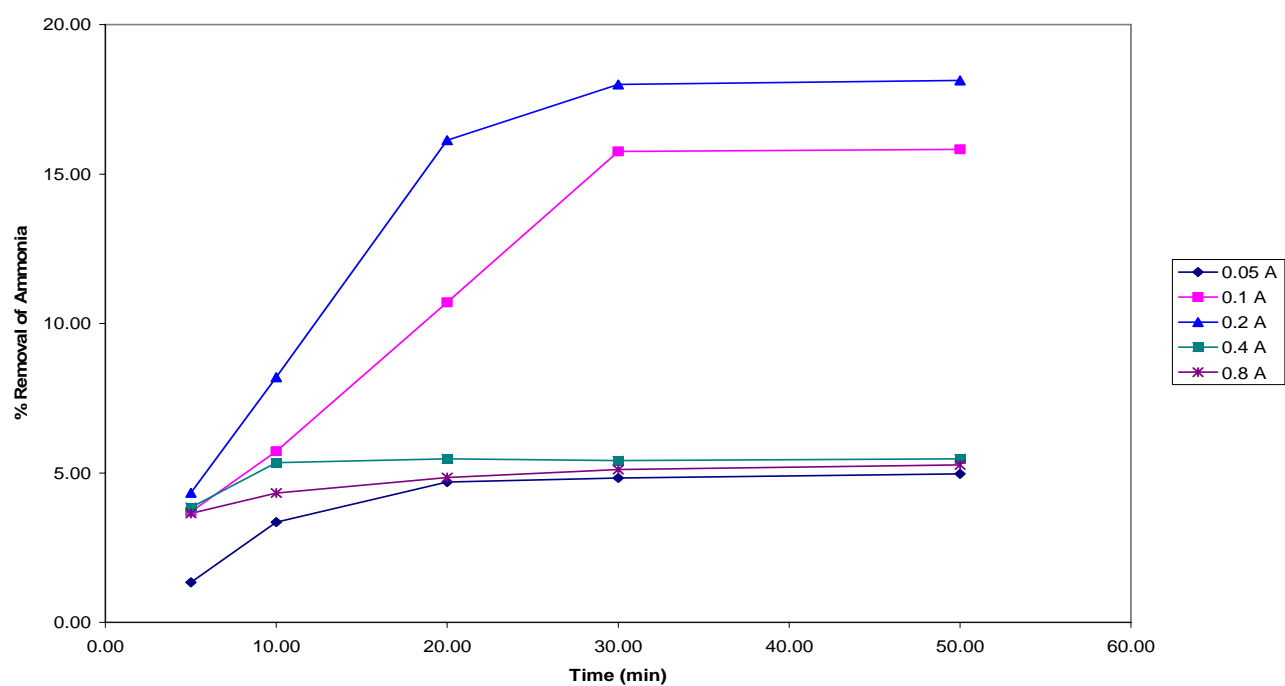


Figure 5.5: Effect of contact time on Ammonia removal efficiency for the range of currents used (Raw Sample).

5.2 Experiments with Filtered Sample

5.2.1 Soluble BOD₅ and Ammonia

The main aim of conducting the experiments with filtered sample is to investigate the effect of suspended solids on the removal of soluble BOD₅ and ammonia, by comparing the results with the raw sample. Figure 5.6 and 5.7 shows the removal efficiencies that were observed working with filtered samples at various currents and contact times. The removal trends of soluble BOD₅ and ammonia were observed to be almost the same as in the case of raw sample. However, when we compared the removal efficiencies in the case of filtered samples with that observed with the raw sample (Figure 5.8 and 5.9), increase in the removal efficiencies is observed in the case of filtered sample. This could be due to the removal of suspended solids, which can absorb some of the amount of oxidizing agents that form during the process. Thus, results in the decrease in the availability of oxidizing agents for the degradation of soluble organics. In addition to that, presence of suspended solids can impede the electrochemical reactions. As Kim et al., 2002 suggested that, wastewaters containing high suspended or colloidal solids have to be sufficiently removed before the electrochemical oxidation. As a reason that, its presence in high concentration impedes the electrochemical reactions that takes place during the process. Although the concentration of TSS in the raw influent sample was not too high, which was in the range of 126-160 mg/l, but removing the TSS resulted in the increase in the removal efficiencies of soluble BOD₅ and ammonia.

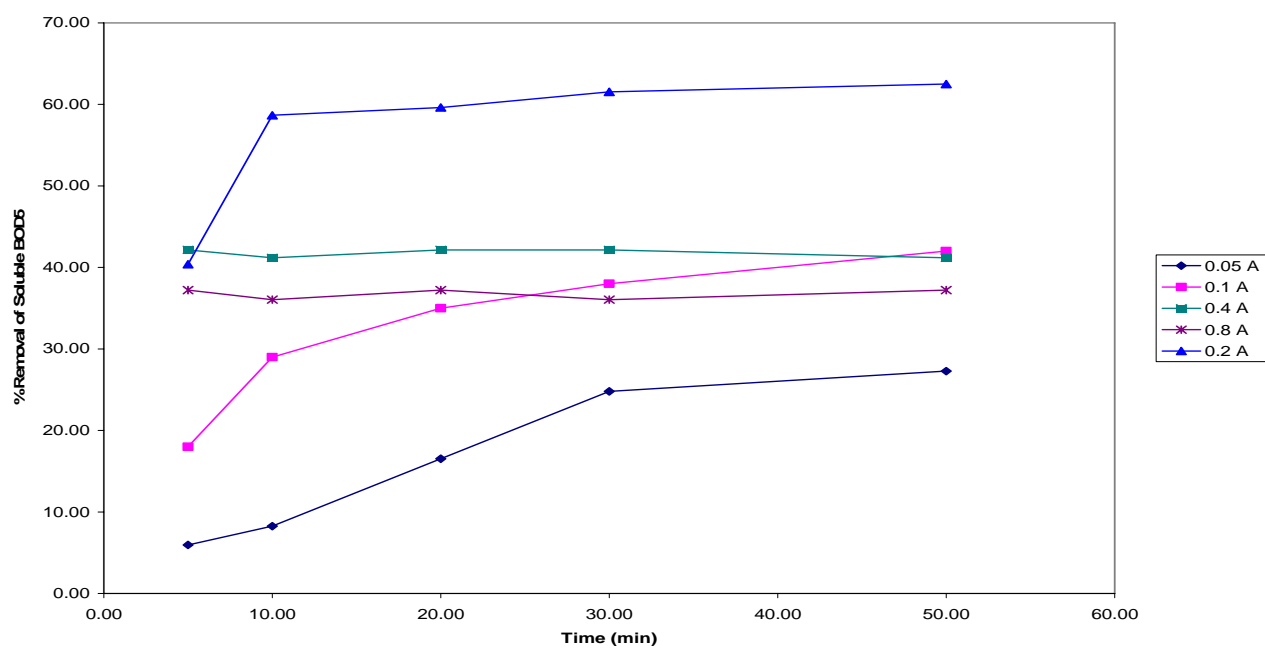


Figure 5.6: Effect of contact time on Soluble BOD₅ removal efficiency for the range of currents used (Filtered Sample)

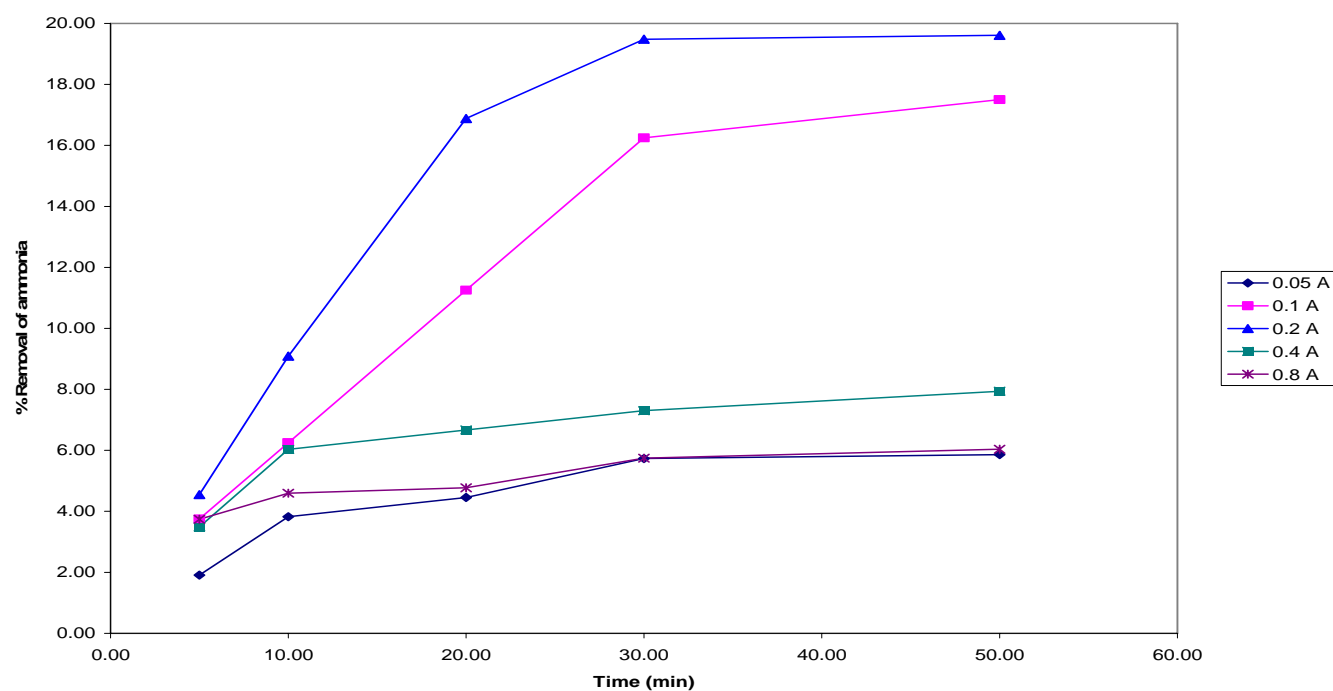


Figure 5.7: Effect of contact time on Ammonia removal efficiency for the range of currents used (Filtered Sample)

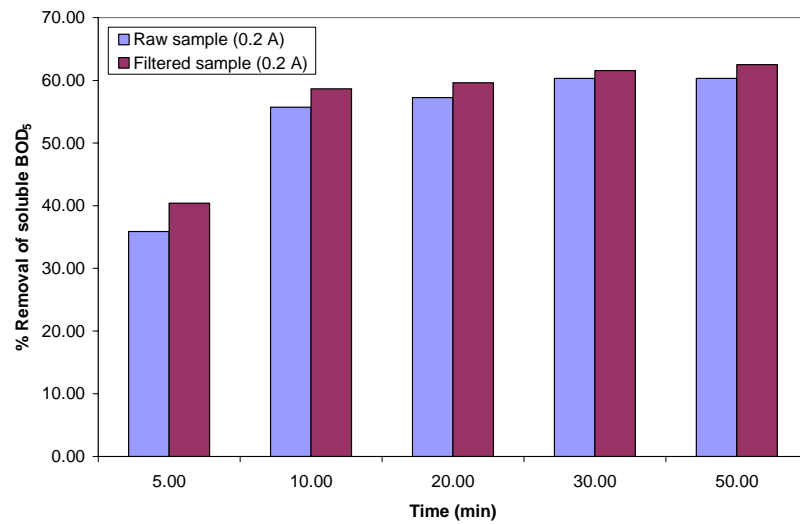
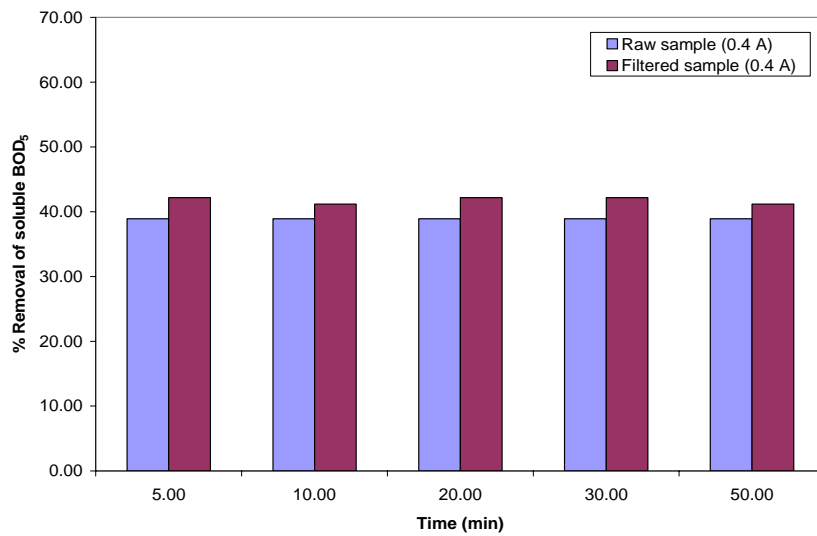


Figure 5.8: Removal of Soluble BOD₅ observed with raw and filtered samples

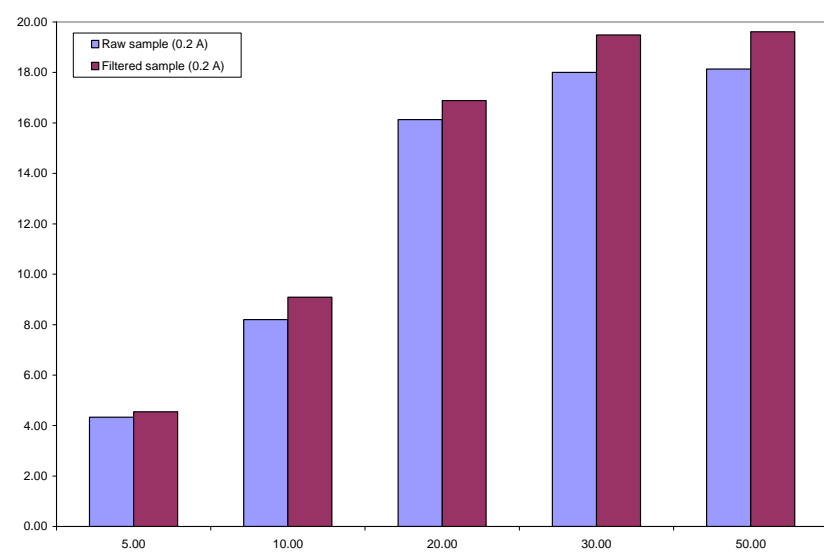
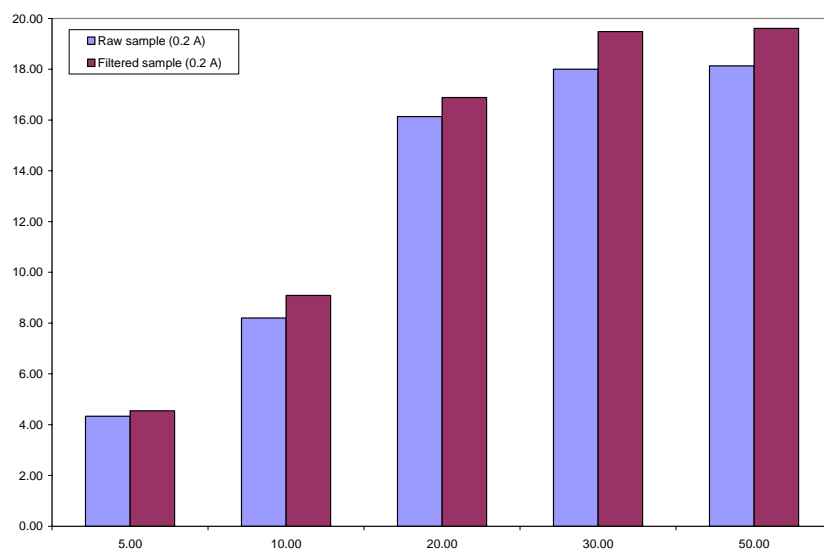


Figure 5.9: Removal of ammonia observed with raw and filtered samples

5.3 Coliform

The investigation of the disinfection efficiency of the electrochemical process was carried out by combining two bacterial disinfection mechanisms, disinfection due to oxidation and disinfection due to precipitation with ferric hydroxide. Figure 5.10 shows the number of log scale removal of total coliform as a function of time of exposure for the settled samples. The disinfection efficiency seems to depend on the applied current and time of exposure. With the increase of current and detention time, the removal of coliform is found to be increasing. The maximum removal of 5.05 log is observed at 0.8 A with a contact time of 20 minutes, beyond which the contact time has no significant effect on the removal. However, the effect of current on disinfection seems to be in contradiction with the organic oxidation. It could be rationalized by the fact that as the current is increased; more ferric hydroxide is produced, which could have contributed more removal of total coliform by precipitation. In addition to the disinfection due to precipitation, other strong short-lived, more powerful germicidal substances that exert strong killing action may have been formed at high currents. It is reported that the electric field can also directly cause the destruction of bacteria by electrochemical reactions taking place inside them and/or are caused by the current transferred from germs to the anode at a potential insufficient even to cause the electrolysis in water (Porta and Kilhanek, 1986). Paternakis and Fountoukidis (1990) cited certain electrochemical reactions that could be responsible for the high germicidal action including ; the formation of short lived and energy rich intermediates products that may include free radicals such as $O_2^{\cdot -}$, $\cdot OH$, $HClO^{\cdot -}$, and $ClO_2^{\cdot -}$. These radicals are unstable and are difficult to detect, but they are extremely reactive

bactericidal agents and can provide instant killing action, the formation of ozone, which produces the free radicals HO_2 , and OH that exert a strong short-lived disinfection action. Saran et al., 1999 reported that the presence of high chloride ions acts as a catalyst and, can extend the life of these radicals by a factor of 10, which makes the radicals many times more full destructive. The carbonate and sulphate ions present in the waster could be oxidized at the anode to form percarbonate or persulphate, which are excellent bacterial oxidizing agents, and the formation of hydrogen peroxide ion, which is very active disinfective agent, produced at the cathode. Therefore, the action of these disinfective agents may explain the observed increase in disinfection with the increase in current.

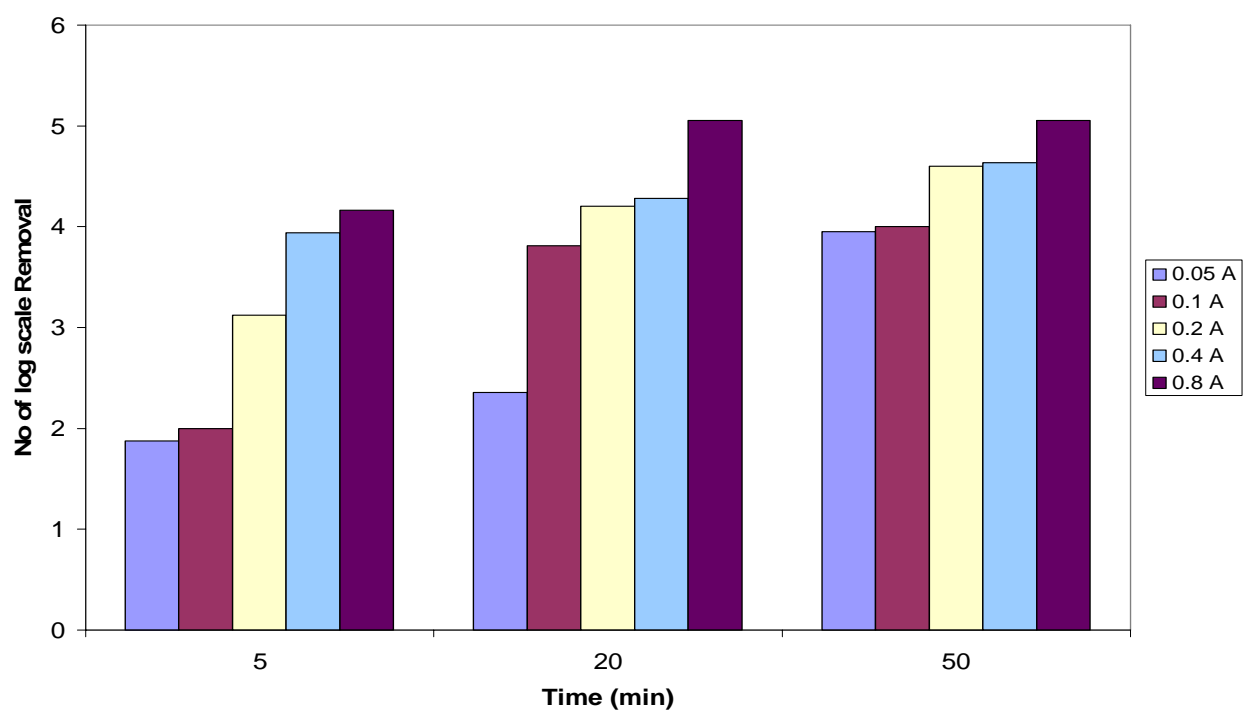


Figure 5.10: Effect of contact time on total coliform removal efficiency for the range of currents used (Raw Sample).

5.4 Turbidity

Figure 5.11 shows the residual turbidity observed working at various currents and detention times. When 0.05 A current is passed the residual turbidity is found to be decreasing with the increase in contact time, and at 0.05A the maximum removal of 75.88 % turbidity is observed with a contact time of 50 minutes. Upon increasing the current from 0.05 to 0.1 A a sharp decrease in the residual turbidity is observed, which resulted in the removal of 82.97 % turbidity with a contact time of 30 minutes. This could be explained by the fact that as the applied current is increased more ferrous ions are electrically produced, results in the formation of more ferric hydroxide flocs, which in turn neutralize the negative charge of the colloidal particles and facilitated agglomeration. When the current was increased from 0.1 to 0.2 A, the residual turbidity is found to be decreasing up to a contact time of 20 min, after which a slight increase in the turbidity is observed. However, when the current was further increased from 0.2 to 0.4 A, after 5 minutes of contact time, a remarkably high increase in the turbidity is observed. It could be due to the restabilization phenomenon, which usually occurs at high coagulant doses resulted in bringing back the particles in suspension. Further increase of current from 0.4 to 0.8 A, resulted in a very high removal of turbidity (93.33 %) with a contact time of 5 minutes. The high removal efficiency of turbidity is mainly due to the pH. As Ching and Tanaka (1994) reported that, although, coagulation with iron salts occurs at a wide range of pH due to different mechanisms, the amorphous ferric hydroxide is least soluble at a pH close to 8. The precipitation of ferric hydroxide at elevated pH gives rise to the

phenomenon of enmeshment, where the precipitated ferric hydroxide flocs acts as a blanket and brings all the stable suspended solids down while settling.

The pH of the sample was found to be sharply increasing from 6.91 to 7.64 at 0.8 A with a short detention time of 5 min. This increase is due to the evolution of hydrogen gas, which is totally current dependent. The pH was found to be continuously increasing with time (Figure 5.12) and the maximum pH was found to be around 7.83 at a contact time of 50 minutes. At this elevated pH, high ferric hydroxide precipitates formed resulted in the sweep flocculation of colloidal particles. From this it can be mentioned that increase in pH due to the evolution of hydrogen during electrocoagulation is also beneficial for the removal of colloidal particles.

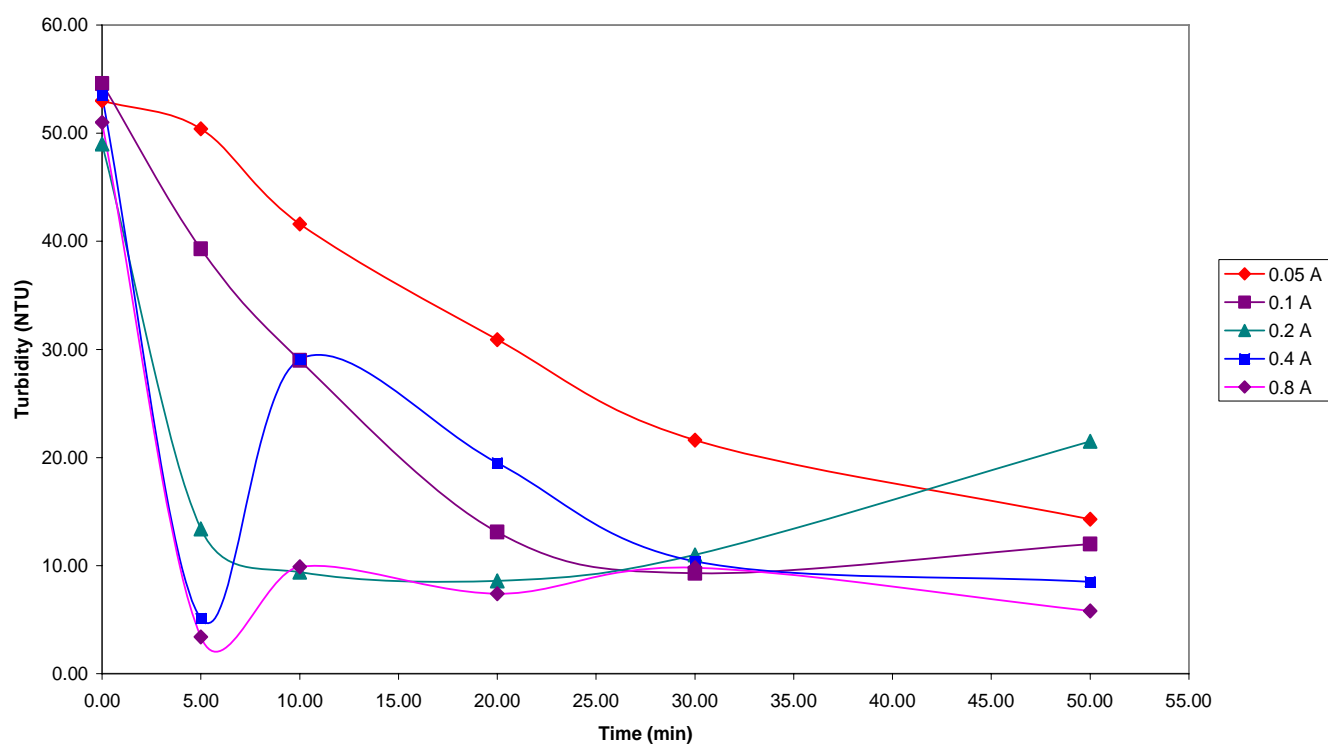


Figure 5.11: Effect of applied current and contact time on the turbidity removal.

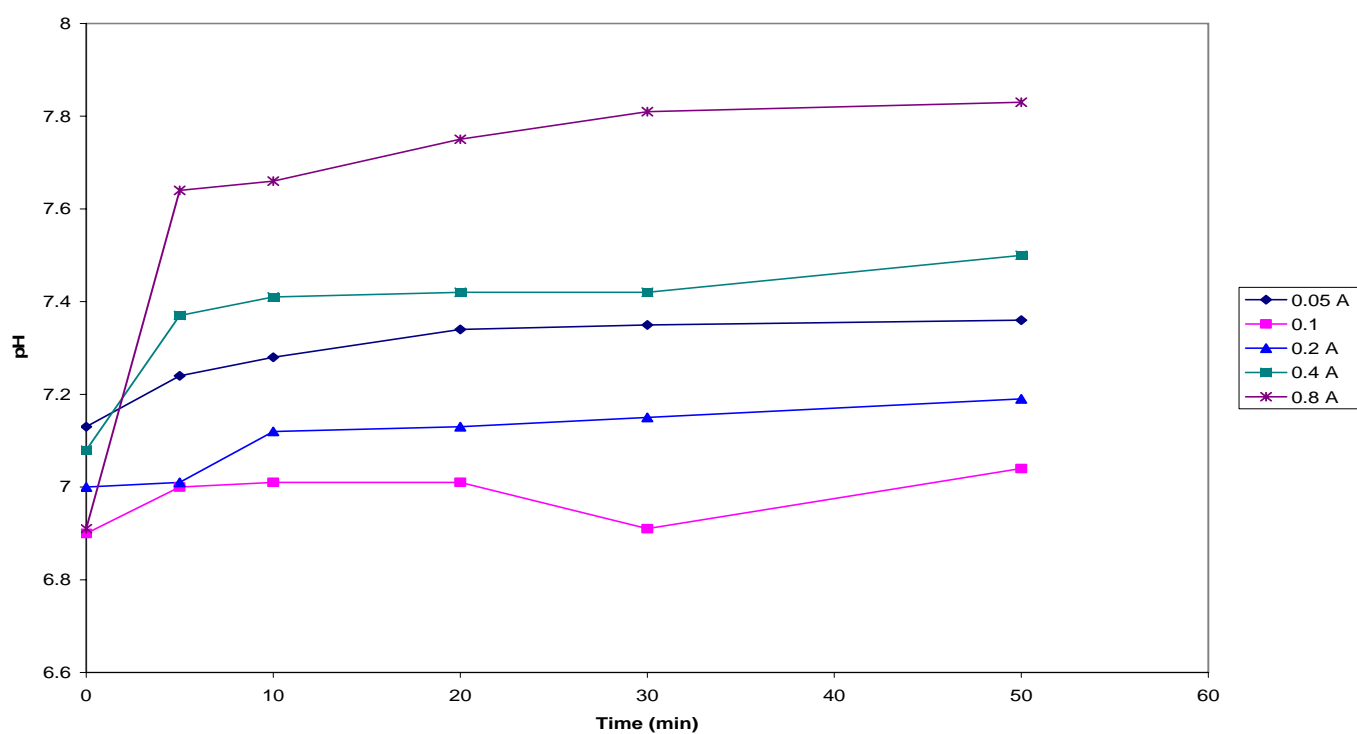


Figure 5.12: Variation of pH with time at different applied current and contact times.

5.5 Total Suspended Solids

Figure 5.13 depicts the relationship between the percent removals of TSS and the current at various contact times. The removal trends are observed to follow the same as in the case of turbidity. TSS concentration is found to be decreasing with the increase in current and detention time in the settled samples. This is due to the more coagulant that is produced with increase in current and detention time that contributes to high removal of suspended solids. Up to 0.2 A, TSS is found to be continuously decreasing with detention time. However at 0.4 A, after a sharp decrease in the concentration of TSS at a contact time of 5 minutes, a sudden increase was observed later. It is due to the restabilization phenomenon that took place because of excess coagulant dose that made the particles restabilize and brought back them in suspension, which can also be observed in the turbidity results (Figure 5.11). With further increase of current from 0.4 to 0.8 A, the TSS concentration is found to be again decreasing, which is due to the precipitation of the ferric hydroxide at elevated pH resulted in the phenomenon of enmeshment, where the precipitated coagulant acts as blanket and brings the particles down while settling. Due to the phenomenon, a very high removal (95.38 %) of TSS is observed at 0.8 A with a short detention of 5 minutes.

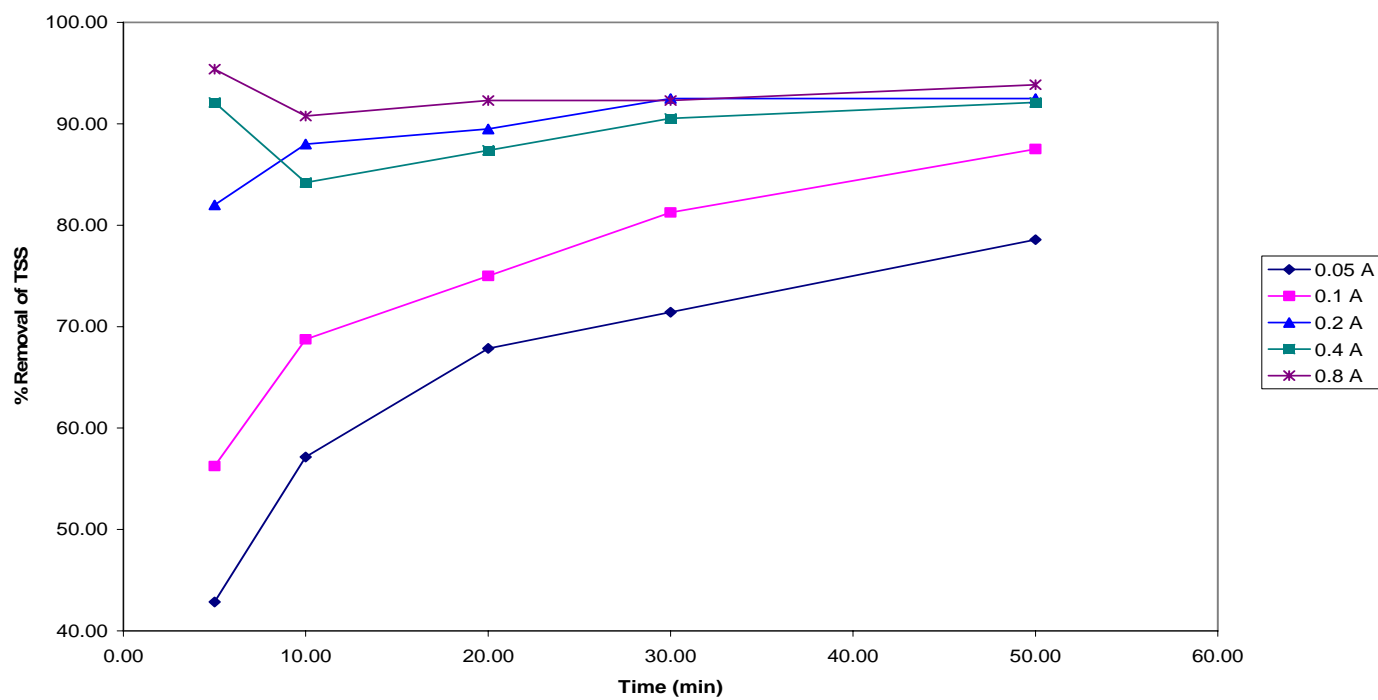


Figure 5.13: Effect of contact time on the removal efficiency of total suspended solids from the supernatant

5.6 Jar Test Experiments with FeCl_3 Coagulant

Jar test experiments were conducted with $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ coagulant, in order to compare the sludge production by conventional coagulant addition process to electrocoagulation process. Experiments were done at various coagulant doses, starting from 2.5 mg/l to 800 mg/l, and at different sample initial pH 7.07, 8.07, 8.69 and 9.11. Figure 5.14 shows the residual turbidity that was observed at various coagulant doses in the settled samples. Experiments with raw sample, which has an initial pH 7.07, resulted in the decrease in the residual turbidity with the increase in the coagulant dosage. The maximum removal is observed at a coagulant dosage of 400 mg/l, where the residual turbidity observed to be 1.58 NTU. Beyond which, further increase in the dosage, resulted in increase in the residual turbidity. Therefore, the optimum dose for the turbidity removal can be taken as 400 mg/l. The sludge that was produced at this dosage was measured, which was 145 mg/l. However, when the sample initial pH was altered by adding NaOH solution from original 7.07 to 8.69 and 9.11, marked decrease in the optimum dosage was observed, which was found to be 25 mg/l (Figure 5.14). The least turbidity was observed in the case of sample with initial pH of 9.11, which was 1.66 NTU at a coagulant dose of 25 mg/l. The sludge produced at this optimum dosage was measured, which was 20 mg/l.

BOD analysis was also done for the optimum dosage sample. The total BOD_5 removal of 72.28 % is observed with 99.61 % particulate and 8.18 % soluble BOD_5 removal. The maximum particulate removal efficiency of 99.53 % is observed with electrochemical process at 0.8 A with a contact time of 5 minutes in the settled sample, which is almost the same as that of with FeCl_3 . However a slight increase in the turbidity removal (97.09

%) is observed with FeCl_3 Coagulant when compared to the electrochemical process (93.03 %).

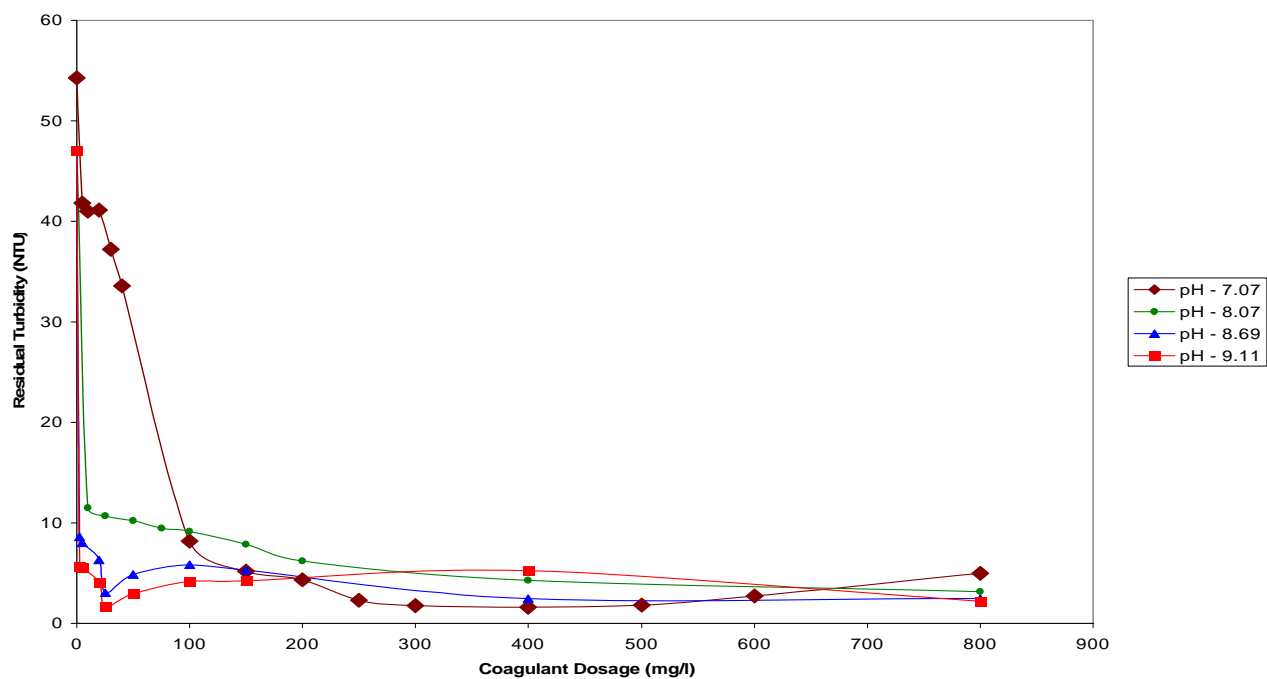


Figure 5.14: Residual turbidity observed at various coagulant dosages

5.7 Sludge Calculations

5.7.1 Sludge Production by Electrochemical Process

The amount of sludge that is electrically produced was calculated by measuring the TSS after the oxidation process with the total filtered sample. Table 5.1 shows the iron sludge that produced during the electrochemical process. Using the above sludge analysis, the total amount of sludge that will be electrically produced, when treating the total flow of 10.5 Mgal/day, coming to the Dhahran sewage treatment plant by electrochemical process was calculated. Maximum turbidity removal was observed at 0.8 A and 5 minutes contact time, where the sludge production measured to be 59 mg/l. Therefore, the total amount of sludge that will be electrically produced from the electrodes to treat the total flow coming to the treatment plant is 2345.05 kg/day^(a).

5.7.2 Sludge Production by Coagulant Addition (FeCl₃ 6H₂O) Process

The sludge that will be produced due to the coagulant addition is also calculated from the above optimum dosage experiments. From the jar test experiments of the sample, whose initial pH was 7.07, the optimum dosage was observed to be 400 mg/l, and the sludge production to be 145 mg/l. Therefore the total sludge production with the original pH of the sample (pH 7.07) will be 5763.3 kg/dy^(a)

Similarly, the sludge that will be produced, when the initial pH of the sample was altered from 7.07 to 9.11 is calculated. From the jar test experiments, the sludge produced was observed to be 20 mg/l, at an optimum dosage of 25 mg/l. By using the amount, the total sludge that will be produced when treating the total flow of 10.5 Mgal/day is calculated, which is found to be

$$= 10.5 \text{ (Mgal/day)} * 10^6 \text{ (gal/Mgal)} * 3.7854 \text{ (liters/gal)} * 20 \text{ (mg/l)} * (1/10^6) \text{ (kg/mg)}$$

$$= 794.93 \text{ kg/day.}$$

5.7.3 Quantitative Comparison of Sludge Production by Electrochemical Process with Conventional Chemical Addition Process.

The sludge production by electrochemical process is calculated to be 2345.05 kg/day, which is observed to be 2.45 times less than the conventional coagulation process. However, when the initial pH of the sample was altered from 7.07 to 9.11, marked decrease in the sludge production was observed with the conventional coagulation process, which was 2.95 times less than the electrochemical process. Therefore, by this, it was observed that increasing the pH during the conventional coagulation process significantly reduces the coagulant dosage, and ultimately results in less sludge production. However, using sodium hydroxide to alter pH could result in higher treatment cost, and also increase the associated handling problems of the strong base.

$$(a) * 10.5 \text{ (Mgal/day)} * 10^6 \text{ (gal/Mgal)} * 3.7854 \text{ (liters/gal)} * 59 \text{ (mg/l)} * (1/10^6) \text{ (kg/mg)} = 2345.05 \text{ kg/day.}$$

Table 5.1: Amount of sludge electrically produced during the electrochemical process (mg/l).

Time (min)	0.05 A	0.1 A	0.2 A	0.4 A	0.8 A
0	0	0	0	0	0
5	2	3	13	28	59
10	3	24	34	79	300
20	7	53.33	68.88	139	442
30	16	83	125	229	461
50	28	182	272	350	544.5

CHAPTER 6

CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

Following are the specific conclusions made in this study:

1. The removal of Soluble BOD₅ is observed to be dependent on the applied current and contact time. It increased with the increase of current and detention time up to 0.2 A. Further increase of current beyond 0.2 A resulted in the decrease of removal efficiency. The maximum removal of 60.31 % is observed at 0.2 A and 30 minutes.
2. Most of the removal of BOD was contributed by the removal of particulate organics by electrocoagulation process. Removal of particulate BOD was observed to be directly dependent on current and contact time. The maximum removal of 99.53 % particulate BOD₅ is observed at 0.8 A with a contact time of 5 minutes.
3. The removal of total BOD₅ is observed to be dependent on applied current and contact time. It increased with the increase in current and contact time up to 0.2 A. Further increase in current from 0.2 to 0.4 and 0.8 A, resulted in the decrease in the removal

efficiency. The maximum removal of 84.82 % is observed at 0.2 A and 50 minutes contact time.

4. With the given operational parameters, ammonia removal was not efficient. Maximum removal of only 18.13 % was observed at 0.2 A and 50 minutes contact time.

5. Experiments with filtered samples resulted in the increase in the removal efficiencies of soluble BOD₅ and ammonia.

6. Disinfection efficiency was observed to be directly dependent on applied current and contact time. Maximum removal of 5.05 log scale removal was observed at 0.8 A and 20 minutes contact time.

7. Processes were found to be promising for the removal of turbidity and TSS. Maximum removal of 93.33 % of turbidity and 95.38 % of TSS was observed.

8. Sludge production by electrochemical process was observed to be 2.45 times less than the conventional coagulation process, when the coagulation experiments were done with samples of initial pH 7.07. However, when the sample pH was altered from 7.07 to 9.11, sludge production by conventional coagulation process was observed to be 2.95 times less than the electrochemical process.

6.2 Recommendations

1) Detailed study is required to investigate the lower removal efficiencies of Soluble BOD at high currents

2) Detailed investigation for the lower removal efficiency of ammonia on the reactive stainless steel electrodes should be done.

- 3) Detailed study should be done to investigate the characteristics of sludge produced.
- 4) Economics of the combined process should be done.

Table A 1.1: 0.05 A (Total BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Total BOD ₅ (ppm)	% Removal
0.0	8.3	2.7	8.9	8.9	5.6	0.0	5.6	112.0	0.00
5.0	8.1	3.3	8.9	8.9	4.8	0.0	4.8	48.0	57.14
10.0	8.1	4.0	8.9	8.9	4.1	0.0	4.1	41.0	63.39
20.0	8.1	4.8	8.9	8.9	3.3	0.0	3.3	33.0	70.54
30.0	8.2	5.3	8.9	8.9	2.9	0.0	2.9	29.0	74.11
50.0	8.3	5.6	8.9	8.9	2.7	0.0	2.7	27.0	75.89

Table A 1.2: 0.05 A (Soluble BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD ₅ (ppm)	% Removal
0.0	7.6	2.0	8.7	8.7	5.6	0.0	5.6	28.0	0.00
5.0	7.6	2.3	8.7	8.7	5.3	0.0	5.3	26.5	5.36
10.0	7.6	2.5	8.7	8.7	5.1	0.0	5.1	25.5	8.93
20.0	7.6	2.8	8.7	8.7	4.8	0.0	4.8	24.0	14.29
30.0	7.6	3.3	8.7	8.7	4.3	0.0	4.3	21.5	23.21
50.0	7.6	3.4	8.7	8.7	4.2	0.0	4.2	21.0	25.00

Table A 1.3: 0.1 A (Total BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Total BOD ₅ (ppm)	% Removal
0.0	8.5	4.5	8.8	8.8	4.1	0.0	4.1	81.0	0.00
5.0	8.4	2.6	8.8	8.8	5.8	0.0	5.8	29.0	64.20
10.0	8.3	3.3	8.8	8.8	5.0	0.0	5.0	25.0	69.14
20.0	8.3	4.2	8.8	8.8	4.1	0.0	4.1	20.5	74.69
30.0	8.4	4.9	8.8	8.8	3.5	0.0	3.5	17.5	78.40
50.0	8.4	5.1	8.8	8.8	3.3	0.0	3.3	16.5	79.63

Table A 1.4: 0.1 A (Soluble BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.0	8.4	3.2	8.8	8.8	3.3	0.0	5.2	26.0	0.00
5.0	8.5	4.2	8.8	8.8	2.7	0.0	4.4	21.8	16.35
10.0	8.5	4.7	8.8	8.8	2.4	0.0	3.8	19.0	26.92
20.0	8.6	5.1	8.8	8.8	2.3	0.0	3.5	17.5	32.69
30.0	8.6	5.3	8.8	8.8	2.1	0.0	3.4	16.8	35.58
50.0	8.6	5.5	8.8	8.8	1.8	0.0	3.1	15.5	40.38

Table A 1.5: 0.2 A (Total BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Total BOD5 (ppm)	% Removal
0.0	8.2	3.9	8.3	8.2	4.3	0.1	4.2	84.0	0.00
5.0	6.8	1.9	8.3	8.2	5.0	0.1	4.9	24.3	71.13
10.0	6.8	3.7	8.3	8.2	3.1	0.1	3.0	15.0	82.14
20.0	6.8	4.0	8.3	8.2	2.9	0.1	2.8	13.8	83.63
30.0	6.8	4.1	8.3	8.2	2.7	0.1	2.6	13.0	84.52
50.0	6.8	4.2	8.3	8.2	2.7	0.1	2.6	12.8	84.82

Table A 1.6: 0.2 A (Soluble BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.0	7.5	1.0	8.3	8.2	6.6	0.1	6.5	32.3	0.00
5.0	7.1	2.9	8.3	8.2	4.2	0.1	4.1	20.5	36.43
10.0	7.1	4.2	8.3	8.2	2.9	0.1	2.8	14.0	56.59
20.0	7.1	4.3	8.3	8.2	2.8	0.1	2.7	13.5	58.14
30.0	7.1	4.5	8.3	8.2	2.6	0.1	2.5	12.5	61.24
50.0	7.1	4.5	8.3	8.2	2.6	0.1	2.5	12.5	61.24

Table A 1.7: 0.4 A (Total BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Total BOD5 (ppm)	% Removal
0.0	8.2	3.9	8.3	8.2	4.3	0.1	4.2	84.0	0.00
5.0	7.0	2.9	8.3	8.2	4.1	0.1	4.0	20.0	76.19
10.0	7.0	2.7	8.3	8.2	4.3	0.1	4.2	21.0	75.00
20.0	7.0	2.8	8.3	8.2	4.2	0.1	4.1	20.3	75.89
30.0	7.0	2.9	8.3	8.2	4.1	0.1	4.0	20.0	76.19
50.0	7.0	2.8	8.3	8.2	4.2	0.1	4.1	20.3	75.89

Table A 1.8: 0.4 A (Soluble BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.0	7.5	1.0	8.3	8.2	6.6	0.1	6.5	32.3	0.00
5.0	7.7	3.7	8.3	8.2	4.0	0.1	3.9	19.5	39.53
10.0	7.7	3.7	8.3	8.2	4.0	0.1	3.9	19.5	39.53
20.0	7.7	3.7	8.3	8.2	4.0	0.1	3.9	19.5	39.53
30.0	7.7	3.7	8.3	8.2	4.0	0.1	3.9	19.5	39.53
50.0	7.7	3.7	8.3	8.2	4.0	0.1	3.9	19.5	39.53

Table A 1.9: 0.8 A (Total BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Total BOD5 (ppm)	% Removal
0.0	8.2	3.9	8.3	8.2	4.3	0.1	4.2	84.0	0.00
5.0	6.8	2.5	8.3	8.2	4.4	0.1	4.3	21.3	74.70
10.0	6.8	2.4	8.3	8.2	4.5	0.1	4.4	21.8	74.11
20.0	6.8	2.5	8.3	8.2	4.4	0.1	4.3	21.3	74.70
30.0	6.8	2.4	8.3	8.2	4.4	0.1	4.3	21.5	74.40
50.0	6.8	2.4	8.3	8.2	4.4	0.1	4.3	21.5	74.40

Table A 1.10: 0.8 A (Soluble BOD₅)

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.0	7.5	1.3	8.3	8.2	6.2	0.1	6.1	30.5	0.00
5.0	7.1	2.8	8.3	8.2	4.3	0.1	4.2	21.0	31.15
10.0	7.1	2.8	8.3	8.2	4.3	0.1	4.2	21.0	31.15
20.0	7.1	2.8	8.3	8.2	4.3	0.1	4.2	21.0	31.15
30.0	7.1	2.8	8.3	8.2	4.3	0.1	4.2	21.0	31.15
50.0	7.1	2.8	8.3	8.2	4.3	0.1	4.2	21.0	31.15

Table A 2.1: Particulate BOD₅ (ppm) at various currents

Time (min)	0.05 A	0.1 A	0.2 A	0.4 A	0.8 A
0	84.00	55.00	51.75	51.75	53.50
5	21.50	7.25	6.63	0.75	0.25
10	15.50	6.00	0.25	1.75	1.25
20	9.00	3.00	0.25	1.00	0.25
30	7.50	0.75	0.25	1.00	0.50
50	6.00	1.00	1.00	1.25	0.50

*Particulate BOD₅ = Total BOD₅ – Soluble BOD₅
Particulate BOD₅ in ppm.

Table A 2.2: Percent Removal of Particulate BOD₅ at various currents

Time (min)	0.05 A	0.1 A	0.2 A	0.4 A	0.8 A
0	0.00	0.00	0.00	0.00	0.00
5	74.40	86.82	92.75	99.03	99.53
10	81.55	89.09	98.07	97.10	98.60
20	89.29	94.55	99.52	98.55	99.53
30	91.07	98.64	99.03	99.03	99.07
50	92.86	98.18	99.52	98.55	99.07

Table B 1.1: 0.05 A

Time (min)	ppm	% Removal
0	14.90	0.00
5	14.70	1.34
10	14.40	3.36
20	14.20	4.70
30	14.18	4.83
50	14.16	4.97

Table B 1.2: 0.1 A

Time (min)	ppm	% Removal
0	14.85	0.00
5	14.30	3.70
10	14.00	5.72
20	13.26	10.71
30	12.51	15.76
50	12.50	15.82

Table B 1.3: 0.2 A

Time (min)	ppm	% Removal
0	15.00	0.00
5	14.35	4.33
10	13.77	8.20
20	12.58	16.13
30	12.30	18.00
50	12.28	18.13

Table B 1.4: 0.4 A

Time (min)	ppm	% Removal
0	15.34	0.00
5	14.75	3.85
10	14.52	5.35
20	14.50	5.48
30	14.51	5.41
50	14.50	5.48

Table B 1.5: 0.8 A

Time (min)	ppm	% Removal
0	19.18	0.00
5	18.48	3.65
10	18.35	4.33
20	18.25	4.85
30	18.20	5.11
50	18.17	5.27

Table C 1.1: 0.05 A

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.00	8.15	2.10	8.90	8.90	6.05	0.00	6.05	30.25	0.00
5.00	8.25	2.56	8.90	8.90	5.69	0.00	5.69	28.45	5.95
10.00	8.25	2.70	8.90	8.90	5.55	0.00	5.55	27.75	8.26
20.00	8.25	3.20	8.90	8.90	5.05	0.00	5.05	25.25	16.53
30.00	8.25	3.70	8.90	8.90	4.55	0.00	4.55	22.75	24.79
50.00	8.25	3.85	8.90	8.90	4.40	0.00	4.40	22.00	27.27

Table C 1.2: 0.1 A

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.0	8.0	3.0	8.8	8.8	3.3	0.0	5.0	25.0	0.00
5.0	8.2	4.1	8.8	8.8	2.7	0.0	4.1	20.5	18.00
10.0	8.2	4.7	8.8	8.8	2.4	0.0	3.6	17.8	29.00
20.0	8.2	5.0	8.8	8.8	2.3	0.0	3.3	16.3	35.00
30.0	8.2	5.1	8.8	8.8	2.1	0.0	3.1	15.5	38.00
50.0	8.2	5.3	8.8	8.8	1.8	0.0	2.9	14.5	42.00

Table C 1.3: 0.2 A

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.0	8.5	3.3	8.8	8.8	5.2	0.0	5.2	26.0	0.00
5.0	8.6	5.5	8.8	8.8	3.1	0.0	3.1	15.5	40.38
10.0	8.6	6.5	8.8	8.8	2.2	0.0	2.2	10.8	58.65
20.0	8.6	6.5	8.8	8.8	2.1	0.0	2.1	10.5	59.62
30.0	8.6	6.6	8.8	8.8	2.0	0.0	2.0	10.0	61.54
50.0	8.6	6.7	8.8	8.8	2.0	0.0	2.0	9.8	62.50

Table C 1.4: 0.4 A

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.0	7.8	2.6	8.3	8.2	5.2	0.1	5.1	25.5	0.00
5.0	7.9	4.9	8.3	8.2	3.1	0.1	3.0	14.8	42.16
10.0	7.9	4.8	8.3	8.2	3.1	0.1	3.0	15.0	41.18
20.0	7.9	4.9	8.3	8.2	3.1	0.1	3.0	14.8	42.16
30.0	7.9	4.9	8.3	8.2	3.1	0.1	3.0	14.8	42.16
50.0	7.9	4.8	8.3	8.2	3.1	0.1	3.0	15.0	41.18

Table C 1.5: 0.8 A

Time (min)	D1	D2	B1	B2	(D1-D2)	(B1-B2)	(D1-D2)-(B1-B2)	Soluble BOD5 (ppm)	% Removal
0.0	8.3	3.9	8.8	8.7	4.4	0.1	4.3	21.5	0.00
5.0	8.3	5.5	8.8	8.7	2.8	0.1	2.7	13.5	37.21
10.0	8.3	5.5	8.8	8.7	2.9	0.1	2.8	13.8	36.05
20.0	8.3	5.5	8.8	8.7	2.8	0.1	2.7	13.5	37.21
30.0	8.3	5.5	8.8	8.7	2.9	0.1	2.8	13.8	36.05
50.0	8.3	5.5	8.8	8.7	2.8	0.1	2.7	13.5	37.21

Table D 1.1: 0.05 A

Time (min)	ppm	% Removal
0	15.70	0.00
5	15.40	1.91
10	15.10	3.82
20	15.00	4.46
30	14.80	5.73
50	14.78	5.86

Table D 1.2: 0.1 A

Time (min)	ppm	% Removal
0	16.00	0.00
5	15.40	1.91
10	15.00	3.82
20	14.20	4.46
30	13.40	5.73
50	13.20	5.86

Table D 1.3: 0.2 A

Time (min)	ppm	% Removal
0	15.40	0.00
5	14.70	1.91
10	14.00	3.82
20	12.80	4.46
30	12.40	5.73
50	12.38	5.86

Table D 1.4: 0.4 A

Time (min)	ppm	% Removal
0	15.75	0.00
5	15.20	1.91
10	14.80	3.82
20	14.70	4.46
30	14.60	5.73
50	14.50	5.86

Table D 1.5: 0.8 A

Time (min)	ppm	% Removal
0	17.40	0.00
5	16.75	1.91
10	16.60	3.82
20	16.57	4.46
3	16.40	5.73
50	16.35	5.86

Table E 1.1: 0.05 A

Time (min)	10 ml	1 ml	0.1 ml	MPN/100 ml	No of log Scale Removal
0	5	3	3	1.80E+14	0.00
5	5	5	0	2.40E+12	1.88
20	5	3	0	7.90E+11	2.36
50	1	0	0	2.00E+10	3.95

Table E 1.2: 0.1 A

Time (min)	10 ml	1 ml	0.1 ml	MPN/100 ml	No of Log Scale Removal
0	5	5	1	3.5E+13	0.00
5	5	5	1	3.5E+11	2.00
20	5	5	2	5.40E+09	3.81
50	5	5	1	3.50E+09	4.00

Table E 1.3: 0.2 A

Time (min)	10 ml	1 ml	0.1 ml	MPN/100 ml	No of Log Scale Removal
0	5	5	4	1.60E+14	0.00
5	2	2	1	1.20E+11	3.12
20	1	1	3	1.00E+10	4.20
50	1	1	0	4.00E+09	4.60

Table E 1.4: 0.4 A

Time(min)	10 ml	1 ml	0.1 ml	MPN/100ml	No of Log Scale Removal
0	5	3	4	2.1E+13	0.00
5	5	5	0	2.40E+09	3.94
20	5	3	1	1.10E+09	4.28
50	5	2	0	4.90E+08	4.63

Table E 1.5: 0.8 A

Time (min)	10 ml	1 ml	0.1 ml	MPN/100ml	No of Log Scale Removal
0	5	3	0	7.90E+12	0.00
5	5	5	2	5.40E+08	4.17
20	5	2	1	7.00E+07	5.05
50	5	2	1	7.00E+07	5.05

Table F1.1: Turbidity observed at various currents and contact times

Time (min)	0.05 A	0.1 A	0.2 A	0.4 A	0.8 A
0	53.00	54.60	49.00	53.50	51.00
5	50.40	39.30	13.40	5.10	3.40
10	41.60	29.00	9.40	29.10	9.90
20	30.90	13.10	8.60	19.50	7.40
30	21.60	9.30	11.00	10.40	9.80
50	14.30	12.00	21.50	8.50	5.80

Table G 1.1: 0.05 A

Time (min)	W2	W1	W2-W1	TSS (mg/l)	% Removal
0	22.5264	22.5250	0.0014	140	0
5	21.7939	21.7931	0.0008	80	42.85
10	20.6534	20.6528	0.0006	60	57.14
20	20.8471	20.8462	0.0009	45	67.85
30	21.8951	21.8943	0.0008	40	71.42
50	22.6054	22.6048	0.0006	30	78.57

Table G 1.2: 0.1 A

Time (min)	W2	W1	W2 - W1	TSS	% Removal
0	22.5065	22.5049	0.0016	160	0
5	21.5325	21.5318	0.0007	70	56.25
10	22.6389	22.6384	0.0005	50	68.75
20	20.6185	20.6181	0.0004	40	75.00
30	23.8542	23.8539	0.0003	30	81.25
50	20.5254	20.5252	0.0002	20	87.50

Table G 1.3: 0.2 A

Time (min)	W2	W1	W2-W1	TSS (mg/l)	% Removal
0	20.4012	20.3992	0.0020	133.33	0
5	22.0539	22.0527	0.0012	24	81.99
10	20.1234	20.1226	0.0008	16	87.99
20	22.3311	22.3304	0.0007	14	89.49
30	22.1452	22.1447	0.0005	10	92.49
50	20.5346	20.5341	0.0005	10	92.49

Table G 1.4: 0.4 A

Time (min)	W2	W1	W2-W1	TSS (mg/l)	% Removal
0	22.2847	22.2809	0.0038	126.66	0
5	23.3185	23.3180	0.0005	10	92.11
10	21.5446	21.5436	0.0010	20	84.21
20	22.7582	22.7574	0.0008	16	87.37
30	20.9222	20.9216	0.0006	12	90.53
50	21.7800	21.7795	0.0005	10	92.11

Table G 1.5: 0.8 A

Time (min)	W2	W1	W2-W1	TSS (mg/l)	% Removal
0	22.2746	22.2720	0.0026	130	0
5	21.5653	21.5650	0.0003	6	95.38
10	21.1852	21.1846	0.0006	12	90.76
20	22.2631	22.2626	0.0005	10	92.30
30	21.4386	21.4381	0.0005	10	92.30
50	22.3900	22.3896	0.0004	8	93.84

Table H 1.1: pH observed at various currents and contact times

Time (min)	0.05 A	0.1 A	0.2 A	0.4 A	0.8 A
0	7.13	6.9	7	7.08	6.91
5	7.24	7	7.01	7.37	7.64
10	7.28	7.01	7.12	7.41	7.66
20	7.34	7.01	7.13	7.42	7.75
30	7.35	6.91	7.15	7.42	7.81
50	7.36	7.04	7.19	7.5	7.83

Table I 1.1: Jar Test Experiments at Various pH

Influent TSS (Raw Sample)

W2	W1	W2-W1	TSS, mg/l	Avg TSS, mg/l
23.3186	23.3145	0.0041	205	207.50
21.2916	21.2874	0.0042	210	

TSS at pH 7.07

W2	W1	W2-W1	TSS, mg/l	Sludge Produced, mg/l
22.5381	22.5313	0.0068	340	145
22.2865	22.2792	0.0073	365	

Supernatant TSS

W2	W1	W2-W1	TSS, mg/l	TSS, mg/l
21.6532	21.652	0.0012	40	40.00

Coagulant dosage = 400 mg/l

TSS at pH 8.07

W2	W1	W2-W1	TSS, mg/l	Sludge Produced, mg/l
22.2865	22.2758	0.0107	535	327.5

Supernatant TSS

W2	W1	W2-W1	TSS, mg/l	TSS, mg/l
22.7571	22.756	0.0011	36.66667	36.67

Coagulant dosage = 800 mg/l

TSS at pH 8.69

W2	W1	W2-W1	TSS, mg/l	Sludge Produced, mg/l
23.5422	23.5411	0.0011	55	17.5
20.535	20.5306	0.0044	220	
Supernatant TSS				
W2	W1	W2-W1	TSS, mg/l	TSS, mg/l
20.922	20.921	0.001	50	42.5
19.3757	19.375	0.0007	35	

Coagulant dosage = 25 mg/l

TSS at pH 9.11

W2	W1	W2-W1	TSS, mg/l	Sludge Produced, mg/l
21.1889	21.1843	0.0046	230	20
22.5357	22.5312	0.0045	225	
Supernatant TSS				
W2	W1	W2-W1	TSS, mg/l	TSS, mg/l
22.1455	22.1448	0.0007	35	35

Coagulant dosage = 25 mg/l

Table I 1.2: Total BOD5 Removal at Optimum Coagulant Dosage

Sample	D1	D2	B1	B2	D1-D2	B1-B2	(D1-D2)-(B1-B2)	% Dilution	Total BOD	% Removal
Raw untreated	7.90	3.20	8.60	8.50	4.70	0.10	4.60	5.00	92.00	0.00
Treated	7.75	2.55	8.60	8.50	5.20	0.10	5.10	20.00	25.50	72.28

Table I.1.3: Soluble BOD5 Removal at Optimum Coagulant Dosage

Sample	D1	D2	B1	B2	D1-D2	B1-B2	(D1-D2)-(B1-B2)	% Dilution	Soluble BOD	% Removal
Filter Untreated	7.90	2.30	8.60	8.50	5.60	0.10	5.50	20.00	27.50	0.00
Treated	7.95	2.80	8.60	8.50	5.15	0.10	5.05	20.00	25.25	8.18

Table I.1.4: Particulate BOD5 Removal at Optimum Coagulant Dosage

Sample	Particulate BOD5	% Removal
Raw untreated	64.50	0.00
Treated	0.25	99.61

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