6-2014

Treatment of Industrial Wastewater Using Electrocoagulation

Shereen W. Hasan

Recommended Citation

Hasan, Shereen W., "Treatment of Industrial Wastewater Using Electrocoagulation" (2014). *Theses*. 280.
https://scholarworks.uaeu.ac.ae/all_theses/280

UAEU College of Engineering

جامعة الإمارات العربيـة المتحدة
United Arab Emirates University

United Arab Emirates University

College of Engineering

TREATMENT OF INDUSTRIAL WASTEWATER USING ELECTROCOAGULATION

Shereen W. Hasan

This thesis is submitted in partial fulfillment of the requirements for the Master of Water Resources

Under the direction of Professor Muftah H. El-Naas

JUNE 2014

Declaration of Original Work

I, Shereen Wajeeh Saleem Hasan, the undersigned, a graduate student at the United Arab Emirates University (UAEU) and the author of the thesis/dissertation titled "Treatment of Industrial Wastewater and CO_2 Capturing by using Electrocoagulation technology", hereby solemnly declare that this thesis/dissertation is an original work done and prepared by me under the guidance of Prof. Muftah H. El-Naas, in the College of Chemical and Petroleum Engineering at UAEU. This work has not been previously formed as the basis for the award of any degree, diploma or similar title at this or any other university. The materials borrowed from other sources and included in my thesis/dissertation have been properly acknowledged.

Student's Signature .... Date ...June 5, 2014.....

Approved

Advisory Committee:

1) Advisor Prof. Muftah El-Naas

Title Professor

Department Chemical and Petroleum Engineering

Institution College of Engineering, UAE University

Signature .... Date June 5, 2014

Thesis Examination Committee:

1) Advisor Prof. Muftah El-Naas
Title Professor
Department Chemical and Petroleum Engineering
Institution College of Engineering, UAEU
Signature .... Date June 5, 2014

2) Internal Examiner Dr. Mohammad Mozumder
Title Assistant professor
Department Chemical and Petroleum Engineering
Institution College of Engineering, UAEU
Signature .... Date June 5/2014

for
3) External Examiner Prof J. Paul Chen
Title Professor
Department Civil and Environmental Engineering
Institution National University of Singapore (NUS), Singapore
Signature ....June 8, 2014.............. Date .....June 8, 2014

Accepted by

Master`s Program Director Prof. Walid El Shorbagy

Signature .... Date ....June 8, 2014............

Dean of the College Prof. Amr El-Dieb

Signature ....25/6/2014........ Date ....25/6/2014............

Copy ____ of ____

Abstract

The aim of this thesis was to evaluate the potential use of electrocoagulation in the treatment of carbide slurry, which is wastewater generated during the production of acetylene. Several experiments using an electrochemical batch reactor were carried out at different current densities, ranging between 140-290 A/m^2. Pure air (EA system) and 10% of carbon dioxide in air (CA system) were supplied to ensure good mixing and solution homogeneity. Aluminum plates were used as electrodes, spaced apart and connected to a DC power supply. After 3 hours, samples from treated effluent and waste slurry were collected and analyzed for total dissolved solids (TDS), total hardness (TH), and chemical oxygen demand (COD), in addition to electrical conductivity (EC).

Response surface methodology (RSM) was used to design a matrix of experiments in order to optimize the conditions for the treatment process and improve product quality over that achieved by current conditions. Box-Behnken design (BBD) is a tool for multivariable optimization. It could be concluded that the quality of the treated wastewater as well as the generated by-products could be enhanced through controlling the operating conditions in the electrochemical reactor The highest reduction efficiencies for the EA system were 47.5%, 47.8%, 69.7%, 36.1%, 71.4% and 53% for COD, TH, EC, pH, TDS and salinity, respectively under specific conditions and the overall optimum conditions for the highest % reduction is under 12, 27.5 and 284 A/m^2 as pH, temperature and current density, respectively. On the other hand, for the CA system, the highest reduction efficiencies were 42%, 75%, 73%, 46, 73 and 74% for COD, TH, EC, pH, TDS and salinity, respectively under specific conditions and the overall optimum conditions for the highest % reduction is under 12, 35 and 213.5 A/m^2 as pH, temperature and current density, respectively. The highest CO_2 capture efficiency was 84%.

Acknowledgments

My special thanks go to Prof. Muftah El-Naas for his supervision and valuable suggestions throughout this endeavor and to the Emirates Industrial Gases and Co. (EIGCO) for providing the wastewater samples used in the study.

I would also like to thank my committee members and all the faculty and staff of the Civil and Environmental Engineering and the Chemical and Petroleum Engineering departments at the United Arab Emirates University for their assistance.

My gratitude goes to my friends and laboratory colleagues for the teamwork spirit that we shared, and unforgettable memories.

Last, but not least, this thesis couldn't have been possible without the support, friendship, guidance, help and the unconditional love and prayers of my parents, and my siblings. A special mention goes to my brother Dr. Shadi W. Hasan, for his valued guidance and special thanks to my wonderful sister in law Yousra for her advices.

Dedication

To my beloved parents…

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	Effective surface area of electrode (m^2)
ASP	activated sludge process
BOD	Biological oxygen demand (mg/L)
CA system	10% CO_2 in air
CD	Current density (A/m^2)
COD	Chemical oxygen demand (mg/L)
$COD_{treated\ effluent}$	Chemical oxygen demand in treated effluent
E	Potential gradient applied (V/m)
EA system	100% pure Air
EC	Electrical conductivity (ms/cm)
F	Faraday`s number (96485 Coulomb/mol)
I	Electric current (A)
M	Relative molar mass of the electrode concerned
MBRs	membrane bioreactors
Mw	Molecular weight (g/mole)
N	Number of electrons in oxidation/reduction reaction
Q	Flow rate (L/ min)
RO	Run Order
t	Time (s)
T	Temperature (°C)
TDS	Total dissolved solid (g/l)
TH	Total hardness (mg/l as CaCO3)
TSS	Total suspended solid (g/l)
V	Voltage (V)
W	The quantity of electrode material dissolved (g of M/m^2)

Greek Symbols

ε	Permittivity of the Solvent (C^2J-1m-1)
ε_0	Permittivity of the vacuum (C^2J-1m-1)
ζ	Zeta potential (V)
μ	Viscosity (kg/ms)
ν	Velocity of ion (m/s)
ν_{H2O}	Flow of [illegible] s
ν_{rise}	Bubble rise velocity (m/s)
υ_{ma}	Maximum ion velocity (m/s)
υ_p	Particle velocity/mobility (m/s)

CONTENTS

CHAPTER ONE: INTRODUCTION

1.1. PROBLEM STATEMENT

The UAE is facing water scarcity issues due to the rapid growth of population as well as the significant industrial developments in recent years. Consequently, the UAE government has considered the treatment of wastewater as a viable alternative in order to increase the water reserves. Industrial wastewater contains several contaminants that pose serious risks on water resources such as surface water (lakes, rivers, and oceans) and groundwater. Examples of those pollutants include organics, heavy metals and nutrients. Several technologies have been widely used for wastewater treatment for better quality effluents that can be either discharged safely into receiving waters or re-used for other applications such as cooling and agriculture. Examples are physicochemical and biological methods such as activated sludge process (ASP), membrane bioreactors (MBRs), aerated lagoons, wetlands, adsorption, and ion exchange. Implementation of electrochemical treatment as a pretreatment method could also contribute to improving the quality of the treated effluent.

In the UAE, acetylene is produced by Emirates Industrial Gases Co. (EIGCO) using the carbide process in their Acetylene Plant in Dubai. The company produces an average of 2370 kg/d of acetylene, while utilizing about 5960 kg/d of calcium carbide in a specially designed reaction chamber. As a result, the company generates 3500 to 4500 metric tons/yr of calcium hydroxide as a by-product waste.

$$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$$

The generated slurry is drained from the reaction chamber and pumped into a holding pond, where the calcium hydroxide settles out. The carbide lime is then removed from the pond and allowed to dry to a moisture content of about 25%, before it is sent for disposal. This huge amount of waste represents a major environmental and economic challenge to the company and to the UAE as a whole. Industrial wastewater permitted for discharge to the Dubai Municipality (DM) sewerage system should be within the DM effluent quality standards shown in (Table 1)

Table 1: Maximum Allowable Limits for Discharge to DM System (DM. 2003)

Parameter	**Maximum Limit** **Sewage**	**Maximum Limit** **Harbor**	**Maximum Limit** **Open sea (Gulf)**
Physico – chemical			
BOD, mg/L	1,000	30	30
COD, mg/L	3,000	100	100
pH	6 – 10	6-9	6-9
TDS, mg/L	3,000	1,500	1,500
Temperature, °C	45 or > 5 of ambient	35	35

The process of wastewater treatment involves many challenges that are not limited to the technical goals of maximizing water quality. In developing any wastewater treatment process, the main factors to be considered are: environmental impact (emission of gases such as carbon dioxide; CO_2), energy efficiency, and cost-effectiveness. Recently, many wastewater treatment units were employed worldwide, each one having its advantages and disadvantages. Electrocoagulation requires simple operation, thus making it an environmentally friendly when compared to chemical coagulation and other treatment processes that require large areas for treatment facilities (Vepsäläinen, 2012).

Therefore, the potential use of electrocoagulation (electrochemical) process for industrial wastewater treatment while capturing CO_2 was worth investigating on the physical and chemical parameters such as chemical oxygen demand (COD), total hardness (TH), total suspended solid (TSS), total dissolved solid (TDS), electrical conductivity (EC), pH, salinity, filterability and settleability.

1.2. RESEARCH OBJECTIVES

The main objective of this research was to investigate the performance of electrochemical reactors to reduce the COD, TDS, EC, TH and pH using air (EA system thereafter) and 10% carbon dioxide (CO_2) in air (CA system thereafter).

This main objective can be divided into the following tasks:

Part 1: Perform comparative study of EA and CA systems at different operating conditions such as current density, temperature and initial pH in terms of the effect on water quality and slurry characteristics. This includes:

1.1. Water quality with respect to TH, TDS, COD, electrical conductivity, and salinity
1.2. Slurry waste characteristics such as filterability and settleability

Part 2: Conduct statistical analysis on the experimental results to determine the significant operating parameters affecting the reduction of TH, TDS, COD, and salinity in carbide slurry wastewater. The model predictions are then compared with experiment results.

1.3. ORGANIZATION OF THE THESIS

This thesis consists of five chapters. Chapter 1 includes introduction, problem statement, and research objectives. Chapter 2 presents a general review of the literature related to the study. Chapter 3 explains the methodology followed to achieve the research objectives. Chapter 4 presents detailed discussion of the results obtained from the laboratory scale experiments. Chapters 5 summarizes the conclusions drawn from this study, highlights the research contributions, and offers recommendations for future work

CHAPTER TWO: LITERATURE REVIEW

2.1. WASTEWATER CHARACTERISTICS

Wastewater refers to the type of water, where the quality has been adversely affected and must be treated before being discharged to surface waters. Each source of wastewater might contain different types of pollutants, with diverse characteristics. Types of wastewaters comprise, but are not limited to, municipal, agricultural wastewaters, and industrial wastewater. Sources of municipal wastewater include domestic and non-domestic sources (Tchobanoglous and Schroeder, 1987).

Non-domestic wastewater, also known as industrial wastewater, is the water that originated from commercial or industrial establishments (Fig. 1). The properties of the water will depend on multiple factors such as climate and the quality of water supply. The flow of the wastewater is contingent to the demographics and levels of industrialization of the area (Metcalf and Eddy, 2003).

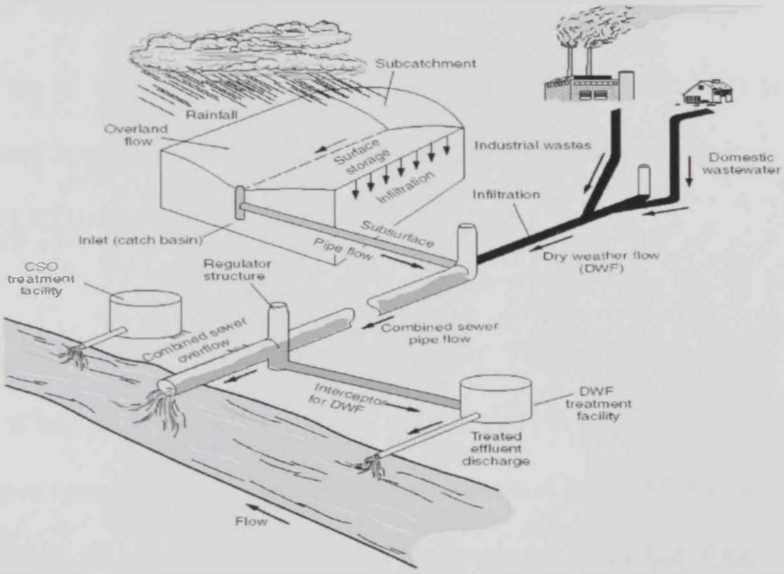


Figure 1: Sources of wastewater (Metcalf and Eddy, 2003)

For the treatment of Industrial wastewater the chemical, biological and physical properties of the influent and the effluent are usually analyzed.

- **Calcium (Ca^{+2})** supplies results from passage over deposits of limestone, dolomite, gypsum, and gypsiferous shale. Calcium contributes to the total hardness of water (Water Environment Federation, 1999). Concentrations of calcium, in normal potable groundwater, are generally between 10 and 100 ppm. Calcium in these concentrations has no known effect on the health of human beings or animals. Indeed, as much as 1000 ppm of calcium may be harmless. The widespread belief that calcium in water causes hardening of the arteries, kidney stones, and liver ailments is without factual support. The most commonly noticed effect of calcium in water is its tendency to react with soap to form a precipitate called soap curd (Hamad, 2008).
- **Magnesium (Mg^{+2})** occurs commonly in the minerals magnetite and dolomite. Magnesium is an important contributor to the hardness of water, magnesium salts break down when heated, forming scale in boilers (Water Environment Federation, 1999).

Exceptionally low values of magnesium and calcium are found in some waters, which have undergone natural softening by cation exchange. Most commonly, clay will exchange sodium, if available for both, magnesium and calcium ions (Hamad, 2008).

3- **Alkalinity** of water may be due to the presence of one or more of a number of ions. These include hydroxides (OH^{-1}), carbonates (CO_3^{-2}) and bicarbonates (HCO_3^{-1}) (www.freedrinkingwater.com).

4- **Chemical Oxygen Demand (COD)** is used to indirectly measure the amount of organic compounds in water. Most applications of COD determine the amount of organic pollutants found in surface water (e.g. lakes and rivers) or wastewater, making COD a useful measure of water quality. It is expressed in milligrams per liter (mg/L) also referred to as ppm (parts per million), which indicates the mass of oxygen consumed per liter of solution.

5- **Salinity** is the saltiness or dissolved salt content (such as sodium chloride, magnesium and calcium sulfates, and bicarbonates) of a body of water or in soil. Salinity is an important factor in determining many aspects of the chemistry of natural waters and of biological processes within it, and is a thermodynamic state variable that, along with temperature and pressure, governs physical characteristics like the density and heat capacity of the water.

6- **Electrical Conductivity (EC)** measures the ability of water to pass an electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge) (www.epa.gov).

2.1.3. BIOLOGICAL PROPERTIES

There are different types of biological constitutes of industrial wastewater. For example: viruses, bacteria, protozoa, algae, and fungi (Metcalf and Eddy, 1979; Sincero and Sincero, 2003). The wastewater treatment should be selected based on the type of the microorganisms existing. Bacteria play a main role in decomposition of organic material and wastes, both in the environment and in wastewater treatment. There are some useful bacteria in wastewater treatment, such as the nitrosomonas and nitrobacter, which are responsible for nitrification and denitrification respectively (Mulligan, 2002). Meanwhile, other bacteria like Escherichia Coli or other coliform bacteria are often indicators of human and animal pollution. Human depletion of water or food contaminated with coliform bacteria can cause severe health problems and disease such as AIDS, mad cow, cholera, typhoid gastroenteritis, bloody diarrhea, and death as shown in table 2 (Aylesworth-Spink, 2009).

Table 2: Types of micro-organisms in wastewater (Aylesworth-Spink, 2009)

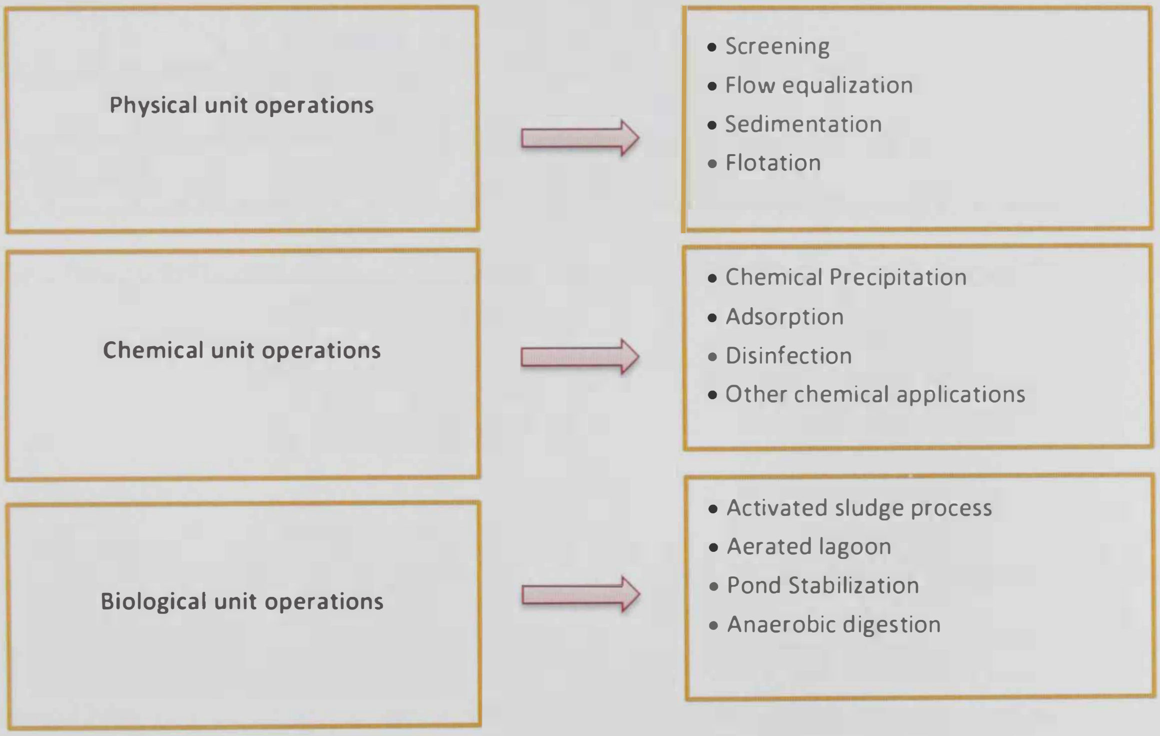
Microorganism	**Size (um)**	**Disease**
Viruses	0.02-0.3	All pathogenic AIDS, hepatitis, mad cow
Bacteria	0.1-10	Some are pathogenic: Cholera, typhoid
Algae	1-100	Non pathogenic

Fungi	Few um-several cm	Many are nonpathogenic
Protozoa	10-300	me are pathogenic: Amebic dysentery, malaria

2.2. WASTEWATER TREATMENT METHODS

Wastewater treatment characteristics are classified into chemical, biological and physical divisions. Furthermore, each case may need more than one treatment; it depends on the quality of the wastewater itself. Physical, chemical and biological methods are used to remove contaminants from wastewater. In order to achieve different levels of contaminant removal, waste-water treatment procedures are classified as primary, secondary, and tertiary waste-water treatment as shown in Fig 2. Industrial waste-water treatment operations are treated by several methods in order to reduce the organic content and make it suitable for final disposal or reuse.

Figure 2: Waste-water treatment unit operations and methods (Aylesworth-Spink, 2009)



2.2.1. PHYSICAL TREATMENT METHODS

This involves the use of physical process for the removal of different pollutants.. These include: screening, mixing, commination, sedimentation, filtration, floatation, flow equalization and aeration (Sincero, 2003).

- SCREENING

It is one of the oldest treatment methods and it uses to remove gross pollutants from the waste stream to protect downstream equipment from damage. Screening devices may consist of parallel bars, rods or wires, grating, wire mesh, or perforated plates, to interrupt large floating or suspended material. The openings may be of any shape, but are generally circular or rectangular (Metcalf and Eddy, 2003).

- SEDIMENTATION

It is a widely used unit operation in wastewater treatment, includes the gravitational settling of heavy particles suspended in a mixture. It is used for the removal of grit, particulate matter in the primary settling basin, biological floc in the activated sludge settling basin, and chemical flow when the chemical coagulation process is used. Sedimentation takes place in a settling tank, also referred to as a clarifier. There are three main designs: horizontal flow solids contact and inclined surface (Metcalf and Eddy, 2003).

- FLOATATION

It is a unit operation used to remove solid or liquid particles from a liquid phase by introducing a fine gas, usually air bubbles. The gas bubbles either adhere to the liquid or are trapped in the particle structure of the suspended solids then raising the buoyant force of the collective particle and gas bubbles. Particles which have a higher density than the liquid can be made to rise. In waste-water treatment, flotation is used to remove suspended matter and to concentrate biological sludge. The various flotation methods are shown in table 3. while a typical flotation unit is illustrated in Fig 3. (Metcalf and Eddy, 2003).

Table 3: Flotation methods (Metcalf and Eddy, 2003)

Process	Description
Dissolved-air flotation	The injection of air while wastewater is under the pressure of several atmospheres . After a short holding time, the pressure is restored to atmospheric level, allowing the air to be released as minute bubbles.
Air flotation	The introduction of gas into the liquid phase directly by means of revolving impeller or through diffusers, at atmospheric pressure.
Vacuum flotation	The saturation of wastewater with air either directly in an aeration tank or by permitting air to enter on the suction side of a wastewater pump. A partial vacuum is applied, causing the dissolved air to come out of solution as minute bubbles which rise with the attached solids to the surface, where they form a scum blanket. The scum is removed by a skimming mechanism while the settled grit is raked to a central sump for removal.
Chemical additives	Chemicals further the flotation process by creating a surface that can easily adsorb or entrap air bubbles. Inorganic chemicals (aluminum and ferric salts and activated silica) and various organic polymers can be used for this purpose.

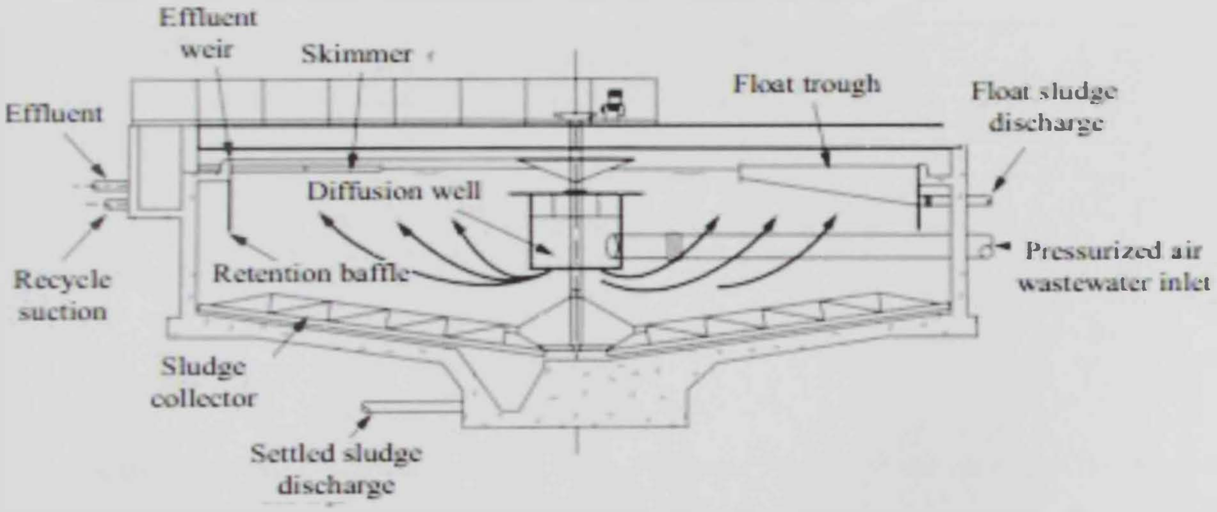


Figure 3: Typical flotation unit (Metcalf and Eddy, 2003)

2.2.2. CHEMICAL TREATMENT METHODS

Chemical processes used in wastewater treatment are designed to bring about some form of change by means of chemical reactions, where a chemical reaction or transformation takes place (Sincero, 2003). The main chemical unit processes, including chemical precipitation, adsorption, disinfection, dechlorination and other applications.

- **CHEMICAL PRECIPITATION**

Chemical coagulation encourages the flocculation of divided solids into more settleable flocs. (Table 4). The degree of clarification depends on the quantity of chemicals used. Chemical coagulants that are commonly used in waste-water treatment include alum ($Al_2(SO_4)_3.14.3\ H_2O$), ferric chloride ($FeCl_3.6H_2O$), ferric sulfate ($Fe_2(SO_4)_3$), ferrous sulfate ($FeSO_4.7H_2O$) and lime ($Ca(OH)_2$).

Organic polyelectrolytes are sometimes used as flocculation aids (Metcalf and Eddy, 2003).

Table 4: Removal efficiency of plain sedimentation vs. chemical precipitation (Metcalf and Eddy, 2003)

Parameters	Percentage removal	
	Plain sedimentations	Chemical precipitation
Total suspended solids (TSS)	40-90	60-90
BOD_5	25-40	40-70
COD		30-60
Phosphorus	5-10	70-90
Bacteria loadings	50-60	80-90

- **ADSORPTION**

It is the process of collecting soluble substances within a solution. It is aimed at removing of the remaining dissolved organic matter. Activated carbon is produced by heating char to a high temperature and then activating it by exposure to an oxidizing gas at high temperature. The internal surface area was created by developing a porous from the gas. The activated carbon can then be separated into various sizes with different adsorption capacities. The two common types of activated carbon are granular activated carbon

(GAC), which has a diameter greater than 0.1 mm (Fig. 4), and powdered activated carbon (PAC), which has a diameter of less than 200 mesh (Metcalf and Eddy, 2003).

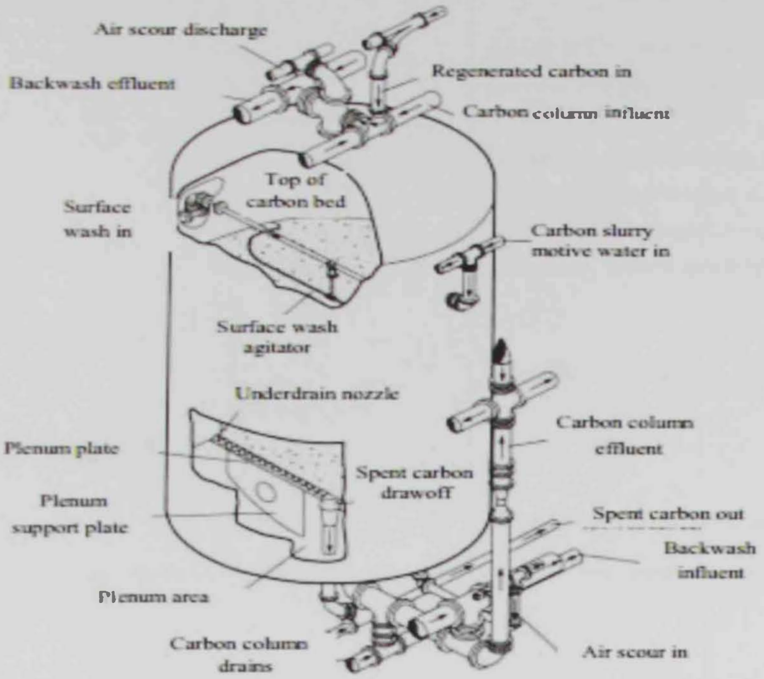


Figure 4: A typical granular activated carbon contactor (Metcalf and Eddy, 2003)

- **DISINFECTION**

It is a process where a significant percentage of pathogenic organisms are killed or controlled. A disinfection efficacy is most often measured using "indicator organisms" that coexist in high quantities where pathogens are present. The most common chemical disinfectants are the oxidizing chemicals, and of these, chlorine is the most widely used (Metcalf and Eddy, 2003).

In addition to the chemical processes described above, various other applications are occasionally encountered in waste-water treatment and disposal. Table 5 lists the most common applications and the chemicals used.

Table 5: Other chemical applications in wastewater treatment and disposal (Metcalf and Eddy, 2003)

pplication	Chemical used	Remarks
eatment		
Grease removal	Cl_2	Added before preaeration
BOD reduction	Cl_2, O_3	Oxidation of organic substances
pH control	KOH, NaOH, $Ca(OH)_2$	
Ferrous sulfate oxidation	Cl_2	Production of ferric sulfate and ferric chloride
Filter - ponding control	Cl_2	Residual at filter nozzles
Filter - fly control	Cl_2	Residual at filter nozzles, used during fly season
Sludge-bulking control	Cl_2, H_2O_2, O_3	Temporary control measure
Digester supernatant oxidation	Cl_2	
Digester and Imhoff tank foaming control	Cl_2	
Ammonia oxidation	Cl_2	Conversion of ammonia to nitrogen gas
Odour control	Cl_2, H_2O_2, O_3	
Oxidation of refractory organic compounds	O_3	
isposal		
Bacterial reduction	Cl_2, H_2O_2, O_3	Plant effluent, overflows, and stormwater
Odour control	Cl_2, H_2O_2, O_3	

2.2.3. BIOLOGICAL TREATMENT METHODS

Micro-organisms, particularly bacteria, are commonly used to convert the colloidal and dissolved carbonaceous organic matter into various gases which removed in sedimentation tanks at the end. Biological processes are used in conjunction with physical and chemical processes. The main objective of the biological treatment is reducing the organic content (measured as BOD, TOC or COD) and nutrient content (nitrogen and phosphorus) of waste-water (Metcalf and Eddy, 2003).

Biological processes used for waste-water treatment may be classified into five major headings:

- ✓ Aerobic processes (activated-sludge)
- ✓ Anoxic processes;
- ✓ Anaerobic processes;
- ✓ Combined processes;
- ✓ Pond processes.

AEROBIC PROCESSES (ACTIVATED-SLUDGE)

It is an aerobic, continuous-flow system having a mass of activated micro-organisms to stabilize the organic matter. The process consists of distributing clarified waste-water, after primary settling, into an aeration basin where it is mixed with an active mass of micro- organisms, mainly bacteria and protozoa, which aerobically degrade organic matter into carbon dioxide, water, new cells, and other end products (Metcalf and Eddy, 2003). Fig 5 shows the typical flow diagram for an activated-sludge process.

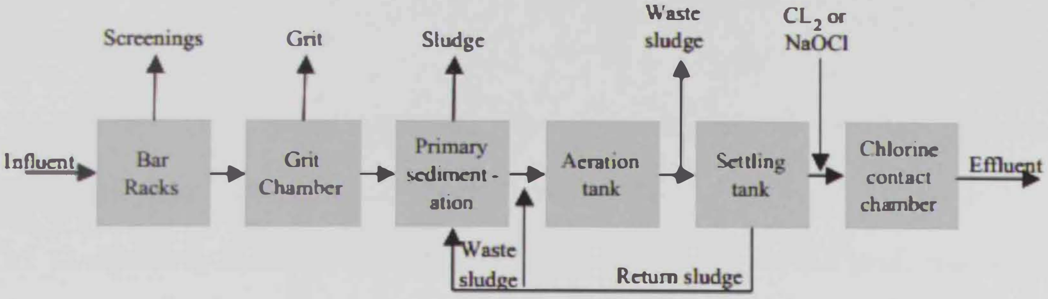


Figure 5: Typical flow diagram for an activated-sludge process (Metcalf and Eddy, 2003)

AERATED LAGOONS

An aerated lagoon is a basin between 1 and 4 meters in depth in which waste-water is treated either on a flow-through basis or with solids recycling. The microbiology involved in this process is similar to that of the activated-sludge process. However, differences arise because the large surface area of a lagoon may cause more temperature effects than are ordinarily encountered in conventional activated-sludge processes.

Waste-water is oxygenated by surface, turbine or diffused aeration. The turbulence created by aeration is used to keep the contents of the basin in suspension. Depending on the retention time, aerated lagoon effluent contains approximately one third to one half the incoming BOD value in the form of cellular mass. Most of these solids must be removed in a settling basin before final effluent discharge (Fig. 6) (Metcalf and Eddy, 2003).

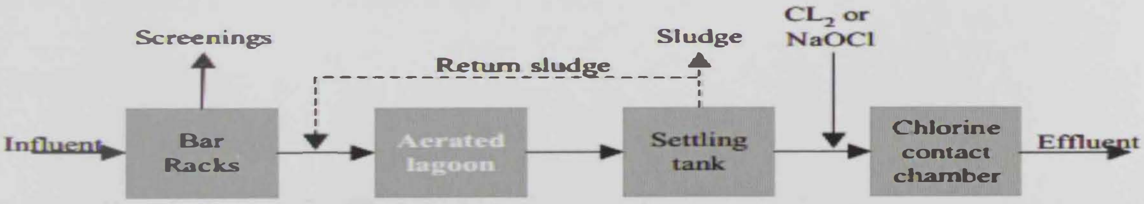


Figure 6: Typical flow diagram for aerated lagoons (Metcalf and Eddy, 2003)

2.3. ELECTROCOAGULATION PROCESS

In an electrocoagulation process, the coagulating ions are produced 'in situ' and it includes three stages: (i) materialization of coagulants by electrolytic oxidation of the 'sacrificial electrode', (ii) deterioration of the pollutants, particulate suspension, and breaking of mixtures and (iii) combination of the destabilized phases to form flocs as shown in Fig.8. The deterioration mechanisms of the contaminants, particulate suspension, and breaking of mixtures have been described in broad steps and may be abridged as follows (Mollah et al., 2004; Hasan, 2012):

- Compression of the diffuse double sheet around the charged types by the interactions of ions produced by oxidation of the sacrificial anode.
- Counter ions obtained by the electrochemical dissolution of the anode reduce the electrostatic inter-particle repulsion, therefore causing coagulation. They are used to charge neutralization of the ionic species present in wastewater. As a result of coagulation, floc is formed. It forms a blanket that absorbs colloidal particles in the aqueous substance.

In electrocoagulation, cathodes and metal anodes are used to test water. The cathode could be stainless steel or graphite, but the choice of the anode metal relies on the wastewater composition. Applied current passes through the metal electrode, and oxidizes the metal (M) to its cation (M^{n+}). Electro oxidation of the sacrificial metal anode generated *in situ* Al^{3+} metal ions, when a DC field was applied (Chen, 2004). Resulting from the oxidation of the water, hydrogen (H^+) and oxygen are usually produced at the anode. Due to the water reduction, hydrogen and hydrogen oxide (OH^-) are generated at the cathode (Abuzaid et al., 1998). Cationic monomeric species (ex: Al^{3+} and $Al(OH)_2^+$) are created by the elctrooxidation of the aluminum anode. At certain pH values, they are converted to $Al(OH)_3$ at first, and then polymerized to $Al_n(OH)_3$ according to the following reactions (Hasan, 2012):

$$Al_{(s)} \rightarrow Al_{(aq)}^{3+} + 3e^- \quad (1)$$

$$Al_{(aq)}^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H_{(aq)}^+ \quad (2)$$

$$nAl(OH)_3 \rightarrow Al_n(OH)_{3n} \quad (3)$$

Depending on the pH, substances such as $Al(OH)^{2+}$, $Al_2(OH)_2^{4+}$ and $Al(OH)_4^-$ are precipitated (Eqs 4 to 7 and Fig.7).

$$Al^{3+} + H_2O \rightarrow Al(OH)^{2+} + H^+ \quad (4)$$

$$Al(OH)^{2+} + H_2O \rightarrow Al(OH)_2^+ + H^+ \quad (5)$$

$$Al(OH)_2^+ + H_2O \rightarrow Al(OH)_3 + H^+ \quad (6)$$

$$Al(OH)_3 + H_2O \rightarrow Al(OH)_4^- + H^+ \quad (7)$$

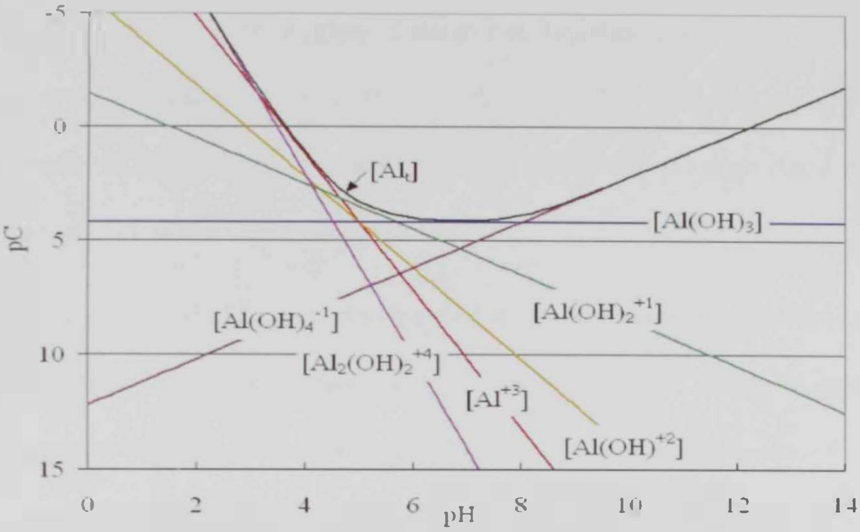


Figure 7: Aluminum solubility diagram (Hasan., 2012)

The amount of metal dissolved is proportional to the applied current density and is calculated using Faraday's law.

$$w = \frac{itM}{nF} \quad (8)$$

Where w is the quantity of electrode material dissolved (g of M/m^2), i the current density (A/cm^2), t the time in s; M the relative molar mass of the electrode concerned, n the number of electrons in oxidation/reduction reaction and F the Faraday's constant, $96{,}500 Cmol^{-1}$.

According to Vepsäläinen (2012), aluminium is more suitable electrode material than Fe(II) for electrocoagulation applications, because it produces Al(III) species. Metal ions and hydroxides produced by iron electrodes are less effective in the destabilisation of pollutants because iron electrodes produce more soluble and less charged than Fe(II) species. However, Fe(II) can be effective in sulphide removal applications. There are some parameters that affect the dissolution of the electrodes such as: Current density, treatment time, temperature and electrolysis cell construction . However, it seems that these parameters have negligible significance in the destabilization of the pollutants besides this effect. Initial pH and final pH have an effect on the dissolution of electrodes, but they also define what aluminium or iron species are formed in the solution and have an effect on the z-potential of all charged species in the solution. According to the results of the study by Vepsäläinen , 2012)., destabilisation mechanisms of pollutants are the same by electrocoagulation and chemical coagulation.

An investigation of the "removal of COD and suspended solids in wastewater treatment by combining field and elctrocoagulation technology" was carried out by Ni'am et al. (2007). Batch experiments were carried out using two monopolar iron plate as electrodes. The DC current used was between 0.5 and 0.8 A, using 30 and 50 minutes as operating times. Milk powder with an initial COD of 1,140 mg/L and suspended solids of 1,400 mg/L in acidic conditions (pH=3) was used for the preparation of the wastewater samples. In that study, the effluent was clear with turbidity of 9 NTU and 30.6 and 75.5% removal efficiency of TSS and COD respectively. The quality of the effluent was above direct discharge standards and the results proved that electrocoagulation could neutralize the pH of wastewater (Ni'am et al. 2007).

The efficiency of electrolytic treatment, electrocoagulation applied to dairy effluents, was investigated by Tchamangp et al. 2009. Solutions of milk powder were used to prepare artificial wastewater. A soluble aluminum anode was used during the experiments, generating flocs that were then separated through filtration. The results demonstrated that turbidity was reduced by a 100%, while nitrogen and phosphorus, were reduced by 81 and 89% respectively. The reduction of the chemical oxygen dem and (COD) only reached 61%. The latter could be explained by the fact that, since lactose was not fully eliminated, COD reduction was affected (Tchamango et. al 2009).

The efficiency of electrocoagulation was also examined in a study by Malkootian and Yousefi (2009) through a pilot facility, using drinking water. A reservoir with aluminum sheet electrodes, connected as monopolar, and a power supply for electrical current were used to make up the pilot plant. The system was tested at different time intervals, voltages and pH. The results demonstrated that water hardness was removed at 95.6% while the highest removal rate was achieved at pH=10.1, a 60 minute detention time and potential difference of 20 volts (Malakootian and Yousefi 2009).

Fenglian and Wang (2010) carried out a general review of the methods used to remove heavy metals from wastewater. They concluded that ion-exchange, adsorption and membrane filtration are the most frequently studied for the treatment of the removal of heavy metals from wastewater (Fenglian and Wang, 2010).

In spite of the considerable amount of literature on the use of electrocoagulation, there is still a need for further research to improve the performance of electrocoagulation processes towards developing cost-effective, environmentally friendly, and sustainable process at wide ranges of applications. Many process deficiencies can be addressed such as the lack of details on the design of an electrocoagulation reactor. Physical issues such as reactor geometry and current density play vital role in the design of an electrocoagulation reactor. For instance, the recommended current density is in the range of 10-150 A/m^2 through which high current density is applied while separation process occurs, whereas low current density is suitable with conventional sand filters. Furthermore, the operation mode, and the chemical interactions of the system have significant effects on the process performance while electrodes material, passivation, and solution pH are important chemical factors to be taken into consideration (Holt et al., 2004).

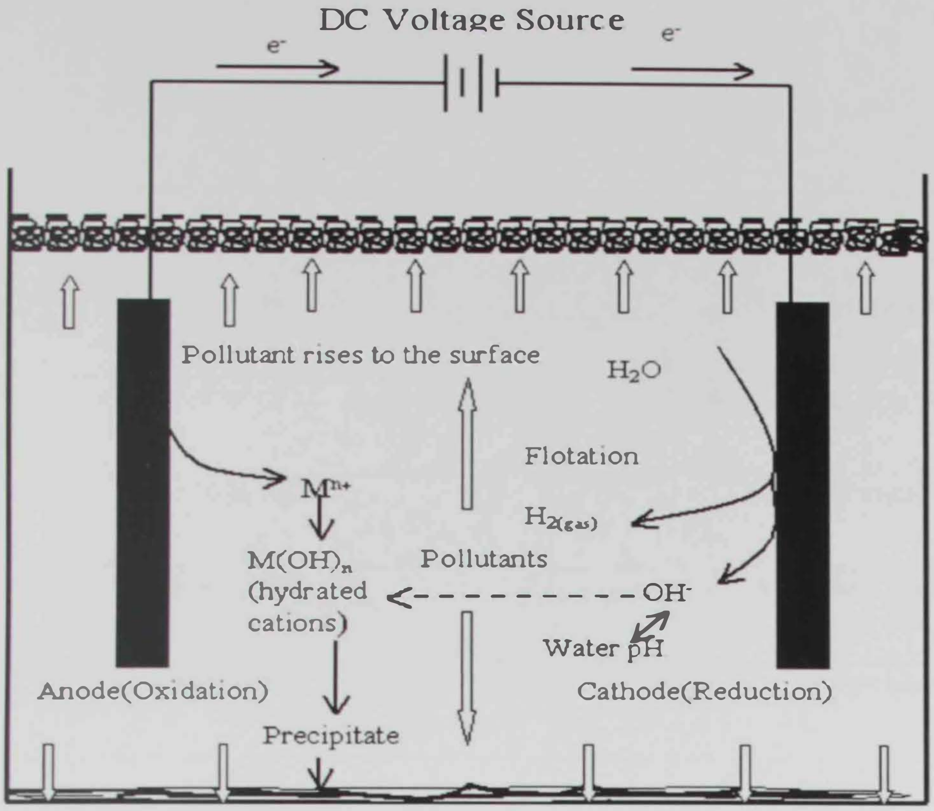


Figure 8: A schematic diagram of an electrocoagulation cell (Mollah et al., 2004)

2.3.1. Zeta potential

Zeta Potential is the potential at the shear plane of the solid/liquid interface (Cosgrove, 2010). Degree of flocculation was indicated by measuring the zeta potential. When the magnitude of Zeta Potential is high, colloids undergo stabilization. Also, when the zeta potential is low, attraction exceeds repulsion and the dispersion will break and flocculate. So, colloids with high magnitude of Zeta Potential (negative or positive) are electrically stabilized while colloids with low magnitude of Zeta Potentials have a tendency to coagulate or flocculate as shown in Table 6 (Hasan, 2011). Eq. 9 is used to calculate the Zeta Potential as a function of electrolyte viscosity, potential gradient, and permittivity of the vacuum and solvent.

Table 6: Colloids stability based on zeta potential (Astem, 1985)

Zeta Potential [mV]	**Colloid stability**
0 to ±5	Rapid coagulation or flocculation
±10 to ±30	Incipient instability
±30 to ±40	Moderate stability
±40 to ±60	Good stability
> ±61	Excellent stability

$$\zeta = \frac{3\upsilon_p\mu}{2E\,\varepsilon_0\varepsilon} \qquad (9)$$

Where ζ is the zeta potential (V); μ is electrolyte viscosity (kg/ms); ε_0 and ε are the permittivity of the vacuum and solvent respectively C2J-1m-1; E is the potential gradient applied (V/m); and υ_p is the particle velocity/mobility (m/s)

2.3.2. Carbon dioxide Capture and Storage

Carbon dioxide capture and storage is the process by which carbon dioxide emissions from power plants and other industrial facilities are captured to transport to a storage location and long-term isolation from the atmosphere. This process is being demonstrated worldwide at commercial scales, the role of carbon dioxide capture is to meet the future climate goals without any pollution. There are five guiding principles such as: protect human health and safety, protect ecosystems, protect underground sources of drinking water and other natural resources and facilitate cost-effective, timely deployment (Dooley and Wise, 2003).

Krishnaveni and Palanivelu (2013) studied the alternatives ways in worldwide for reducing the emissions of greenhouse gases, particularly carbon dioxide. The existing techniques to sequester carbon dioxide from power plants are forestation, ocean fertilization, mineral carbonation, underground injection, and direct ocean dump. Also, it was talking about the benefits of carbon dioxide products in disposal side. Carbon dioxide gas has a good value for making industrially useful carbon based products in the disposal using in chemical processing. Carbonation is capable of binding significant amount of carbon dioxide. New technologies and methods, which involve the use of the carbon dioxide in the production of carbonate materials, offer a new route to reduce the carbon dioxide concentration in the atmosphere (Krishnaveni and Palanivelu, 2013)

2.3.3. Response Surface Method

RSM is a set of techniques for developing a series of experimental designs, determining relationship between experimental factors and responses, and using these relationships for finding the optimum conditions by building a model that describes the response over the applicable ranges of the factors of interest, and it is referred to as the fitted model in many industrial applications, because the response can then be graphed as a curve in one dimension (one factor of interest) or a surface in two dimensions (two factors of interest) (Mason et al. 2003; Jo et al. 2008).

RSM is used to identify new conditions that improve product quality over that achieved by current conditions. Box-Behnken design (BBD) is a tool for multivariate optimization. It is a class of rotatable second-order designs based on three-level factorial designs. The number of experiments (N) required for the development of BBD is defined as $N=2k(k-1)+C_0$, (where k is number of factors and C_o is the number of central points). For comparison, the number of experiments for a central composite design (CCD) is $N=2k+2k+C_0$. Tables 7 and 8 contain the coded values of the factor levels for BBD on three, four and five factors, respectively. There are some advantages to use the BBD design. First, the BBD design is more efficient than the central composite design. Table 9 establishes a comparison among the efficiencies of the BBD and other response surface designs for the quadratic model. Second, it is useful in avoiding experiments performed under extreme conditions. BBD for four and five factors can be arranged in orthogonal blocks, as shown in Table 8. In this table, each (±1, ±1) combination within a row represents a full 22 designs. This orthogonal blocking is a desirable property when the experiments have to be arranged in blocks and the block effects are likely to be large (Ferreira et. al 2007).

Table 7: Coded factor levels for a Box-Behnken design of a three-variable system (S.L.C. Ferreira et. al 2007)

RunOrder	X1	X2	X3
1	-1	-1	0
2	1	-1	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
C	0	0	0
C	0	0	0
C	0	0	0

Table 8: Coded factor levels for Box-Behnken designs for optimizations involving four and five Factors (S.L.C. Ferreira et. al 2007)

Four-factor				Five-factor				
x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4	x_5
±1	±1	0	0	±1	±1	0	0	0
0	0	±1	±1	0	0	±1	±1	0
0	0	0	0	0	±1	0	0	±1
				±1	0	±1	0	0
±1	0	0	±1	0	0	0	±1	±1
0	±1	±1	0	0	0	0	0	0
0	0	0	0					
				-				
				0	±1	±1	0	0
±1	0	±1	0	±1	0	0	±1	0
0	±1	0	±1	0	0	±1	0	±1
0	0	0	0	±1	0	0	0	±1
				0	±1	0	±1	0
				0	0	0	0	0

Table 9: Comparison of - efficiency of central composite design (CCD). Box-Behnken design (BBD) and Doehlert design (DM) (Ferreira et. al 2007)

Factors (k)	Number of coefficients (p)	Number of experiments (f)			Efficiency (p/f)		
		CCD	DM	BBD	CCD	DM	BBD
2	6	9	7	–	0.67	0.86	–
3	10	15	13	13	0.67	0.77	0.77
4	15	25	21	25	0.60	0.71	0.60
5	21	43	31	41	0.49	0.68	0.61
6	28	77	43	61	0.36	0.65	0.46
7	36	143	57	85	0.25	0.63	0.42
8	45	273	73	113	0.16	0.62	0.40

2.4. ELECTROCOAGULATION APPLICATIONS

- **Ground Water Cleanup**

Electrocoagulation is suitable for the reclamation of groundwater that has been contaminated with heavy metals, high molecular weight hydrocarbons and Halogenated hydrocarbons (Mollah et al., 2004).

- **Surface Water Cleanup**

Electrocoagulation is used to remove bacteria, viruses and cysts from surface water, thereby representation contaminated waste streams into potable water. It is particularly effective in the removal of life threatening contaminants such as giardia and cryptosporidium (Mollah et al., 2004).

- **Process Rinse Water and Wash Water**

Electrocoagulation routinely treats process and rinse water from the electroplating, computer board manufactures, textile industry, paint rinse water, mining industry, automotive industry and pulp and paper. In most cases, the treated water can be recycled (Mollah et al., 2004).

- **Sewage Treatment**

Electrocoagulation has recognized effective in treating sewage water, sewage sludge concentrations, and sewage sludge metal fixation sufficiently to enable land application (Mollah et al., 2004).

- **Cooling Towers**

Electrocoagulation is used to pre-treat water entering towers as well as blow down water to remove algae, suspended solids, calcium, and magnesium buildup, thereby eliminating costly replacement water (Mollah et al., 2004).

- **Water Pretreatment**

Water pretreatment with Electrocoagulation has proven effective in removing bacteria, silica and TSS prior to subsequent polishing with reverse osmosis, nanofiltration, and photocatalytics (Mollah et al., 2004).

2.5. ADVANTAGES AND DISADVANTAGES OF ELECTROCOAGULATION PROCESS

Electrocoagulation treatment of wastewater has many advantages and disadvantages as shown in Table 10.

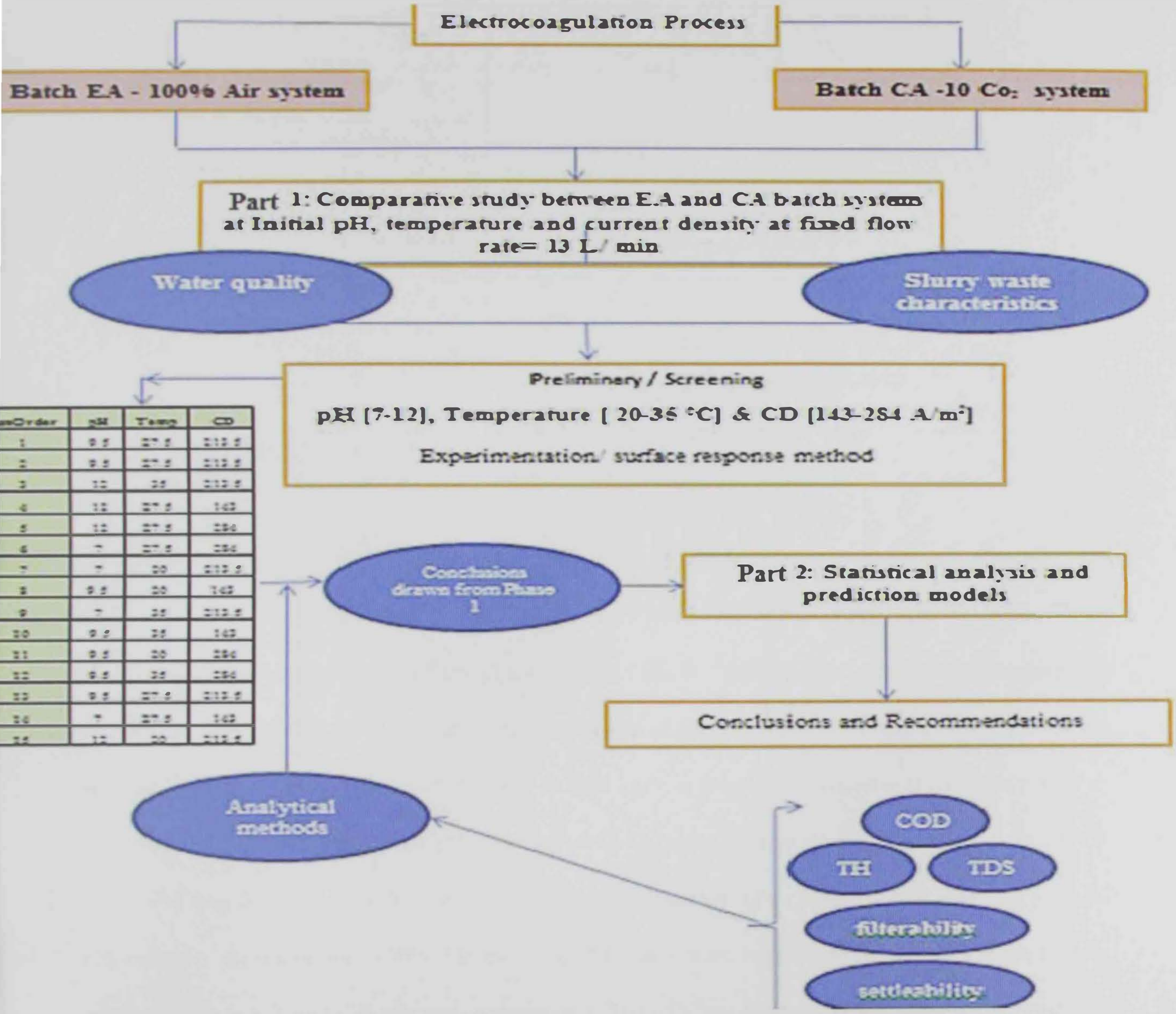
Table 10. Advantages and disadvantages of an Electrocoagulation Process (Mollah et al., 2004).

dvantages	• Removes suspended, colloidal solids, fats, oil, and grease • Breaks oil emulsions in water • Removes complex organics, bacteria, viruses and cysts • Low operating costs, maintenance and power requirements • Minimal chemical additions • Sludge minimization
sadvantages	• The 'sacrificial electrodes' are dissolved into wastewater streams as a result of oxidation, and need to be regularly replaced. • The use of electricity may be expensive in many places. • An impermeable oxide film may be formed on the cathode leading to loss of efficiency of the Electrocoagulation unit. • High conductivity of the wastewater suspension is required. • Gelatinous hydroxide may tend to solubilize in some cases

CHAPTER THREE: MATERIALS AND METHODOLOGY

To achieve the aforementioned objectives, this thesis was divided into two parts as shown in Fig.9:

- Part 1: Batch EA - Pure Air and CA -10% CO_2 systems
- Part 2: Statistical approach/analysis



nOrder	pH	Temp	CD
1	9.5	27.5	213.5
2	9.5	27.5	213.5
3	12	35	213.5
4	12	27.5	143
5	12	27.5	284
6	7	27.5	284
7	7	20	213.5
8	9.5	20	143
9	7	35	213.5
10	9.5	35	143
11	9.5	20	284
12	9.5	35	284
13	9.5	27.5	213.5
14	7	27.5	143
15	12	20	213.5

Figure 9: Research Methodology

3.1. WASTEWATER SAMPLES

The wastewater samples were collected from the Emirates Industrial Gases Co. (EIGCO) which is located in Dubai, UAE. The physical-chemical characteristics of the industrial wastewater are shown in Table 11.

Table 11: Characteristics of wastewater collected from EIGCO

pH	12 - 12.2
COD (mg/l)	300 – 350
EC (ms/cm)	5 – 6
TDS (g/l)	2.5 - 3.5
TH (mg/l as caco$_3$)	1000 – 1200
Salinity (%)	3 - 3.5
TSS (g/l)	1 – 2

3.2. EXPERIMENTAL APPARATUS

Preliminary experiments were prepared to determine the ranges of pH, temperature and current density as [7-12], [20-35], [143-284 A/m^2], respectively. The Electrocoagulation experiments were conducted in 2 L cylindrical reactor made of Plexiglas having an effective volume of 1 L and an internal diameter of 14.5 cm. Two aluminum electrodes with dimensions of 6x5x3 mm that are spaced apart by 5.5 cm were immersed in the reactor and connected to a DC power supply. A magnetic stirrer was placed at the bottom of the reactor to ensure good mixing while adjusting the mixing speed so as not to break the flocs. The best duration of each experiment was 3 hours because any additional time will give same % reduction for all responses. 100% Air and 10% CO$_2$ gases were injected from the top and the bottom of the reactor in EA and CA systems, respectively. The CO$_2$ gas leaving the CA system was analysed using the gas analyzer (California Analytical Instruments - CAI). Samples of 15 ml were collected using a pipette in every 60 min and filtered using Schleicher & Schuell- MicroScience filter paper circles No.595 (185 mm) to obtain the COD and TH measurements using HACH vials/HACH DR-3000 spectrophotometer and solution titration using ammonium hydroxide and silver chloride, respectively. TSS after treatment was analyzed via drying at 105°C for 2 hours according to standard methods (APHA, 1998). TDS, salinity, pH, and electrical conductivity were measured using the HACH meter (MODEL HQ11d and HQ14d), respectively. Filterability test was conducted through allowing 50 ml of treated water to pass through the Schleicher and Schuell- MicroScience filter paper circles No.595 (185 mm) while recording the volume of filtrate every min as shown in Fig. 12. Settleability test was carried out by allowing the 50 ml of the slurry waste to settle over 90 min as shown in Fig 13. Samples were tested twice and an average value was recorded. After the treatment of wastewater, samples were analyzed for each parameter; consequently more than 500 samples were tested. Repeating all the sample tests would have required an excessive number of sample vials, test kits and storage space. Nevertheless, in the interest of maintaining a high level of reliability, samples that did not fit within a certain trend were repeated; and at least 3 samples were repeated for each parameter. Both electrodes were cleaned at the beginning of each experiment.

Figure 10: Laboratory filterability test

Figure 11: Laboratory settling test

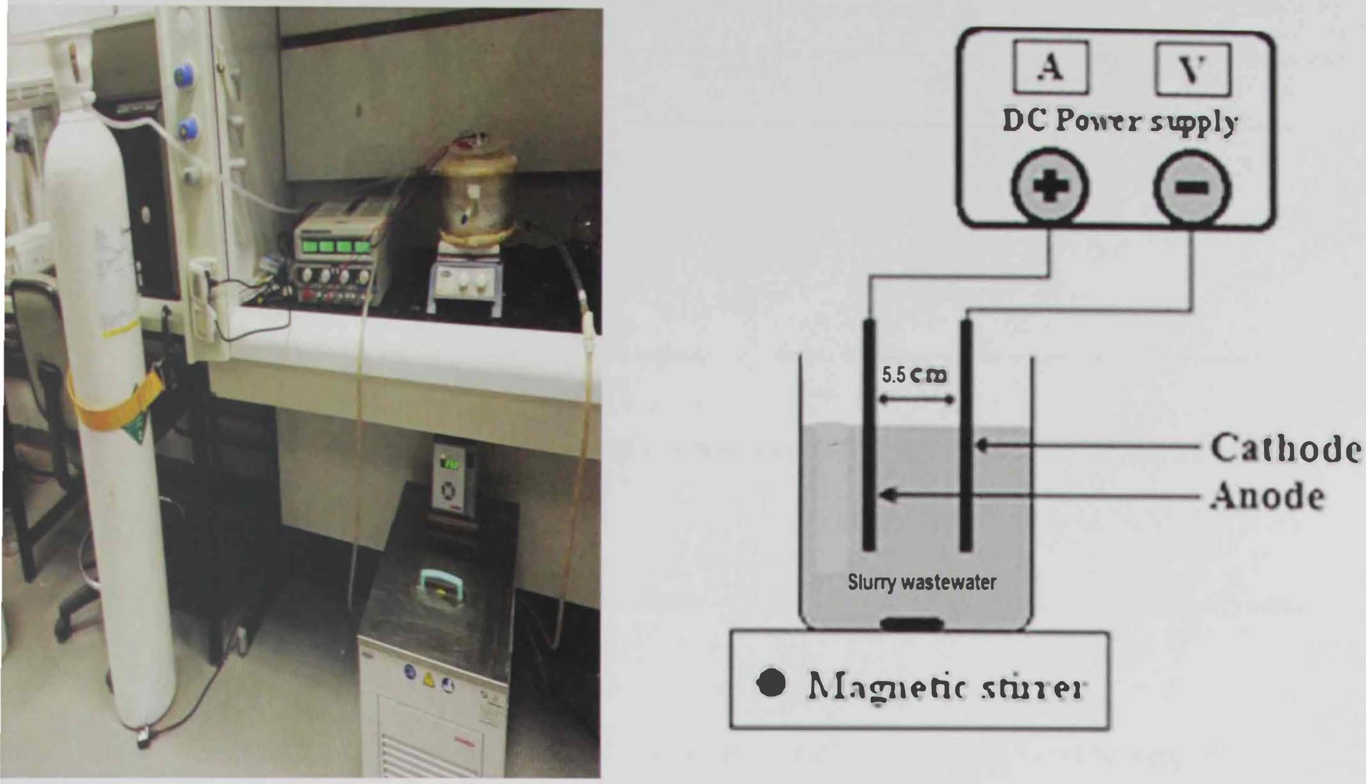


Figure 12: Lab schematic diagram of the experimental reactor used in electrocoagulation

3.3. STATISTICAL ANALYSIS

Box-Behnken design (BBD), which is a class of rotatable or nearly rotatable second-order design based on three-level incomplete factorial design, was used to design the model. The three most important operating factors (initial wastewater pH (x1), temperature (x2) and current density (x3)) were optimized for the treatment of the wastewater. The range of pH, temperature and current density variations were between 7 to 12, 20 to 35 °C, and 143 to 284 A/m^2, respectively as shown in Table 12.

Table 12: Range and level of independent variables

Independent variable	**Symbol**	**Level**		
		-1	**0**	**+1**
pH	X1	7	9.5	12
Temperature (°C)	X2	20	27.5	35
CD (A/m^2)	X3	143	213	284

The number of experiments (N) required for the development of BBD is defined as $N=2k(k-1)+C0$, (where k is number of factors and Co is the number of central points) (S.L.C. Ferreira et. al 2007).

The prediction of the % reduction of each variable were studied and calculated using RSM estimated Regression Coefficients.

The supernatant for COD measurement was measured by taking samples of 15 ml between electrodes using a pipette every 60 min and filtered using Schleicher and Schuell- MicroScience filter paper circles No.595 (185 mm) and using HACH vials/HACH DR-3000 spectrophotometer. For TH measurements, solution titration using ammonium hydroxide and silver chloride were used. TDS, salinity, pH, and electrical conductivity were measured using the HACH meter (MODEL HQ11d and HQ14d), respectively.

In the EA system, the average percentage error between the experimental and prediction reduction for these parameters COD, TH, EC, pH, TDS and Salinity were 3.5%, 5.6%, 6.5%, 4.5%, 5.9% and 5.4%, respectively. In the CA system, the average percentage error between the experimental and prediction reduction for these parameters COD, TH, EC, pH, TDS and Salinity were 5.4%, 5.5%, 3.4%, 2.9%, 3.9 % and 3.2%, respectively.

3.4. SOFTWARE USED

Three software programs were used:

3.4.1. Sigma Plot

"Sigma Plot is an industry leader in Scientific Graphing with over 300,000 users from research institutes, universities, and commercial laboratories worldwide". It used to plot and customize every detail of charts and graphs (http://www.sigmaplot.com).

3.4.2. Graph

"A potentially invaluable tool for math students or engineers, this tightly focused program draws and analyzes two dimensional graphs". Graph software used to find the area under the curve to estimate the CO_2 capturing efficiency. (http://download.cnet.com).

3.4.3. Minitab

"Minitab is the leading statistical software for analyzing data and in statistics education to discover the relationships between variables, to identify important variables" by building the model using response surface method and to find optimum condition settings with response optimizer" (www.wikipedia.com).

CHAPTER FOUR: RESULTS AND DISCUSSIONS

The efficiency of electrocoagulation treatment in part 1 was evaluated based on the reduction of six main parameters: COD, TH, TDS, EC, and Salinity. The Carbon Dioxide capturing efficiency at different operating conditions was also calculated.

The % reduction was calculated using the following equation:

% Reduction = (Initial value – Final value) / Initial value

As mentioned in the methodology chapter, the Minitab software was used to build a model by using the response surface method (RSM) as shown in Table 13 to check the optimum conditions for the best performance of the Electrocoagulation process.

Table 13: SRM model

Run Order	pH	Temp	CD
1	9.5	27.5	213.5
2	9.5	27.5	213.5
3	12	35	213.5
4	12	27.5	143
5	12	27.5	284
6	7	27.5	284
7	7	20	213.5
8	9.5	20	143
9	7	35	213.5
10	9.5	35	143
11	9.5	20	284
12	9.5	35	284
13	9.5	27.5	213.5
14	7	27.5	143
15	12	20	213.5

4.1. PARAMETRIC STUDY

Preliminary experiments were carried out to determine the ranges of pH, temperature and current density as (7-12), (20-35), (143-284 A/m^2), respectively. Series of laboratory scale experiments were conducted using the batch electrochemical reactors fed with industrial raw wastewater based on the same initial pH. Two aluminum electrodes were immersed in the reactors and connected to DC power supply. Pure Air and 10% CO_2 in Air were supplied to the reactors to ensure good mixing. Several experiments were carried out at different operating conditions so as to compare the electrochemical reactors' performance with respect to COD, TH, TDS, salinity and EC reduction in EA and CA systems. Detailed descriptions are provided in the subsequent sections as follow:

Run Order 1, 2 and 13: Water quality and slurry characteristics at pH 9.5, temperature 27.5 °C and current density 213.5 A/m^2 in EA and CA batch systems

The electrochemical EA and CA systems were fed with industrial raw wastewater (Table 14).

Table 14: Industrial feed wastewater characteristics for Run Orders 1, 2 and 13

Contaminant	Feed	Treated CA system	Treated EA system
COD, mg/L	272	212.4	181.4
TDS, g/L	1.8	1.4	1.2
TH, mg/L as $CaCO_3$	600	371	409
pH	9.5	6.8	7.6
EC, ms/cm	3.4	2.5	2.3
Salinity, %	1.8	1.3	1.2

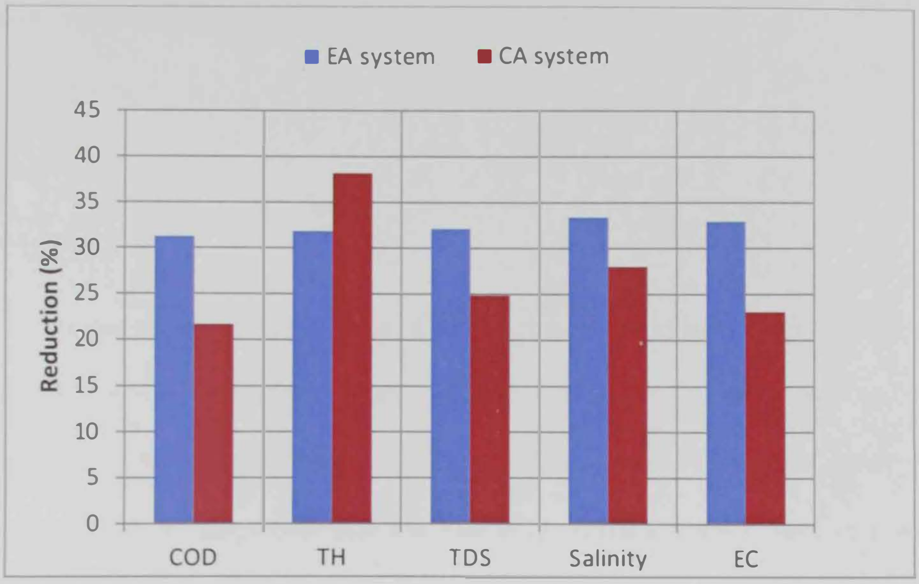


Figure 13: % Reduction of COD, TH, TDS and salinity in the treated wastewater (RO 1) in EA and CA batch systems

Fig.13 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 9.5, Temperature of 27.5 oC and current density of 213.5 A/m^2. For example, the %COD reduction was 21.9 and 31.3% in CA and EA systems, respectively. TH was reduced by 31.8 and 38.2% while 32.1 and 24.9% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 33.4 and 28.1% with effluent 1.2 and 1.3% in EA and CA systems, respectively. pH was reduced to 7.6 and 6.8 due to the formation of carbonic acid (Eq.9) whereas EC dropped to 2.3 and 2.5 ms/cm in EA and CA systems, respectively.

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \qquad (9)$$

It could be concluded that the use of CO_2 had a positive impact on water quality with respect to TH and the pure air with respect to COD, EC, TDS and salinity. This could be attributed not only to the presence of electric field (i.e. anodic electro-oxidation resulting in more available insoluble compounds which could be adsorbed in the Al $(OH)_3$ flocs and hence to be removed Al^{+3} (Ramesh et al., 2007), but also to the formation of the carbonic acid (Eq.9), thus, both Mg^{+2} and Ca^{+2} ions have reacted with CO^{-3} forming calcium carbonate and magnesium carbonate (Eqs 11 and 12).

$$HCO_3 + OH^- \rightarrow CO_3^{-2} + H_2O \tag{10}$$

$$CO_3^{-2} + Ca^{+2} \text{–>} CaCO_3 \tag{11}$$

$$CO_3^{-2} + Mg^{+2} \rightarrow MgCO_3 \tag{12}$$

Therefore, the deposition on the surface of the electrodes could likely be occurring (Malakootian and Yousefi, 2009). These results were in line with the pH reduction in the CA system compared to the pH variation across EA system. On the other hand, EA system showed better results regarding salinity reduction. It could be speculated that the solubility of the inorganic ions and salts was adversely affected at low pH (i.e. CA system) . Consequently, the injection of CO_2 has resulted in 62.4% removal (i.e. Capturing) Fig.14, therefore, contributing to the green and sustainable wastewater treatment technology.

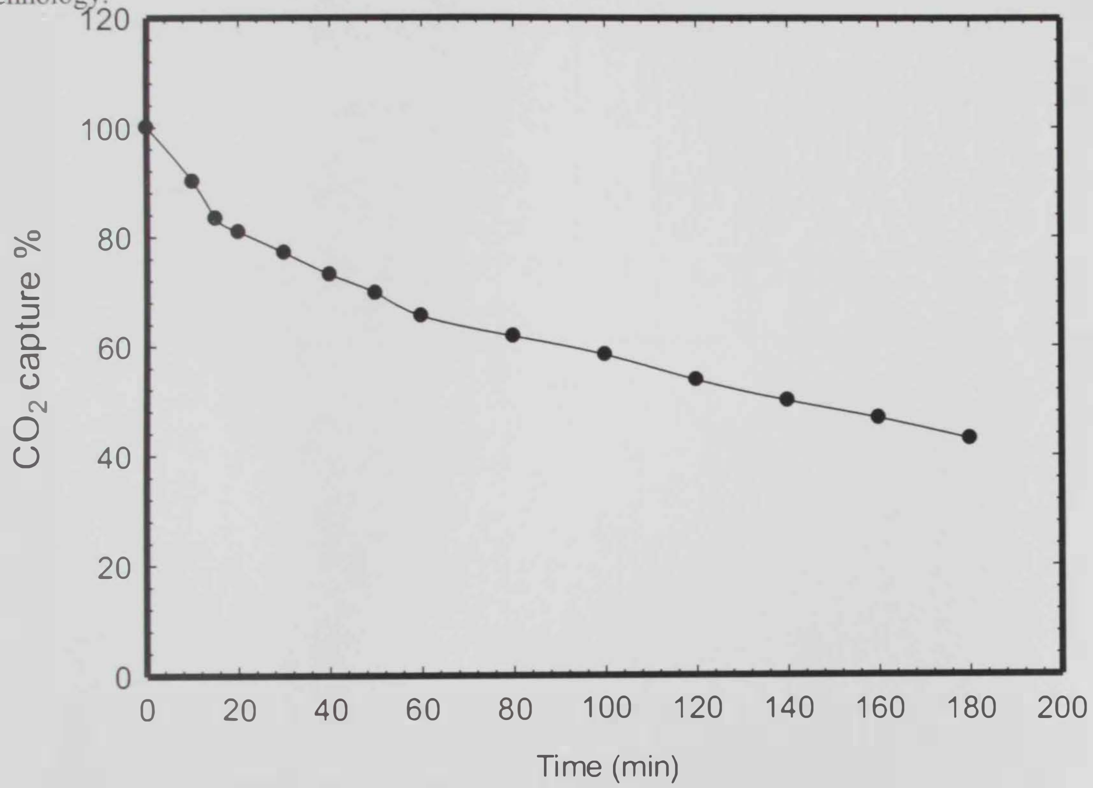


Figure 14: CO_2 variation in CA system at pH 9.5, Temperature 27.5 °C and current density 213.5 A/m^2

Run Orders 3, 4, 5 and 15: Water quality and slurry characteristics at pH 12, temperatures 35, 27.5, 27.5 and 20 °C, respectively and current densities 213.5, 143, 284, 213.5 A/m^2, respectively in EA and CA batch systems. The electrochemical EA and CA systems were fed with industrial raw wastewater (Table 15).

Table 15: Industrial feed wastewater characteristics for Run Orders 3, 4, 5 and 15

Contaminant	RO. 3 Feed	RO. 3 Treated		RO. 4 Feed	RO. 4 Treated		RO. 5 Feed	RO. 5 Treated		RO. 15 Feed	RO. 15 Treated	
		CA	EA		CA	EA		CA	EA		CA	EA
COD, mg/L	303	178	202	400	261	217	345	258	205	323	244	242
TDS, g/L	3.68	0.96	1.6	2.6	1.3	1.5	4.25	1.2	1.2	3.07	1.16	1.8
TH, mg/L as $CaCO_3$	1200	564	626	1175	787	899	1050	263	696	1400	560	896
pH	12.09	7.06	10.6	11.9	6.1	7.6	12.2	7.2	10.6	11.98	6.7	9.3
EC, ms/cm	6.89	1.9	3.2	5.09	2.6	3.1	7.8	2.3	2.3	5.9	2.3	3.5
Salinity, %	3.79	0.97	1.78	2.8	1.4	1.8	4.4	1.2	2.7	3.15	1.2	1.9

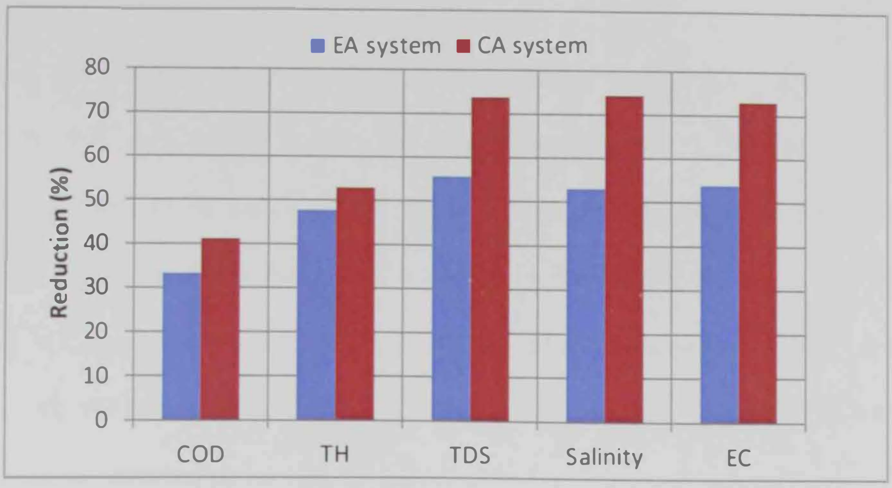


Figure 15: % Reduction of COD, TH, TDS, EC and salinity in treated effluent (RO3) in EA and CA batch systems

Fig. 15 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 12, Temperature 35 °C and current density 213.5 A/m^2. For example, the %COD reduction was 33.26 and 41.16 % in EA and CA systems, respectively. TH was reduced by 47.75 and 52.94% while 55.67 and 73.84% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 53.01 and 74.39% with effluent 1.78 and 0.97 % in EA and CA systems, respectively. pH was reduced to 10.6 and 7.06 whereas EC dropped to 3.2 and 1.9 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 51% removal (i.e. Capturing) Fig.77, therefore, contributing to the green and sustainable wastewater treatment technolog

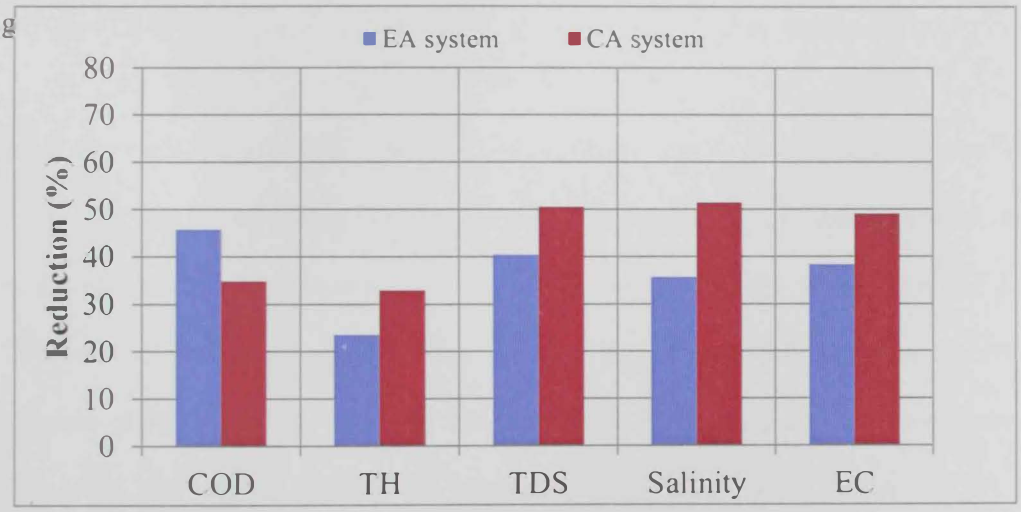


Figure 16: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO4) in EA and CA batch systems

Fig 16 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 12, Temperature 27.5 °C and current density 143 A/m^2. For example, the %COD reduction was 45.76 (CODtreated effluent 216.96 mg/L) and 34.82% (CODtreated effluent 260.72 mg/L) in EA and CA systems, respectively. TH was reduced by 23.52 and 32.88% while 40.38 and 50.55% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 35.72 and 51.45% with effluent 1.8 and 1.36% in EA and CA systems, respectively. pH was reduced to 7.6 and 6.1 whereas EC dropped to 3.1 and 2.6 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO2 has resulted in 55% removal (i.e. Capturing) Fig.78, therefore, contributing to the green and sustainable wastewater treatment technology.

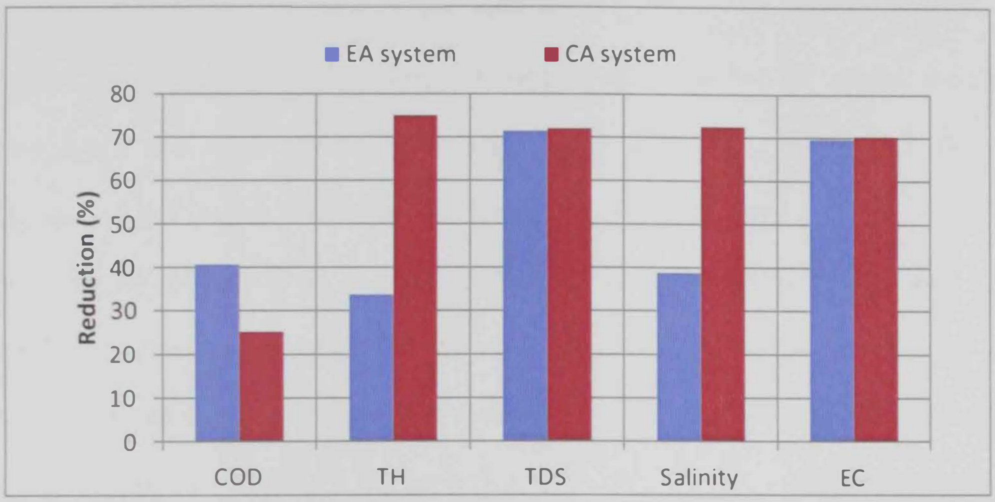


Figure 17: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO5) in EA and CA batch systems

Fig.17 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 12, Temperature 27.5 °C and current density 284 A/m^2. For example, the %COD reduction was 40.64 and 25.25% in EA and CA systems, respectively. TH was reduced by 33.71 and 75% while 71.41 and 71.99% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 38.72 and 72.5% with effluent 2.7 and 1.2% in EA and CA systems, respectively. pH was reduced to 10.6 and 7.2 whereas EC dropped to 2.3 and 2.3 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 33% removal (i.e. Capturing) Fig.79, therefore, contributing to the green and sustainable wastewater treatment technology.

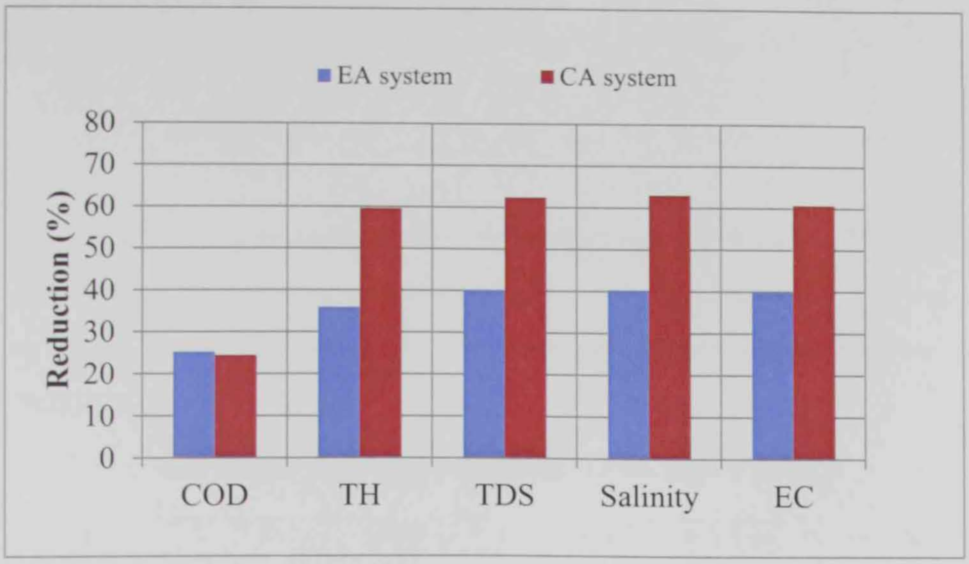


Figure 18: % Reduction of COD, TH, TDS, EC and salinity in treated effluent (RO15) in EA and CA batch systems

Fig 18 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 12, Temperature 20 °C and current density 213.5 A/m^2. For example, the %COD reduction was 25.21 ($COD_{treated\ effluent}$ 241.6 mg/L) and 24.38% ($COD_{treated\ effluent}$ 244.3 mg/L) in EA and CA systems, respectively. TH was reduced by 35.84 and 59.57% while 40.1 and 62.34% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 40.41 and 63.02% with effluent 1.9 and 1.2% in EA and CA systems, respectively. pH was reduced to 9.3 and 6.7 whereas EC dropped to 3.5 and 2.3 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 23 % removal (i.e. Capturing) Fig.80, therefore, contributing to the green and sustainable wastewater treatment technology.

Run Orders 6, 7, 9, 14: Water quality and slurry characteristics at pH 7, temperatures 27.5, 20, 35 and 27.5 °C, respectively and current densities 284, 213.5, 213.5 and 143 A/m^2 respectively in EA and CA batch systems. The electrochemical EA and CA systems were fed with industrial raw wastewater (Table16).

Table 16: Industrial feed wastewater characteristics for Run Orders 6, 7, 9 and 14

Contaminant	RO.6 Feed	RO.6 Treated		RO.7 Feed	RO.7 Treated		RO.9 Feed	RO.9 Treated		RO.14 Feed	RO.14 Treated	
		CA	EA		CA	EA		CA	EA		CA	EA
COD, mg/L	297	229	191	266	210	216	269	212	210	319	266	180
TDS, g/L	1.7	1.1	1.5	1.8	1.1	1.6	1.9	1.2	1.86	1.85	1.4	1.6
TH, mg/L as $CaCO_3$	740	562	651	720	597	590	1090	774	752	1080	724	950
pH	7.1	5.4	7.5	7.08	5	8.4	7	5.7	7.8	7.3	5.9	8.1
EC, ms/cm	3.3	2.2	2.9	3.6	2.3	3.2	3.6	2.3	3.4	3.6	2.8	3.1
Salinity, %	1.7	1.1	1.6	1.9	1.2	1.6	1.9	1.2	1.7	2	1.5	1.9

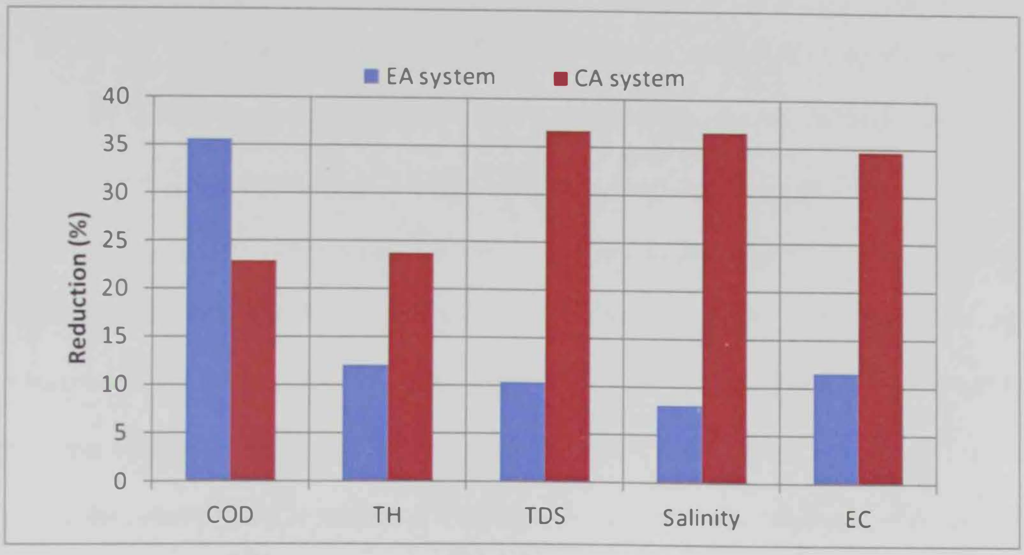


Figure 19: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO6) in EA and CA batch systems

Fig 19 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 7, Temperature 27.5 °C and current density 284 A/m^2. For example, the %COD reduction was 35.59 and 22.89% in EA and CA systems, respectively. TH was reduced by 12.06 and 23.77% while 10.34 and 36.69% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 8.08 and 36.62% with effluent 1.6 and 1.1% in EA and CA systems, respectively. pH was increased to 7.5 and reduced to 5.4 whereas EC dropped to 2.9 and 2.2 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 62 % removal (i.e. Capturing) Fig 81, therefore, contributing to the green and sustainable wastewater treatment technology.

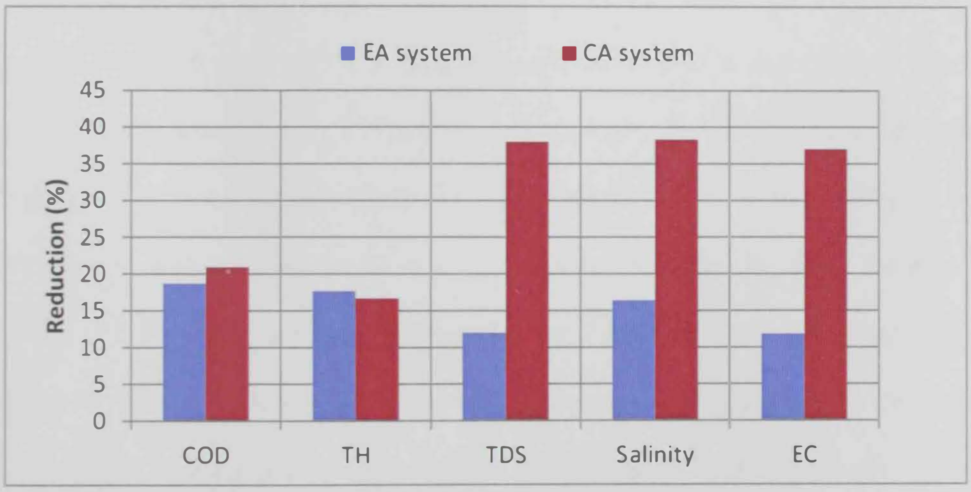


Figure 20: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO7) in EA and CA batch systems

Fig. 20 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 7, Temperature 20 °C and current density 213.5 A/m^2. For example, the %COD reduction was 18.68 and 20.96% in EA and CA systems, respectively. TH was reduced by 17.69 and 16.67% while 12.01 and 37.99% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 16.39 and 38.3% with effluent 1.6 and 1.2% in EA and CA systems, respectively. pH was increased to 8.4 and reduced to 5.03 whereas EC dropped to 3.2 and 2.3 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 65 % removal (i.e. Capturing) Fig. 82 therefore, contributing to the green and sustainable wastewater treatment technology.

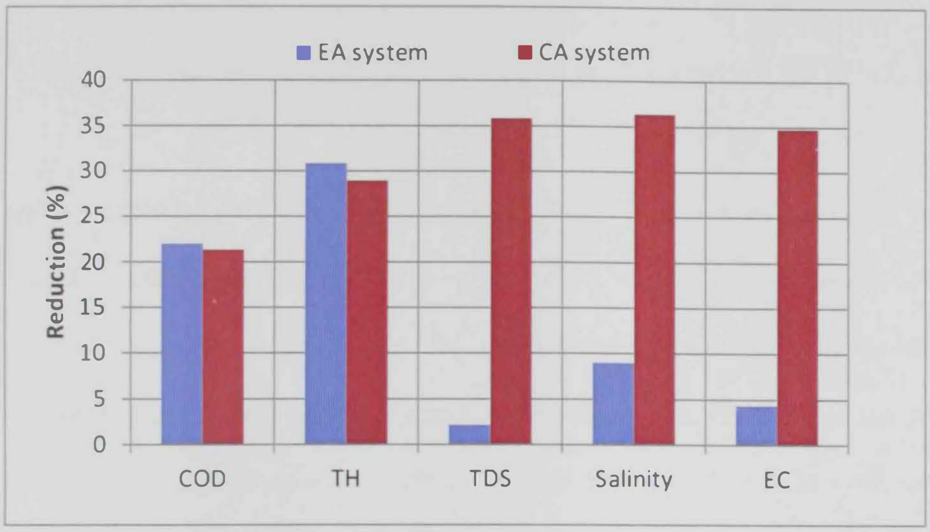


Figure 21: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO9) in EA and CA batch systems

Fig.21 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 7, Temperature 35 °C and current density 213.5 A/m^2. For example, the %COD reduction was 21.98 and 21.33% in EA and CA systems, respectively. TH was reduced by 30.86 and 28.9% while 2.09 and 35.83% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 8.97 and 36.36% with effluent 1.7 and 1.2% in EA and CA systems, respectively. pH was increased to 7.8 and reduced to 5.7 whereas EC dropped to 3.4 and 2.3 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 65 % removal (i.e. Capturing) Fig. 83, therefore, contributing to the green and sustainable wastewater treatment technology.

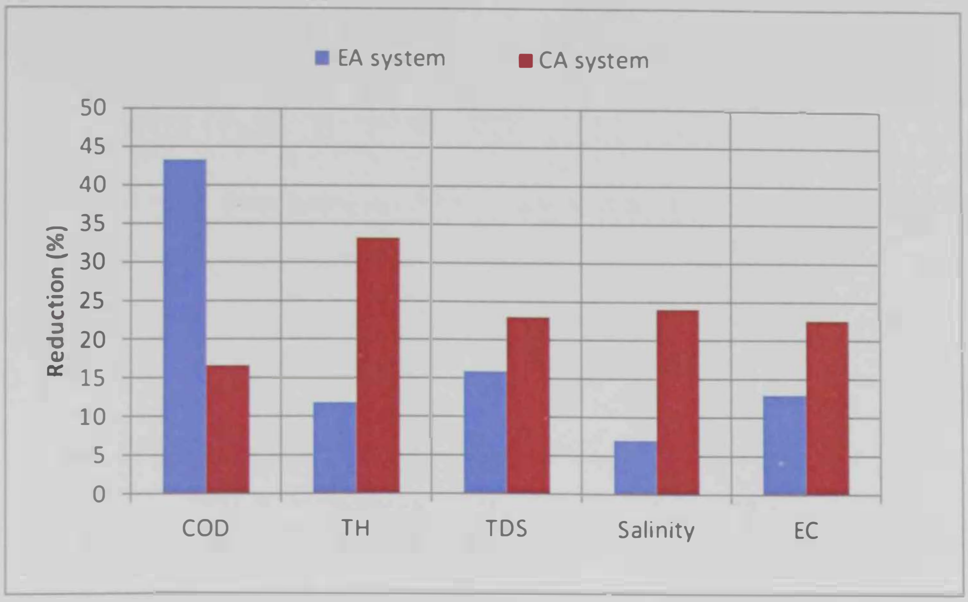


Figure 22: % Reduction in of COD, TH, TDS, EC and salinity treated wastewater (RO14) in EA and CA batch systems

Fig.30 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 7, Temperature 27.5 °C and current density 143 A/m^2. For example, the %COD reduction was 43.32 and 16.61% in EA and CA systems, respectively. TH was reduced by 11.81 and 33.21% while 15.93 and 23.01% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 7.01 and 24.08% with effluent 1.9 and 1.5% in EA and CA systems, respectively. pH was increased to 8.1 and reduced to 5.9 whereas EC dropped to 3.1 and 2.8 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 53 % removal (i.e. Capturing) Fig.84, therefore, contributing to the green and sustainable wastewater treatment technology.

Run Orders 8, 10, 11 & 12: Water quality and slurry characteristics at pH 9.5, temperatures 20, 35, 20 and 35 °C, respectively and current densities 143, 143, 285 and 284 A/m^2 ,respectively in EA and CA batch systems. The electrochemical EA and CA systems were fed with industrial raw wastewater (Table 17).

Table 17: Industrial feed wastewater characteristics for RunOrders 8, 10, 11 and 12

Contaminant	**RO. 8 Feed**	**RO. 8 Treated**		**RO. 10 Feed**	**RO. 10 Treated**		**RO. 11 Feed**	**RO. 11 Treated**		**RO. 12 Feed**	**RO. 12 Treated**	
		CA	**EA**		**CA**	**EA**		**CA**	**EA**		**CA**	**EA**
COD, mg/L	307	236	179	325	216	171	309	231	213	368	280	203
TDS, g/L	1.8	1.4	1.7	1.7	1.27	1.6	2.02	1.3	1.7	1.8	1.17	1.46
TH, mg/L as $CaCO_3$	730	606	657	845	769	659	1055	847	838	1010	566	788
pH	9.58	5.7	7.9	9.61	6.1	7.9	9.5	5.1	8.5	9.6	5.5	8.6
EC, ms/cm	3.5	2.7	3.4	3.3	2.5	3.1	3.9	2.5	3.3	3.95	2.6	3.2
Salinity, %	1.8	1.4	1.6	1.7	1.3	1.5	2.1	1.4	1.96	2.09	1.3	1.8

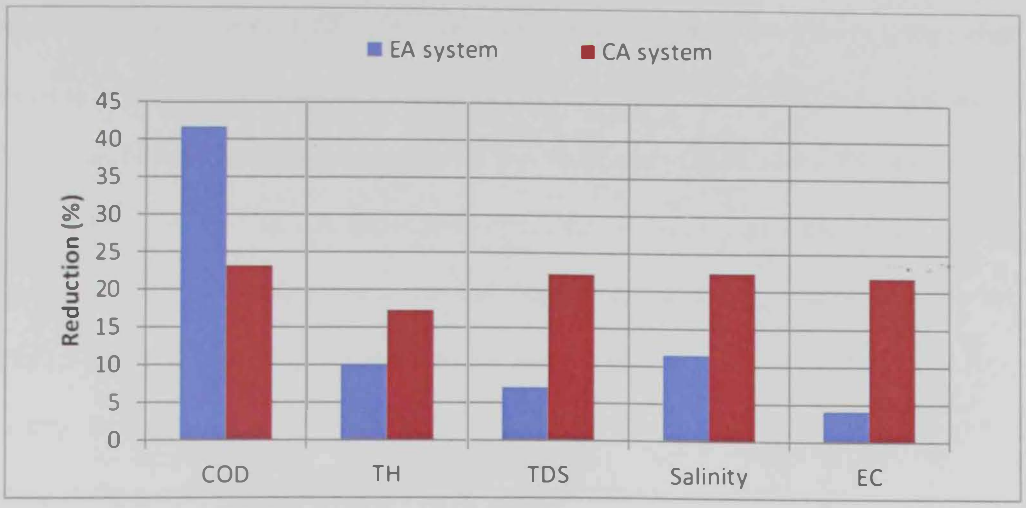


Figure 23: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO8) in EA and CA batch systems

Fig.23 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 9.5, Temperature 20 oC and current density 143 A/m2. For example, the %COD reduction was 41.64 and 23.17% in EA and CA systems, respectively. TH was reduced by 10.08 and 17.29% while 7.06 and 22.19% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 11.47 and 22.44% with effluent 1.6 and 1.4% in EA and CA systems, respectively. pH was reduced to 7.9 and 5.7 whereas EC dropped to 3.4 and 2.7 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 23 % removal (i.e. Capturing) Fig.85, therefore, contributing to the green and sustainable wastewater treatment technology.

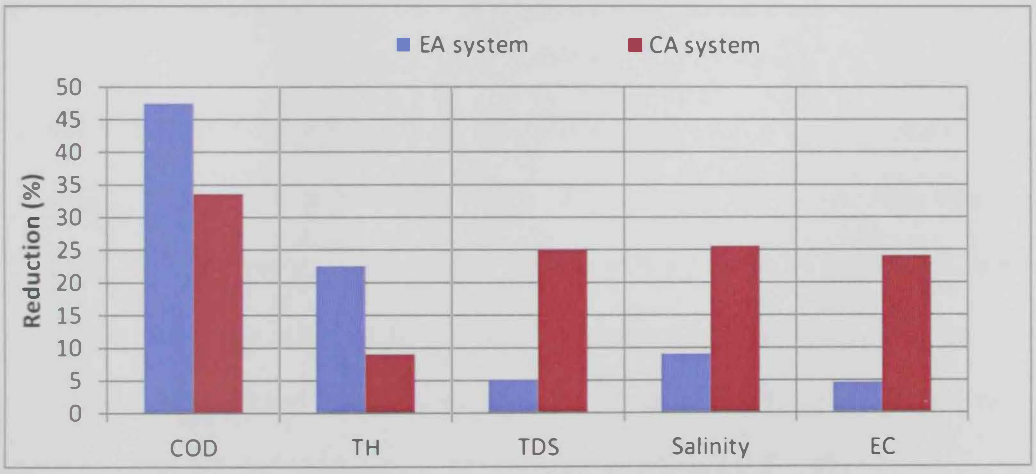


Figure 24: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO 10) in EA and CA batch systems

Fig.24 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 9.5, Temperature 35 °C and current density 143 A/m^2. For example, the %COD reduction was 47.47 and 33.61% in EA and CA systems, respectively. TH was reduced by 22.56 and 9.07% while 5.17 and 25% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 9 and 25.55% with effluent 1.5 and 1.3% in EA and CA systems, respectively. pH was reduced to 7.9 and 6.1 whereas EC dropped to 3.1 and 2.5 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO2 has resulted in 25 % removal (i.e. Capturing) Fig.86, therefore, contributing to the green and sustainable wastewater treatment technology.

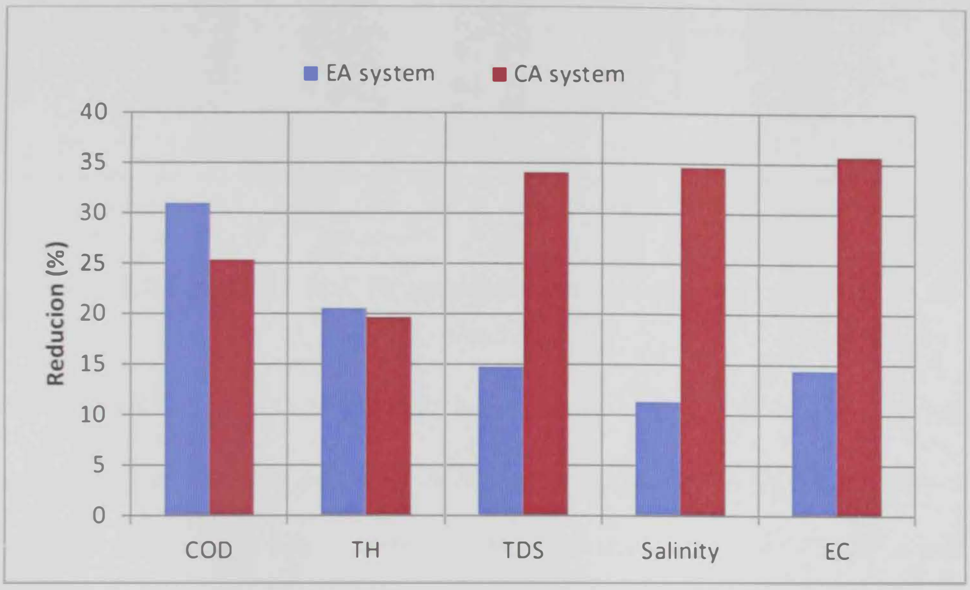


Figure 25: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO11) in EA and CA batch systems

Fig.36 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 9.5, Temperature 20 °C and current density 284 A/m^2. For example, the %COD reduction was 30.96 and 25.35% in EA and CA systems, respectively. TH was reduced by 20.54 and 19.68% while 14.73 and 34.1% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 11.28 and 34.62% with effluent 1.9 and 1.4% in EA and CA systems, respectively. pH was reduced to 8.5 and 5.1 whereas EC dropped to 3.3 and 2.5 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 73 % removal (i.e. Capturing) Fig.87, therefore, contributing to the green and sustainable wastewater treatment technology.

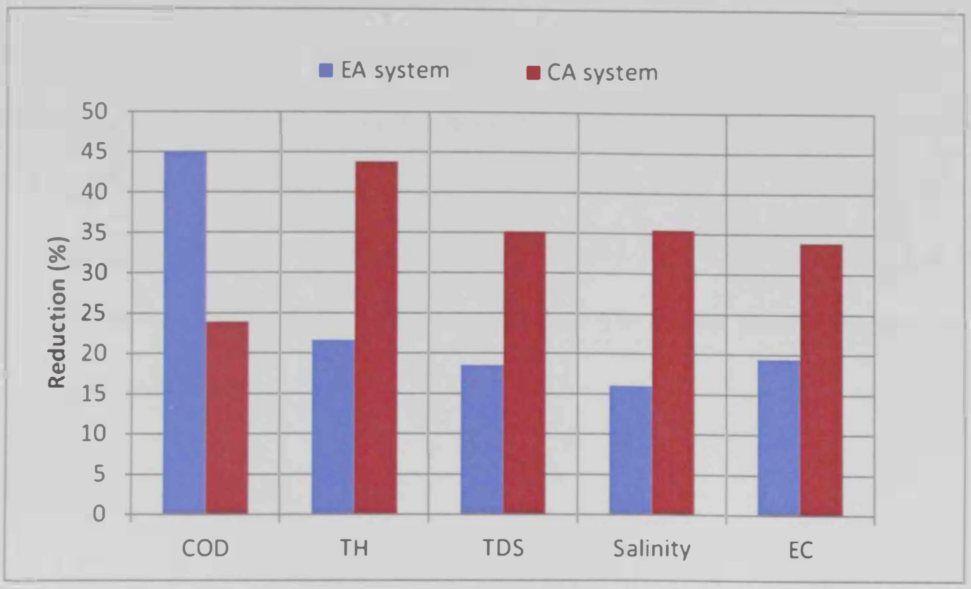


Figure 26: % Reduction of COD, TH, TDS, EC and salinity in treated wastewater (RO12) in EA and CA batch systems

Fig.26 shows the variation of COD, TH, TDs and salinity over 3 h of operation time at pH 9.5, Temperature 27.5 °C and current density 284 A/m^2. For example, the %COD reduction was 44.91 and 23.91% in EA and CA systems, respectively. TH was reduced by 21.58and 43.83% while 18.49 and 35.14% TDS removal was achieved in EA and CA systems, respectively. Also, the results showed salinity reduction of 16.01 and 35.44% with effluent 1.8 and 1.3% in EA and CA systems, respectively. pH was reduced to 8.6 and 5.5 whereas EC dropped to 3.2 and 2.6 ms/cm in EA and CA systems, respectively. Consequently, the injection of CO_2 has resulted in 84 % removal (i.e. Capturing) Fig 88, therefore, contributing to the green and sustainable wastewater treatment technology.

4.2. STATISTICAL ANALYSIS

To study the correlation between the parameters for each response, statistical analyses were done. Therefore, the statistical tests have a null hypothesis and an alternate hypothesis. The P-value reported from a statistical test is the likelihood of the result given that the null hypothesis was correct. That's why small P-values were highly desirable. The smaller they are, the less likely the result would be if the null hypothesis was correct. If the P-value is small enough (i.e. < 0.05), then the null hypothesis is rejected. In addition, the p-value of lack of fit must be > 0.05 to be statistically insignificant to mention that the model represent the data.

4.2.1. COD % REDUCTION

In CA and EA systems, the optimum conditions for giving a good performance efficiency of COD reduction is when pH, temperature, current density are 12, 35, 213.5 A/m^2 and 12, 27.5 and 143 A/m^2, respectively. According to the statistical analysis performed in the CA system using Minitab, pH, temperature and current density (independent variables) had no significant impact on the COD reduction (dependent variable) as P-values of 0.142, 0.418 and 0.536 ($R^2 = 0.59$, lack of fit = 0.685) were obtained under full quadratic linear fit, respectively. Fig.27 shows 3D graphs data points. Also, there was no interaction correlation between the aforementioned indepeandent variables as 0.445, 0.376, and 0.650 P-values were reported between pH and temperature, pH and current density, and temperature and current density, respectively. On the other hand, pH, temperature and current density were significant parameters affecting the COD reduction in the EA system as 0.015, 0.011, and 0.017 P-values ($R^2 = 0.9694$, lack of fit = 0.091) were obtained as shown in Fig.41. However, no interaction correlation between pH and temperature, pH and current density, and temperature and current density as 0.409, 0.641, and 0.184 P-values were reported, respectively. The model adequacy was further verified by plotting the normal probability and residual plots for the response, as depicted in Fig.29. The residuals analysis shows that there was no evidence of outliers as all the residuals fell within the range of -2 to +2 and they were randomly distributed around zero, which indicates a high degree of correlation between the observed values and predicted values. In addition, the p-values of lack-of-fit were 0.685, 0.091 in CA and EA systems; respectively indicate that the model is insignificant for both systems. When the estimated p-value of the lack-of-fit is less than 0.05, there is statistically significant lack-of-fit at the 95% confidence level, i.e., the model does not adequately represent the data.

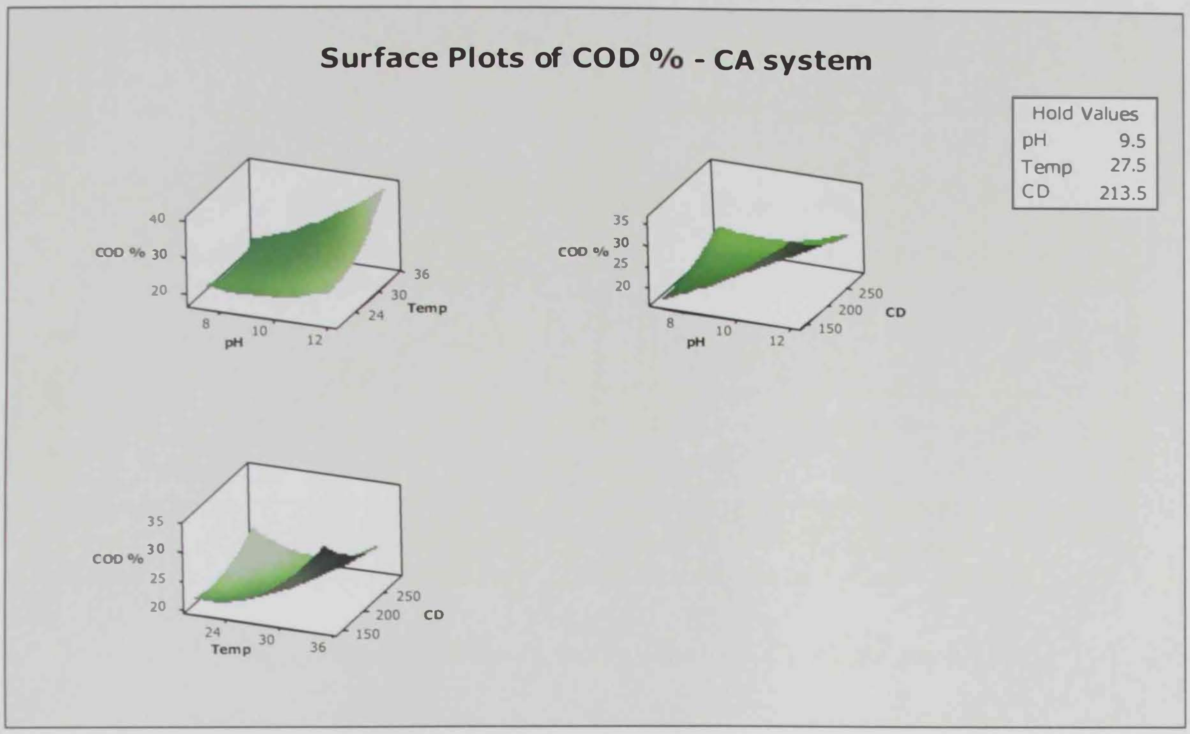


Figure 27: Correlations between pH, temperature and current density of COD% reduction in CA system

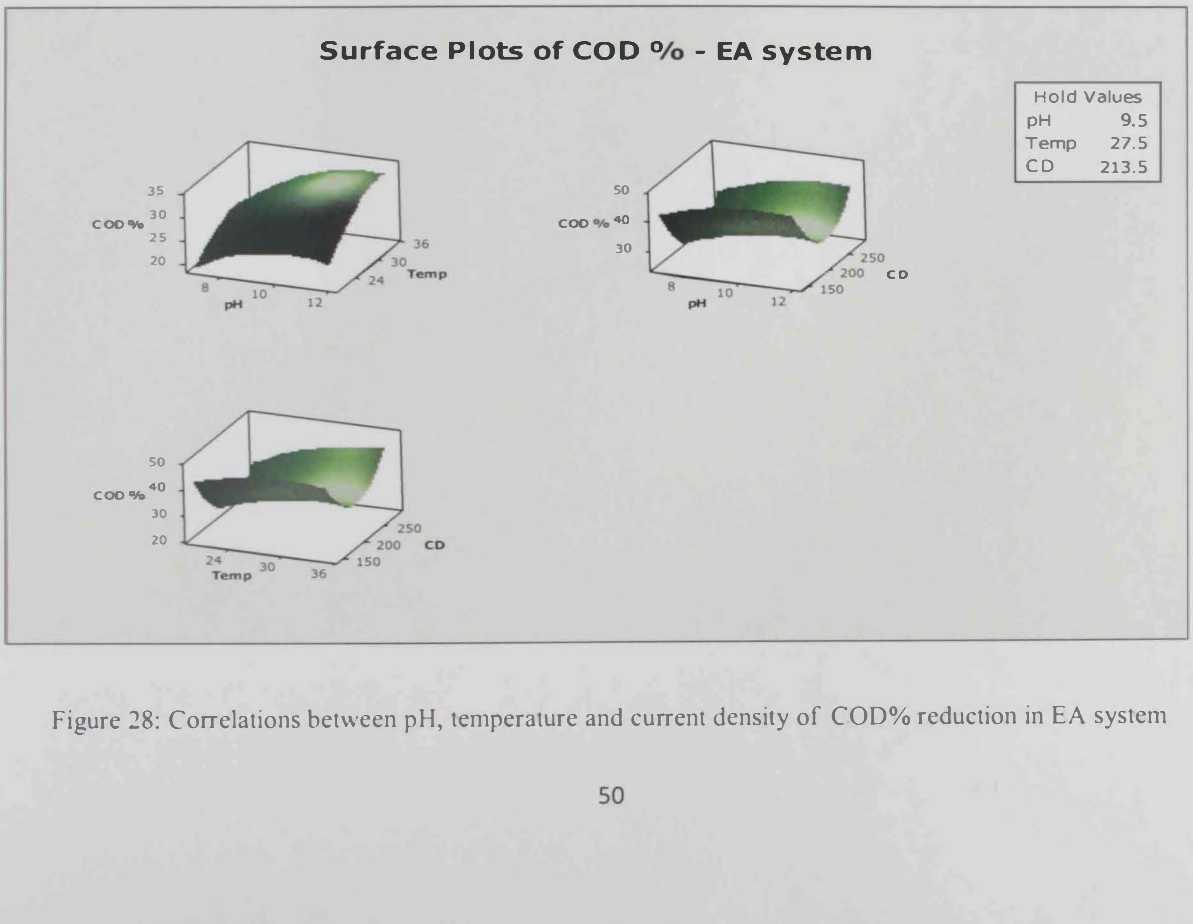
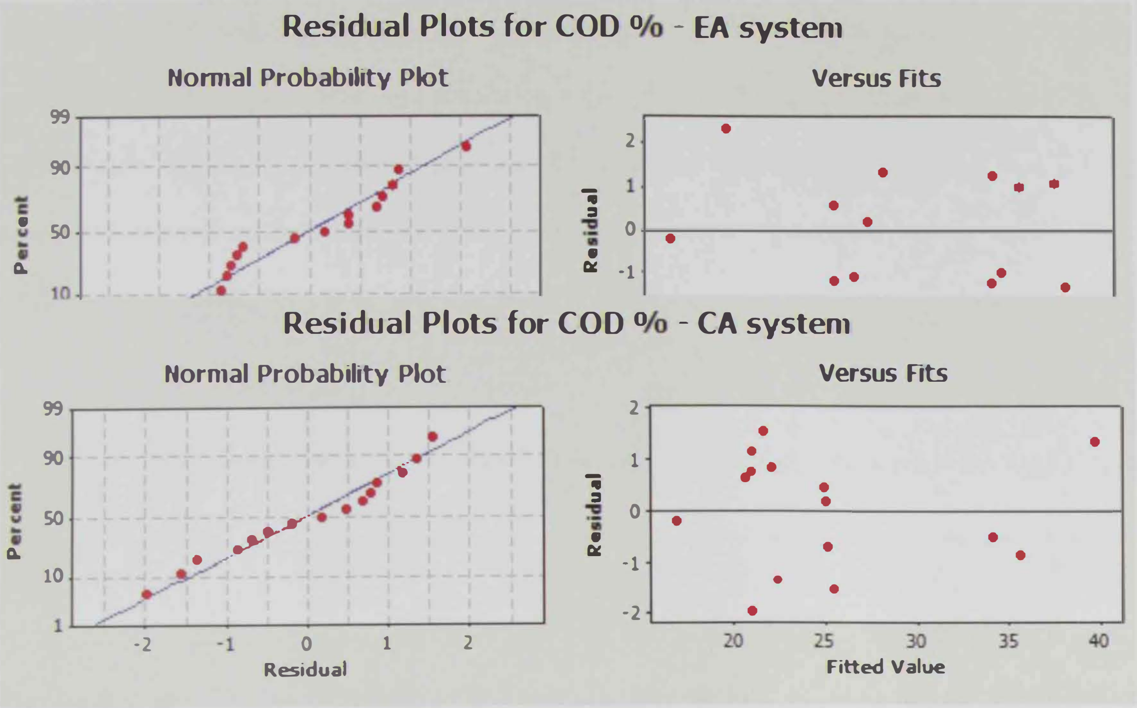


Figure 28: Correlations between pH, temperature and current density of COD% reduction in EA system


Residual Plots for COD % - EA system

Residual Plots for COD % - CA system

Figure 29: Residual Plots for COD% reduction – CA and EA systems

- **COD % prediction - CA system and EA System**

Minitab and RSM were used to create the model and calculate the predicted vales of the COD % reduction in CA and EA systems by estimation the regression coefficients. Table 18 shows the comparison of the experimental and prediction vales of the COD % reduction in CA and EA systems. Fig 30 and 31 show the scattered plot that R^2 were 94, 98, respectively in CA and EA systems, meanwhile the values are too closed between the experiment and prediction values and the error was a randomly distributed.

Table 18: Comparison between the COD% reduction experimentally and prediction in CA and EA systems

				CA System		EA system	
RunOrder	**pH**	**Temp**	**CD**	**COD %Exp.**	**COD %Prediction**	**COD %Exp.**	**COD %Prediction**
1	9.5	27.5	213.5	21.7	20.5	31.2	30.6
2	9.5	27.5	213.5	22.1	20.5	31.2	30.6
3	12	35	213.5	41.2	38.1	33.3	33
4	12	27.5	143	34.8	36.2	45.8	47.3
5	12	27.5	284	25.2	23.7	40.6	42.1
6	7	27.5	284	22.9	21.5	35.6	33.9
7	7	20	213.5	20.9	22	18.7	18.9
8	9.5	20	143	23.2	24.6	41.6	42.8
9	7	35	213.5	21.3	20.2	21.9	23.8
10	9.5	35	143	33.6	34.2	47.5	46.1
11	9.5	20	284	25.3	24.7	30.9	32.3
12	9.5	35	284	23.9	25.9	44.9	43.7
13	9.5	27.5	213.5	18.9	20.5	29.4	30.6
14	7	27.5	143	16.6	17.1	43.3	41.8
15	12	20	213.5	24.4	25.5	25.2	23.4

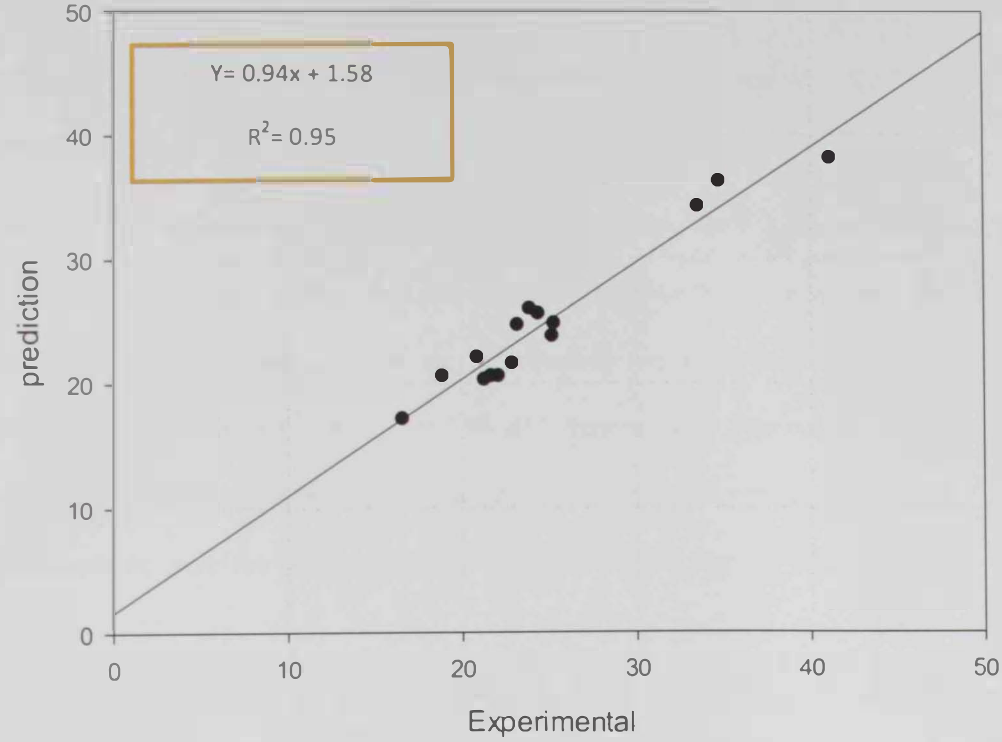


Figure 30: COD % reduction - CA system - Exp. vs Prediction

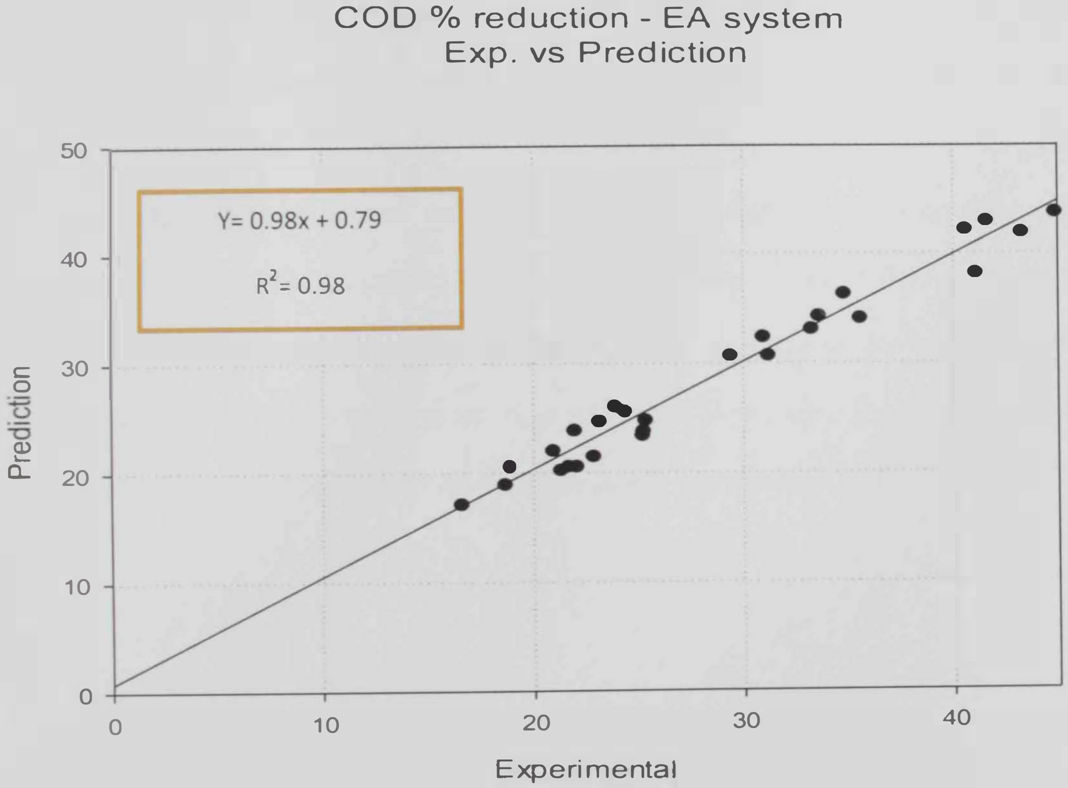

COD % reduction - EA system
Exp. vs Prediction

Figure 31: COD % reduction - EA system - Exp. vs Prediction

4.2.2. TH% REDUCTION

In CA and EA systems the optimum condition for giving a good performance efficiency of TH reduction is when pH, temperature, current density are 12, 27.5 and 284 A/m^2 and 12, 35 and 213.5 A/m^2 respectively.

Furthermore, pH was the only significant parameter affecting the TH reduction in the CA system with P-value of 0.016 while 0.563 and 0.089 were reported for temperature and current density, respectively. No correlation between the independent variables was obtained as 0.516, 0.078, and 0.260 P-values (lack of fit = 0.096, R^2 = 0.8618).) were reported between pH and temperature, pH and current density, and temperature and current density, respectively as shown in Fig.32. In contrary, pH and temperature were the most significant parameters affecting the TH reduction with P-values of 0.001 and 0.008, respectively. Similarly, no correlation between the independent variables was obtained as 0.462, 0.192, and 0.175 P-values (lack of fit = 0.147, R^2 = 0.9646)) were reported between pH and temperature, pH and current density, and temperature and current density, respectively as shown in Fig. 33. The model adequacy was further verified by plotting the normal probability and residual plots for the response, as depicted in Fig.34. The residuals analysis shows that there was no evidence of outliers as all the residuals fell within the range of -3 to +3 which is acceptable and they were randomly distributed around zero, which indicates a high degree of correlation between the observed values and predicted values. In addition, the p-values of lack-of-fit were 0.096, 0.147 in CA and EA systems; respectively indicate that the model is insignificant for both systems. When the estimated p-value of the lack-of-fit is less than 0.05, there is statistically significant lack-of-fit at the 95% confidence level, i.e., the model does not adequately represent the data.

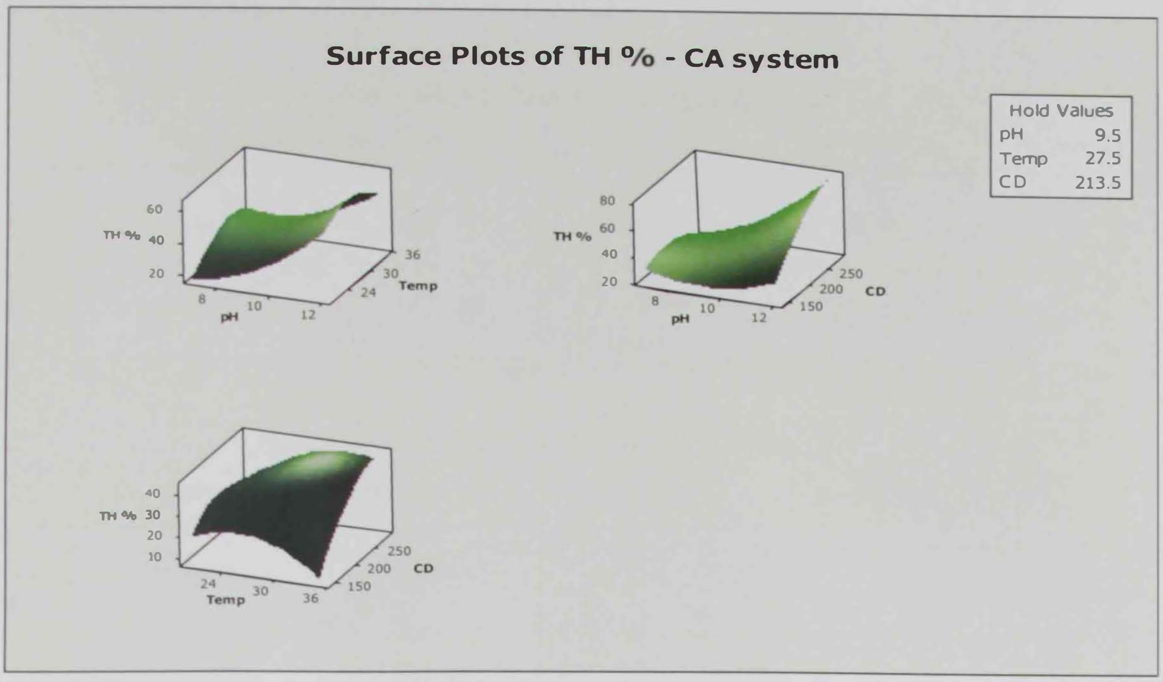


Figure 32: Correlations between pH, temperature and current density of TH% reduction in CA system

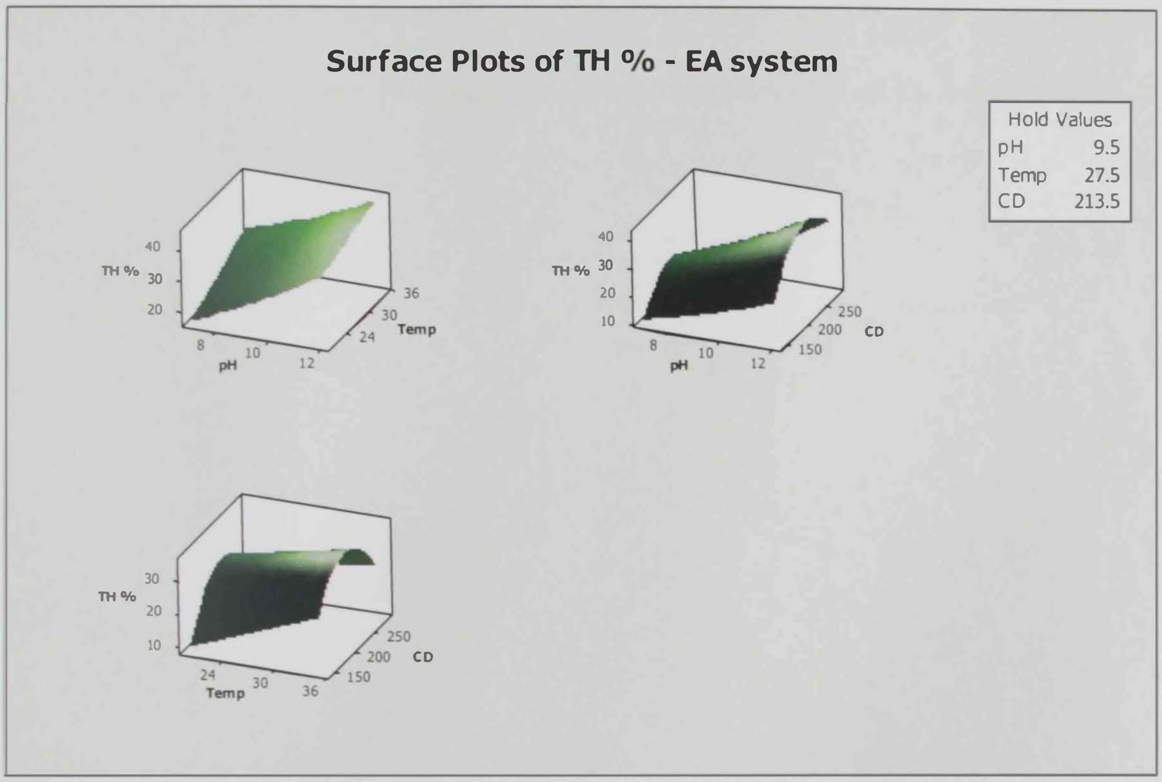


Figure 33: Correlations between pH, temperature and current density of TH% reduction in EA system

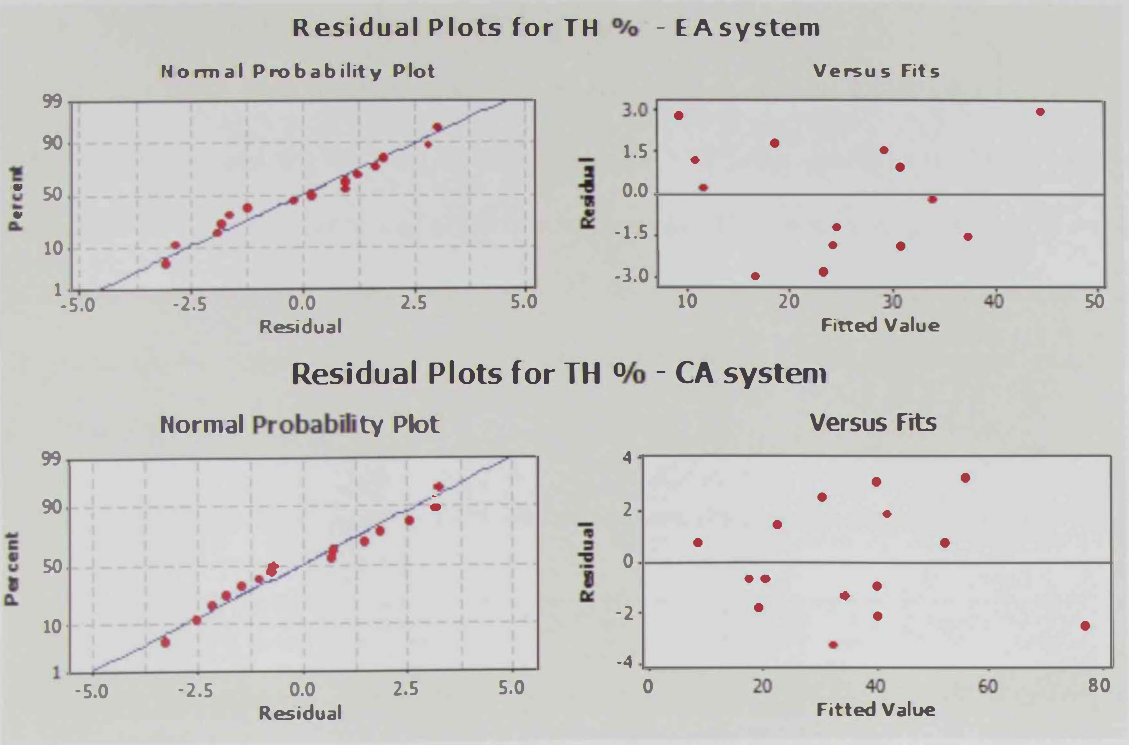


Figure 34: Residual plots for TH% reduction – CA and EA systems

- **TH % reduction in CA and EA systems**

Minitab and RSM were used to create the model and calculate the predicted vales of the TH % reduction in CA and EA systems by estimation the regression coefficients. Table 19 shows the comparison of the experimental and prediction vales of the TH % reduction in CA and EA systems. Fig 35 and 36 show the scattered plot that R^2 were 98, 98, respectively in CA and EA systems, meanwhile the values are too closed between the experiment and prediction values and the error was a randomly distributed.

Table 19: Comparison between the TH% reduction experimentally and prediction in CA and EA systems

				CA System		EA System	
RunOrder	pH	Temp	CD	TH %Exp	TH %Prediction	TH %Exp	TH %Prediction
1	9.5	27.5	213.5	38.2	41	31.8	30.8
2	9.5	27.5	213.5	39.3	41	31.8	30.8
3	12	35	213.5	52.9	52.7	47.7	44.7
4	12	27.5	143	32.8	34.5	23.5	24.7
5	12	27.5	284	75	79.4	33.7	33.9
6	7	27.5	284	23.8	22.1	12.1	10.8
7	7	20	213.5	16.6	16.9	17.7	16.7
8	9.5	20	143	17.3	18.4	10.1	9.3
9	7	35	213.5	28.9	30.7	30.8	29.2
10	9.5	35	143	9.1	8.3	22.6	24.4
11	9.5	20	284	19.7	21.1	20.5	18.7
12	9.5	35	284	43.8	41.7	21.6	23.4
13	9.5	27.5	213.5	43.5	41	28.9	30.8
14	7	27.5	143	33.2	30.8	11.8	11.6
15	12	20	213.5	59.6	55.8	35.8	37.5

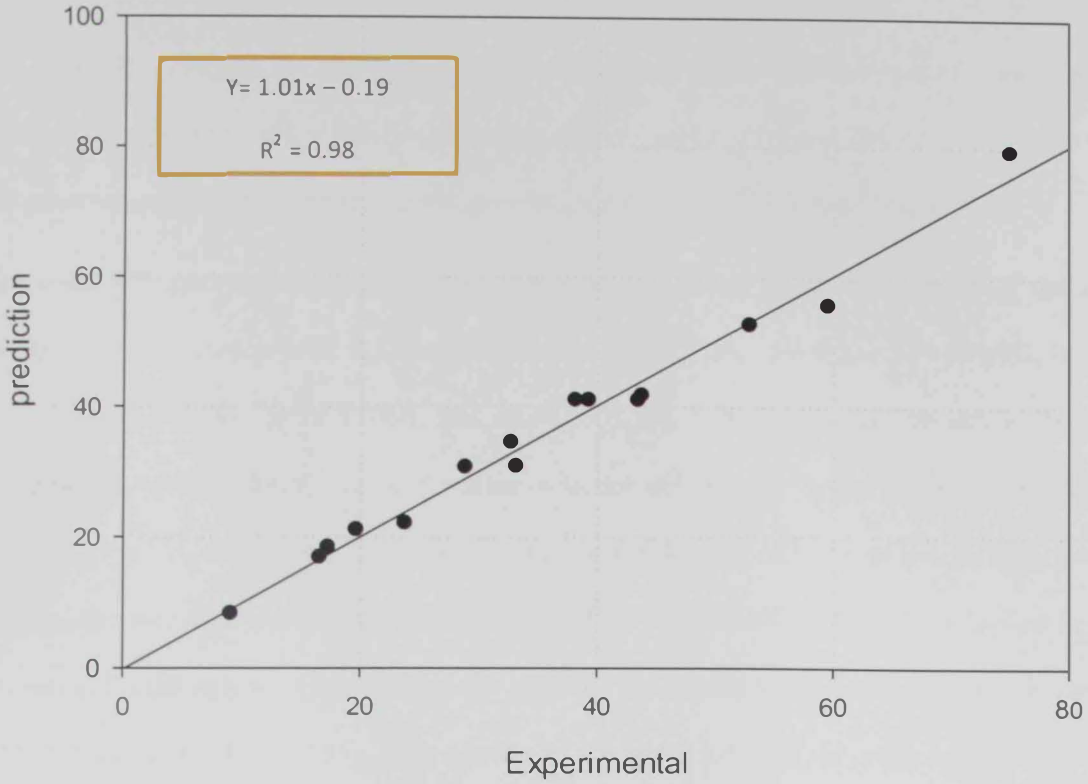


Figure 35: TH % reduction – CA system- Exp. Vs Prediction

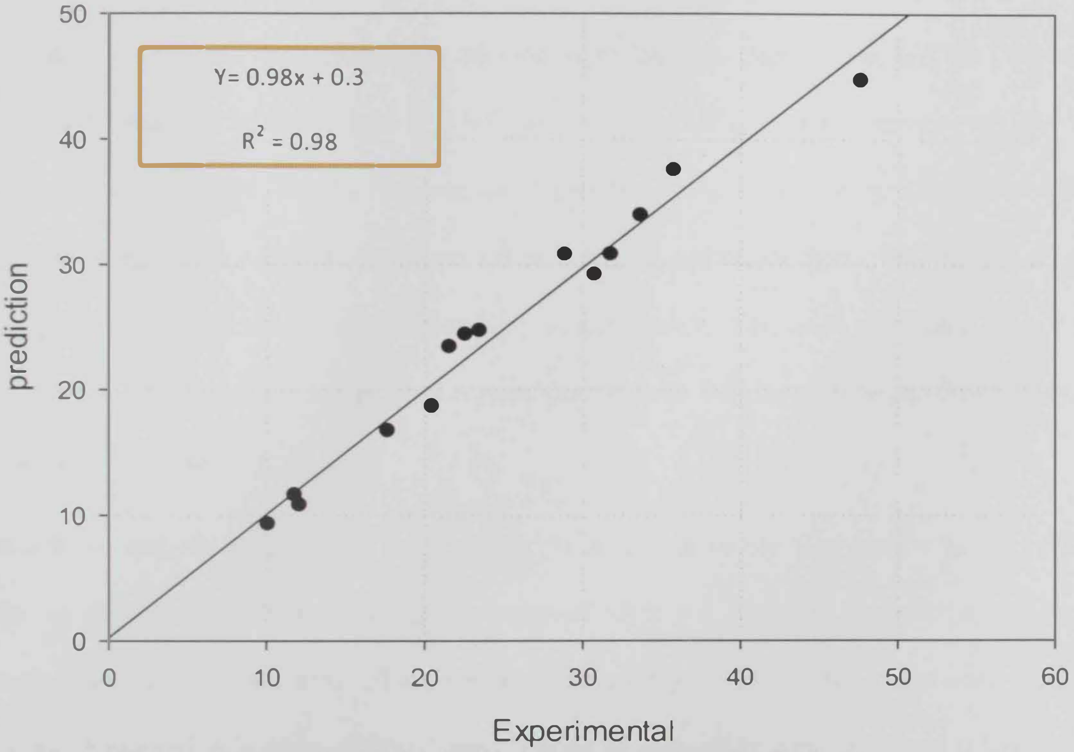


Figure 36: TH % reduction – EA system- Exp. Vs Prediction

4.2.3. EC, SALINITY AND TDS REDUCTION

In CA and EA systems the optimum condition for giving a good performance efficiency of EC and TDS reduction is when pH, temperature, current density are 12, 27.5 and 284 A/m^2, but for the salinity reduction when pH , temperature, current density are 12, 35 and 213.5 A/m^2 respectively.

Moreover, pH and current density were the most significant parameters affecting the electrical conductivity and salinity in the CA system with P-values of 0.000 and 0.001 (R^2 = 0.9892, lack of fit = 0.07), 0.000 and 0.001 (R^2 = 0.9897, lack of fit = 0.129), respectively. No correlations between the independent variables were observed neither with respect to salinity nor electrical conductivity as shown in (Fig. 37 and 39). Controversy, pH and current density were the most significant parameters affecting the electrical conductivity with P-values of 0.000 and 0.003 (R^2 = 0.9879, lack of fit = 0.561) whereas pH is the only significant parameter affecting the salinity in the EA system with P-value 0.000 (R^2 = 0.9911, lack of fit = 0.595). A correlation was obtained between pH and temperature, and pH and current density with P-values of 0.05 and 0.007, and between pH and temperature (P-value 0.008) for electrical conductivity and salinity, respectively as shown in Fig. 46 and Fig. 48

Additionally, pH and current density were the most significant parameters affecting the TDS reduction in CA and EA systems with P-values of 0.000 and 0.001, 0.000 and 0.01, respectively (R^2 = 0.9892, 0.9876, lack of fit = 0.136, 0.338). No correlation between the independent variables was obtained as 0.076, 0.277, and 0.906 P-values were reported between pH and temperature, pH and current density, and temperature and current density, respectively in CA system. Yet, two correlations were observed between pH and temperature, and pH and current density with P-values 0.024 and 0.005, respectively as shown in Fig. 38 and Fig. 47.

The residuals analysis in EC, TDS and Salinity % reduction shows that there was no evidence of outliers as all the residuals fell within the range of -2 to +2 which is acceptable and they were randomly distributed around zero, which indicates a high degree of correlation between the observed values and predicted values. In addition, the p-values of lack-of-fit were 0.07 and 0.561, 0.136 and

0.338 and 0.129 and 0.595 in CA and EA systems; respectively that indicate the model is insignificant that means the model is fit. When the estimated p-value of the lack-of-fit is less than 0.05, there is statistically significant lack-of-fit at the 95% confidence level, i.e., the model does not adequately represent the data as shown in Fig. 49, Fig. 50 and Fig. 51

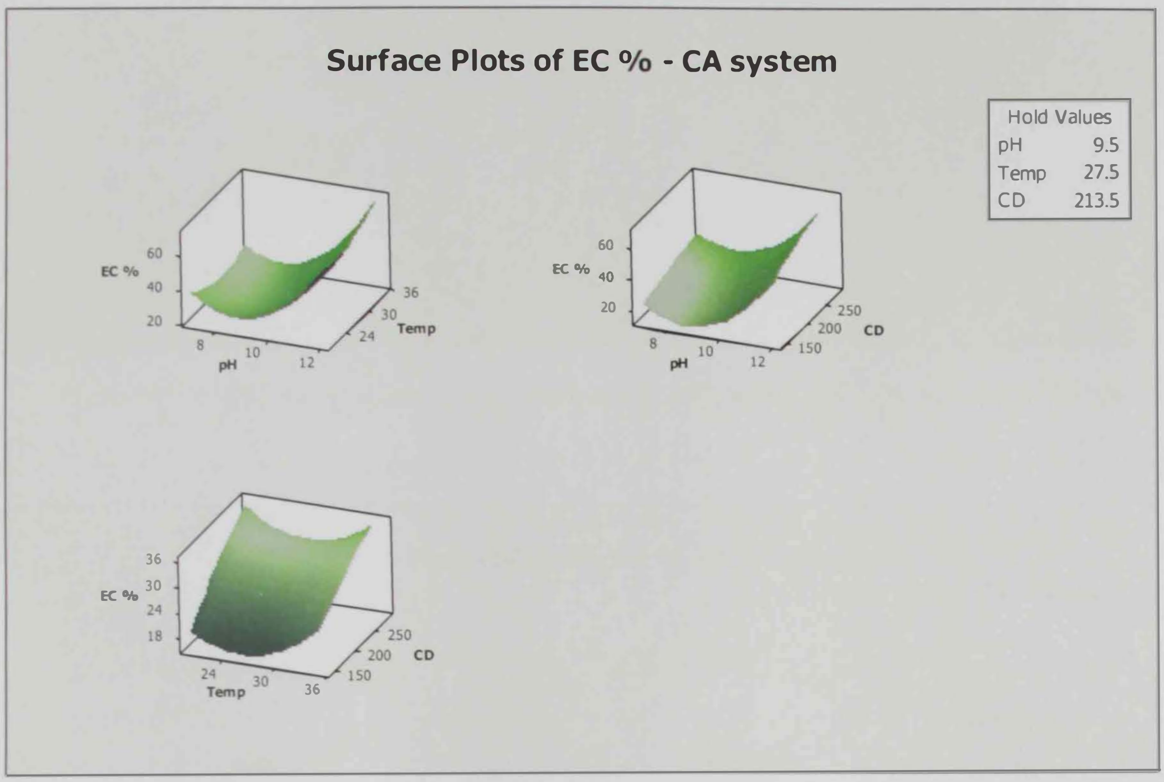


Figure 37: Correlations between pH, temperature and current density of EC% reduction in CA system

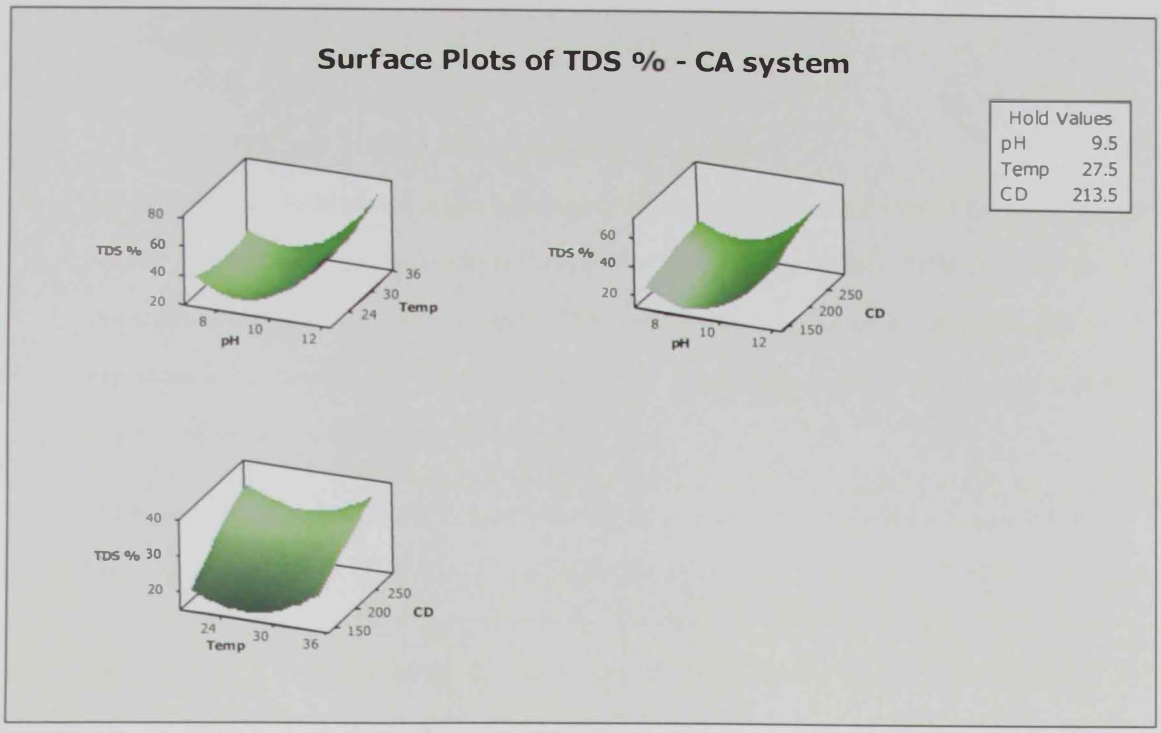


Figure 38: Correlations between pH, temperature and current density of TDS% reduction in CA system

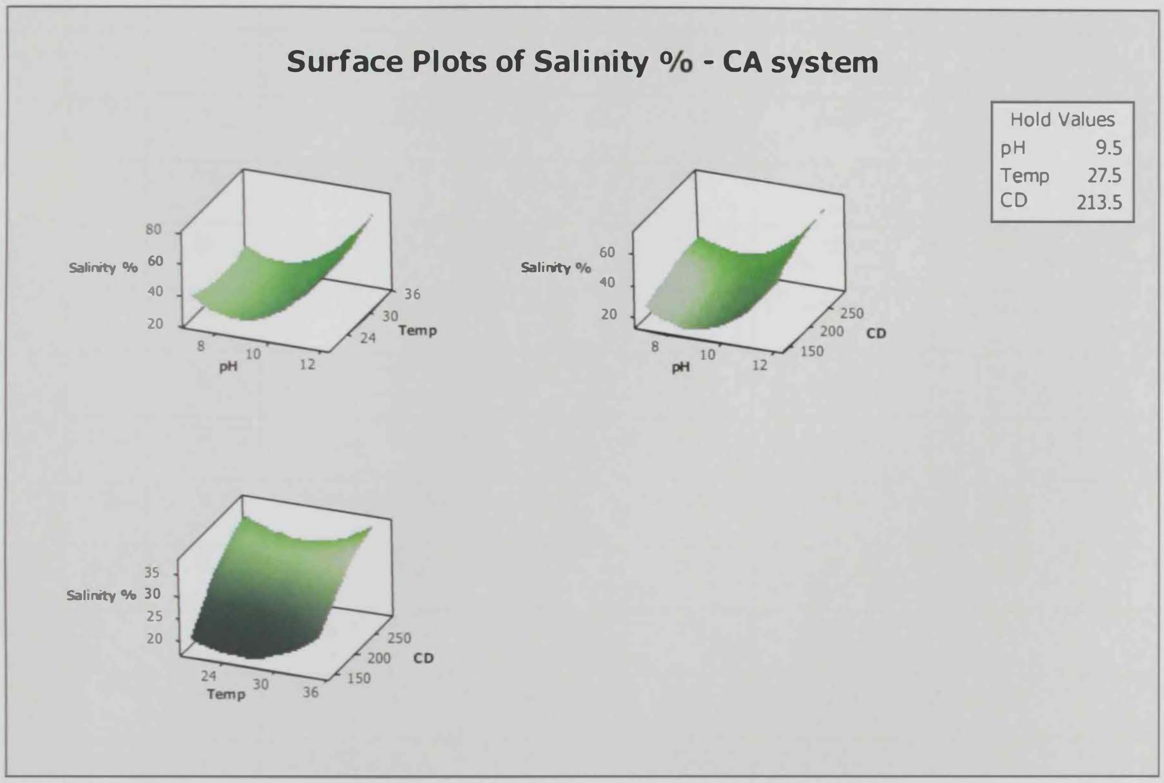


Figure 39: Correlations between pH, temperature and current density of Salinity% reduction in CA system

- **EC, TDS and Salinity % prediction in CA system**

Minitab and RSM were used to create the model and calculate the predicted vales of the EC, TDS and Salinity % reduction in CA system by estimation the regression coefficients. Table 20 shows the the experimental and prediction vales of the EC, TDS and Salinity % reduction in CA system. Fig 40,42 and 44 show the scattered plot that R^2 were 99, 99, 99, respectively for EC, TDS and Salinity in CA system, and the error was randomly distributed.

Table 20: Comparison between EC, TDS and Salinity % reduction experimentally and prediction in CA system

CA system									
RunOrder	pH	Temp	CD	EC %Exp	EC %Prediction	TDS %Exp	TDS %Prediction	Salinity %Exp	Salinity %Prediction
1	9.5	27.5	213.5	24.8	24.3	24.8	24.7	28	27.6
2	9.5	27.5	213.5	23.1	24.3	23.1	24.7	27.4	27.6
3	12	35	213.5	72.9	71.6	73.8	72.9	74.4	73.5
4	12	27.5	143	49.1	50.7	50.6	52.5	51.5	53.2
5	12	27.5	284	70.4	68.5	71.9	69.8	72.5	70.4
6	7	27.5	284	34.7	33.1	36.7	34.7	36.6	34.9
7	7	20	213.5	36.9	38.4	37.9	38.9	38.3	39.2
8	9.5	20	143	21.8	20.6	22.2	21.1	22.4	21.4
9	7	35	213.5	34.7	33	35.8	34.7	36.4	35.1
10	9.5	35	143	24.1	23.9	25	24	25.5	24.7
11	9.5	20	284	35.7	35.8	34.2	35.1	34.6	35.5
12	9.5	35	284	33.9	36.2	35.1	37.2	35.4	37.4
13	9.5	27.5	213.5	24.9	24.3	26	24.7	26.3	27.6
14	7	27.5	143	22.6	23.5	23	24.8	24.1	25.2
15	12	20	213.5	60.7	62.5	62.3	63.5	63	64.3

- **EC, TDS and Salinity % prediction in EA system**

Minitab and RSM were used to create the model and calculate the predicted vales of the EC, TDS and Salinity % reduction in EA system by estimation the regression coefficients. Table 21 shows the the experimental and prediction vales of the EC, TDS and Salinity % reduction in CA system. Fig 41,43 and 45 show the scattered plot that R^2 were 99, 99, 99, respectively for EC, TDS and Salinity in EA system, and the error was randomly distributed.

Table 21: Comparison between EC, TDS and Salinity % reduction experimentally and prediction in EA system

EA system									
RunOrder	pH	Temp	CD	EC %Exp	EC %Prediction	TDS %Exp	TDS %Prediction	Salinity %Exp	Salinity %Prediction
1	9.5	27.5	213.5	32.9	30.8	32.1	30.5	33.4	31.9
2	9.5	27.5	213.5	32.9	30.8	32.1	30.5	33.4	31.9
3	12	35	213.5	53.9	54.3	55.7	55.1	53	51.4
4	12	27.5	143	38.3	38.1	40.4	41.1	35.7	35.4
5	12	27.5	284	69.7	67	71.4	68.8	38.7	40.4
6	7	27.5	284	11.5	11.8	10.3	9.6	8.1	7.4
7	7	20	213.5	11.8	11.4	12	12.6	16.4	17.9
8	9.5	20	143	4.1	3.9	7.1	7.8	11.5	11.6
9	7	35	213.5	4.3	5.9	2.1	1.5	8.9	9.8
10	9.5	35	143	4.7	4.5	5.2	5.1	8.9	9.7
11	9.5	20	284	14.4	14.6	14.7	14.8	11.3	10.4
12	9.5	35	284	19.4	20.6	18.5	18.8	16	15.9
13	9.5	27.5	213.5	28.6	30.8	28.2	30.5	29.9	31.9
14	7	27.5	143	12.9	13.9	15.9	16.6	7	6.3
15	12	20	213.5	39.8	42.3	40.1	42.7	40.4	39.6

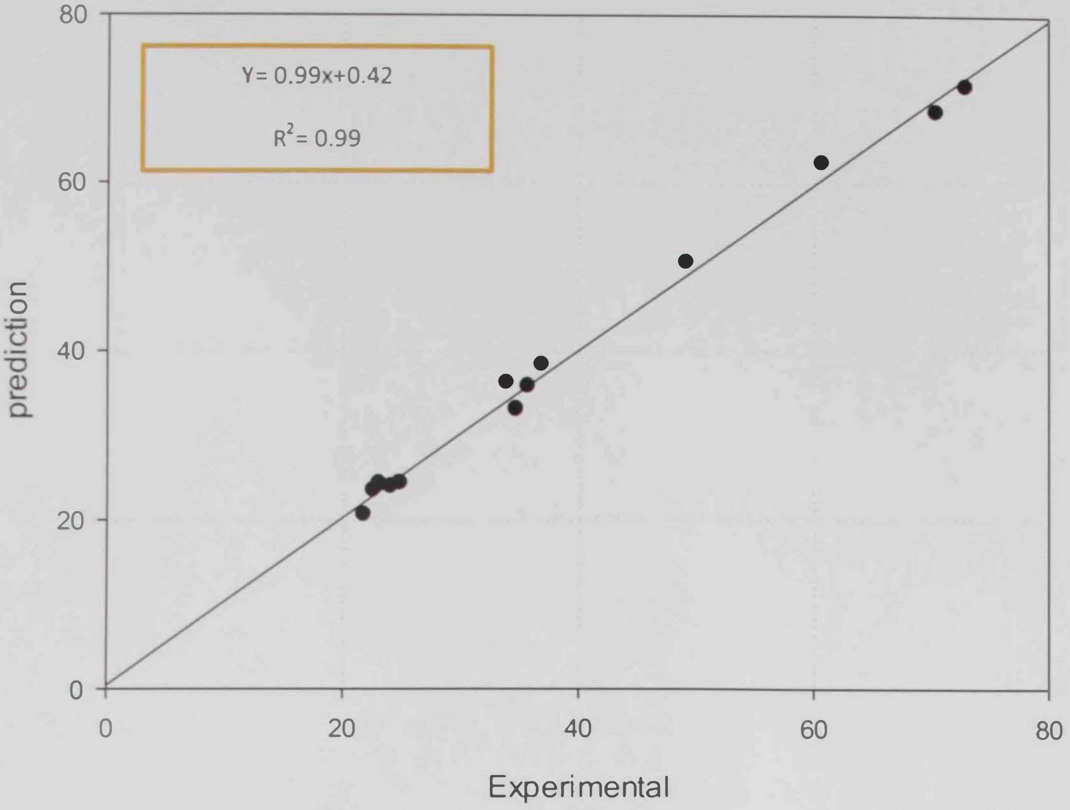


Figure 40: EC % reduction – CA system- Exp. Vs Prediction

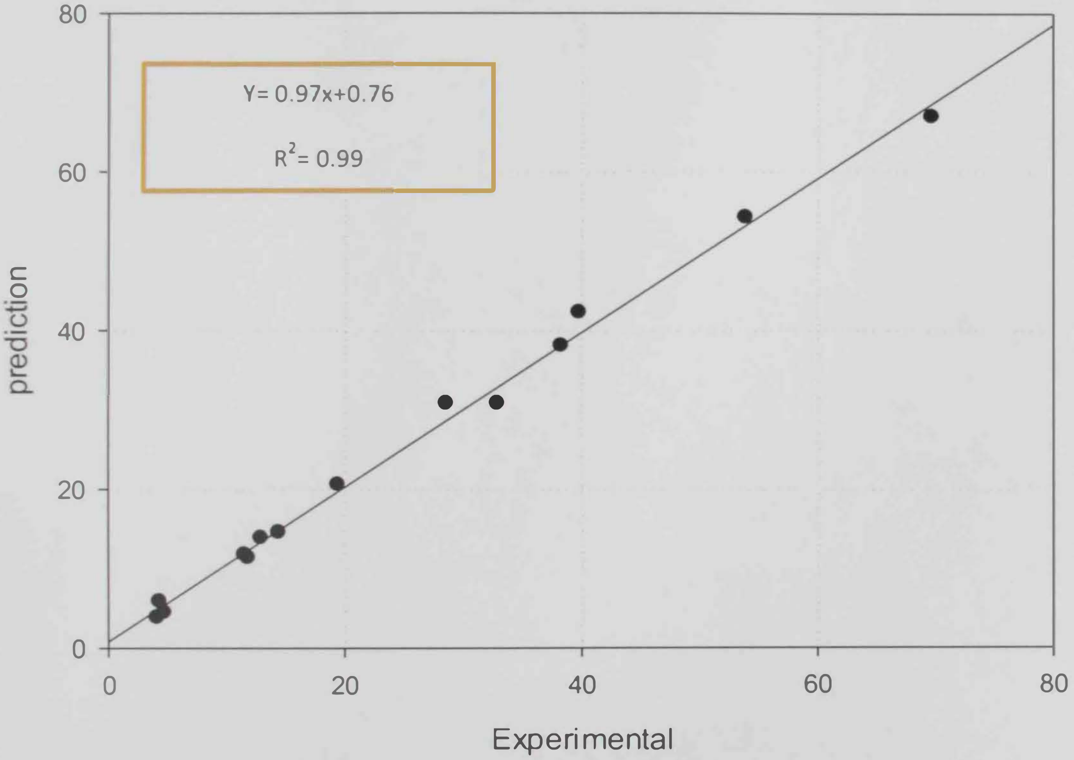


Figure 41: EC % reduction – EA system- Exp. Vs Prediction

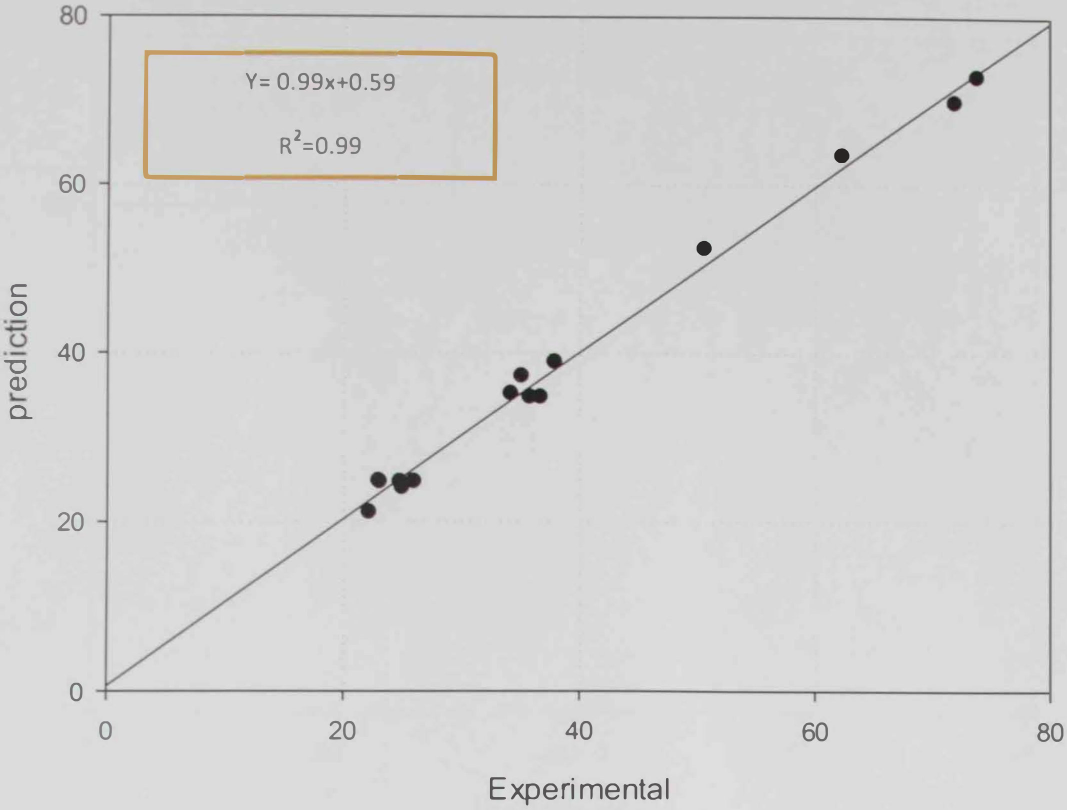


Figure 42: TDS % reduction - CA system - Exp. vs Prediction

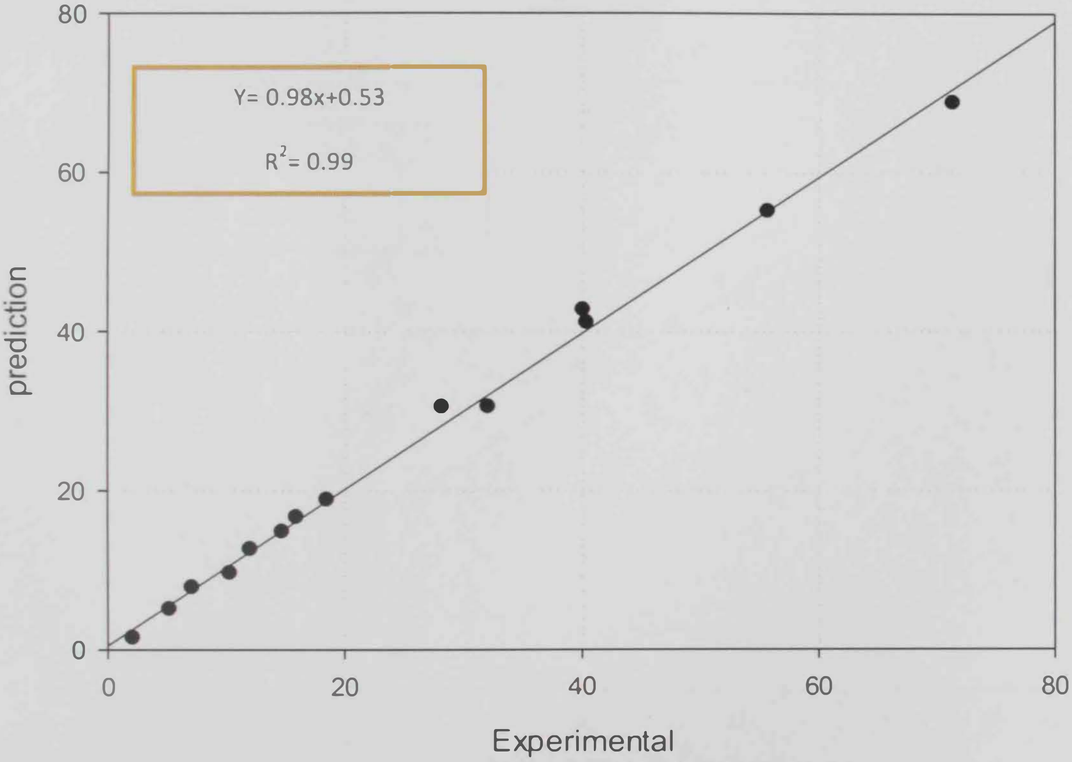


Figure 43: TDS % reduction - EA system - Exp. vs Prediction

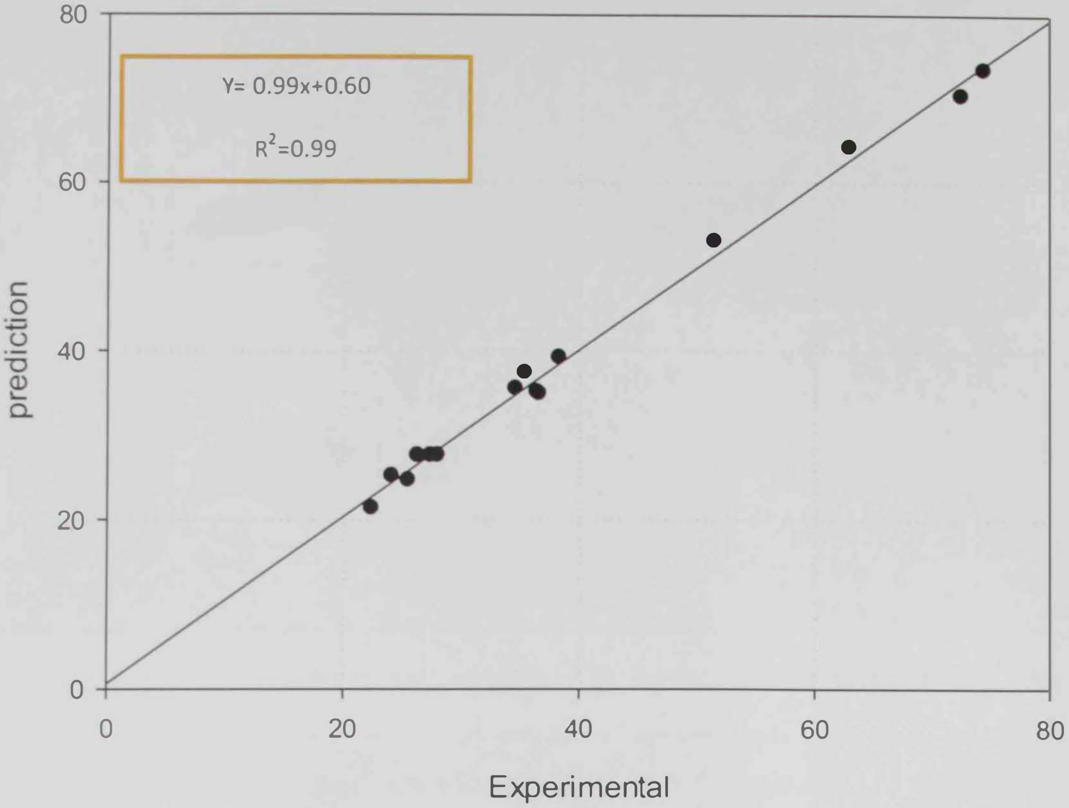


Figure 44: Salinity % reduction - CA system - Exp. vs Prediction

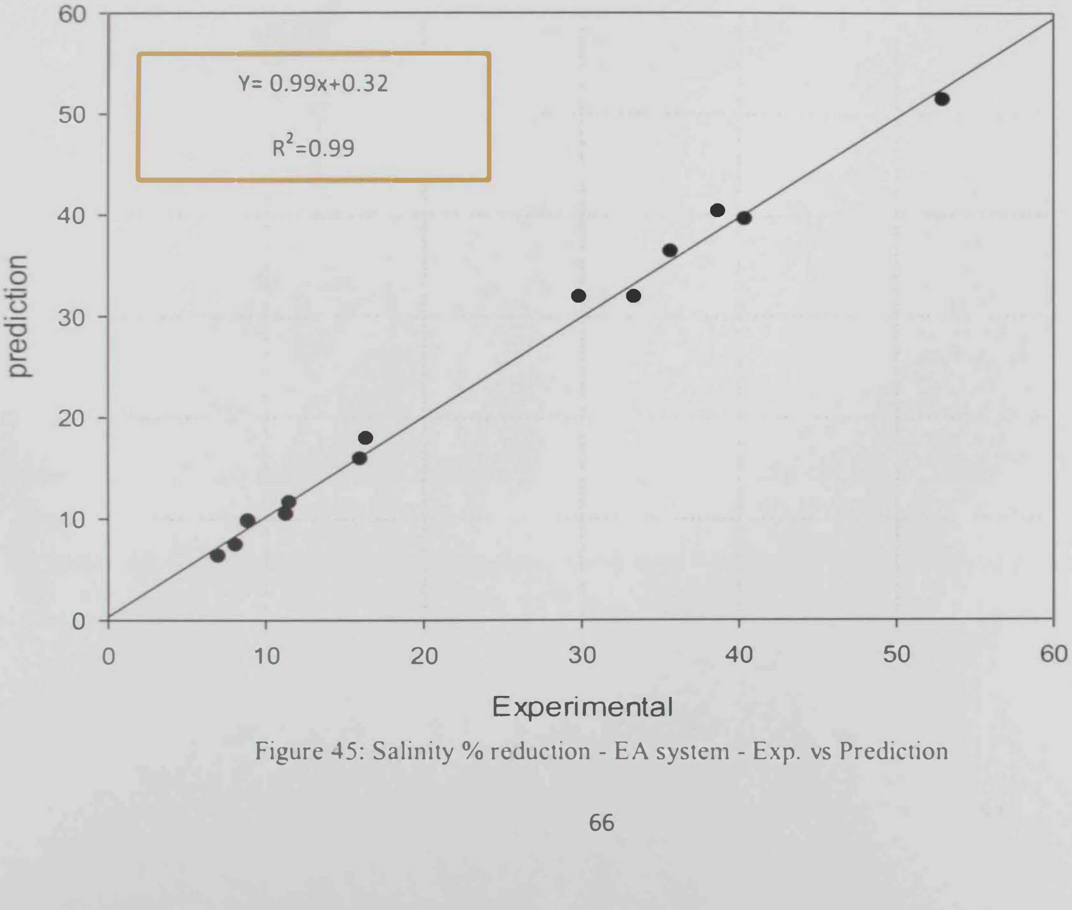


Figure 45: Salinity % reduction - EA system - Exp. vs Prediction

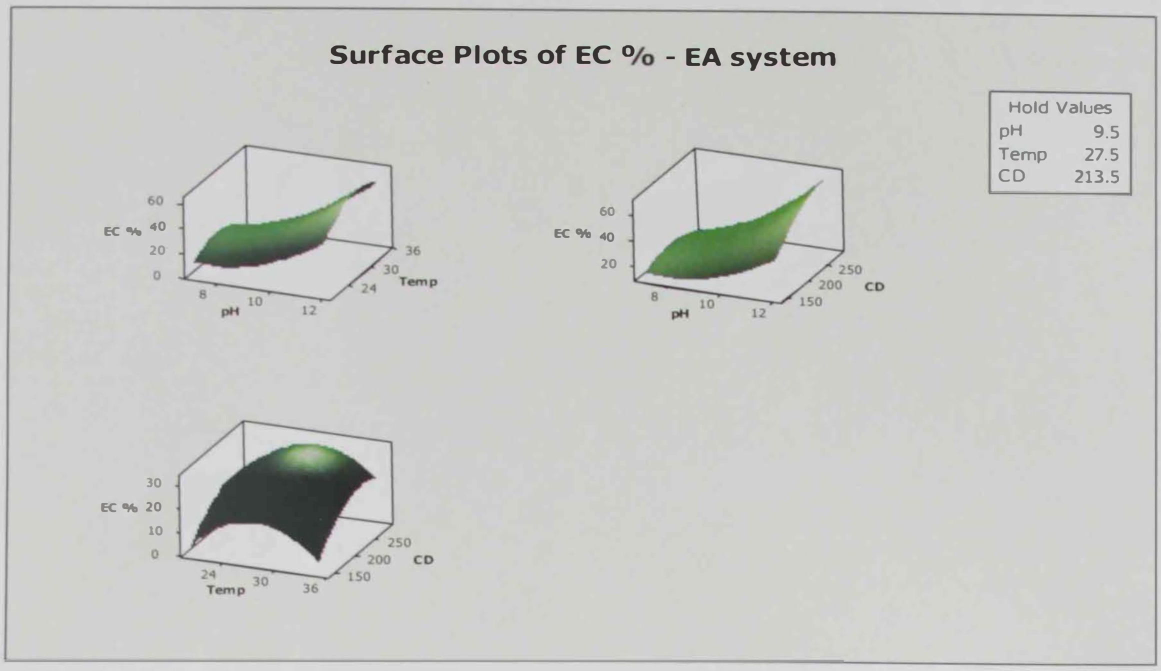


Figure 46: Correlations between pH, temperature and current density of EC% reduction in EA system

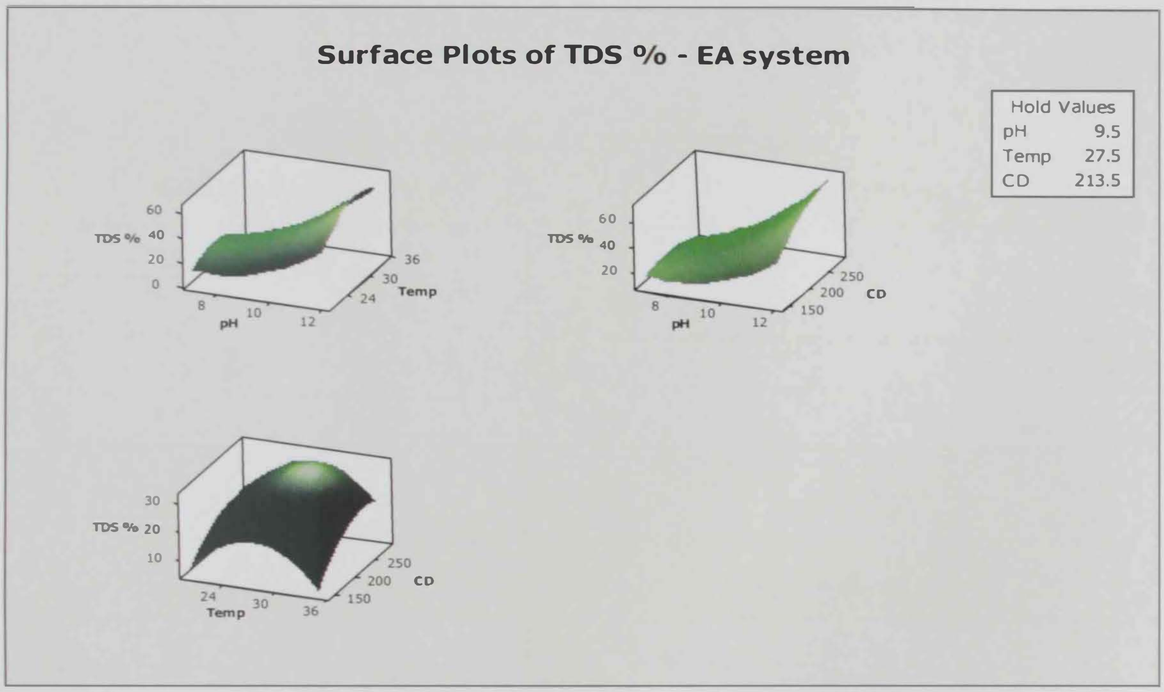


Figure 47: Correlations between pH, temperature and current density of TDS% reduction in EA system

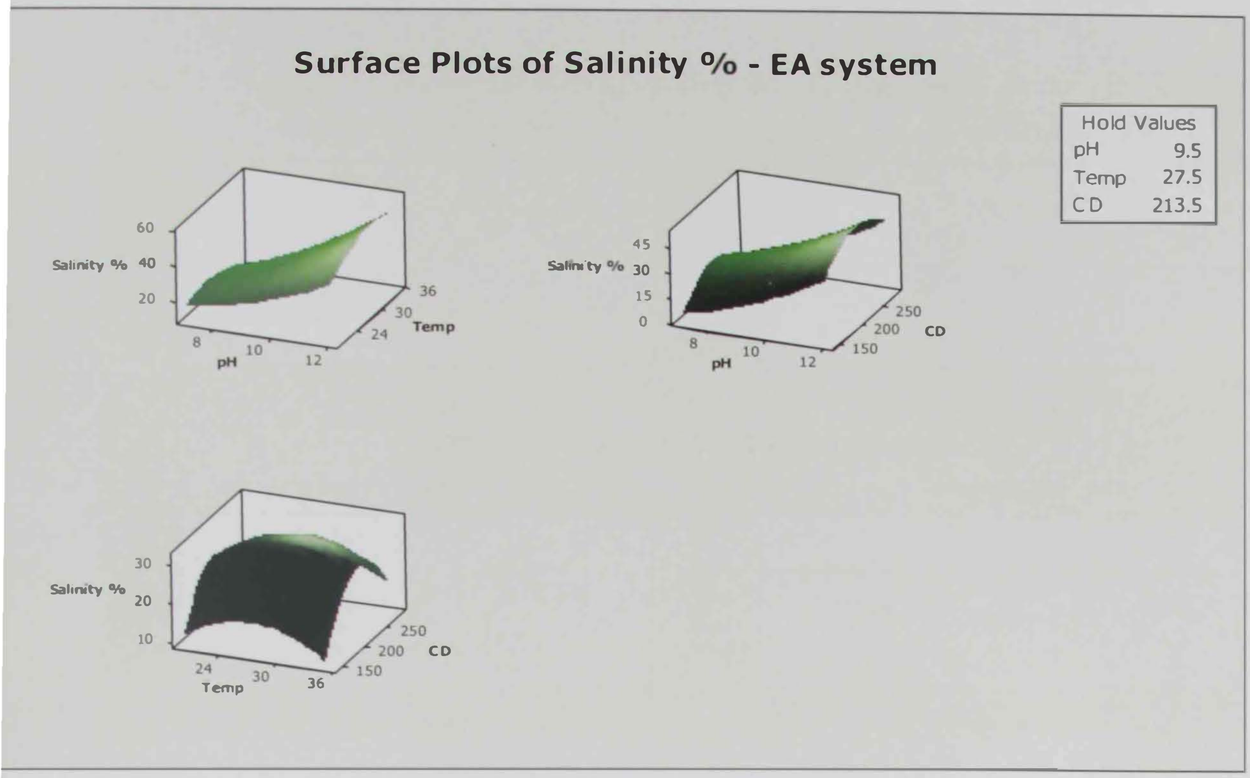


Figure 48: Correlations between pH, temperature and current density of Salinity% reduction in EA system

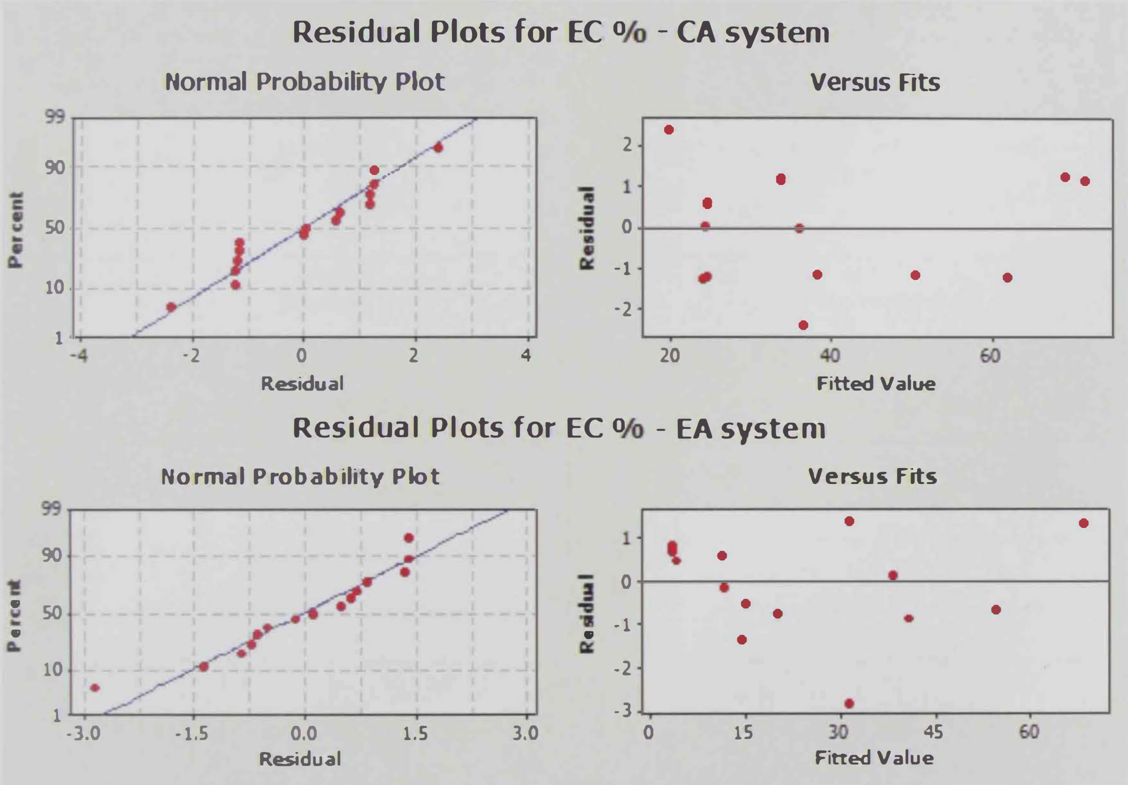


Figure 49: Residual plots for EC % reduction – CA and EA systems

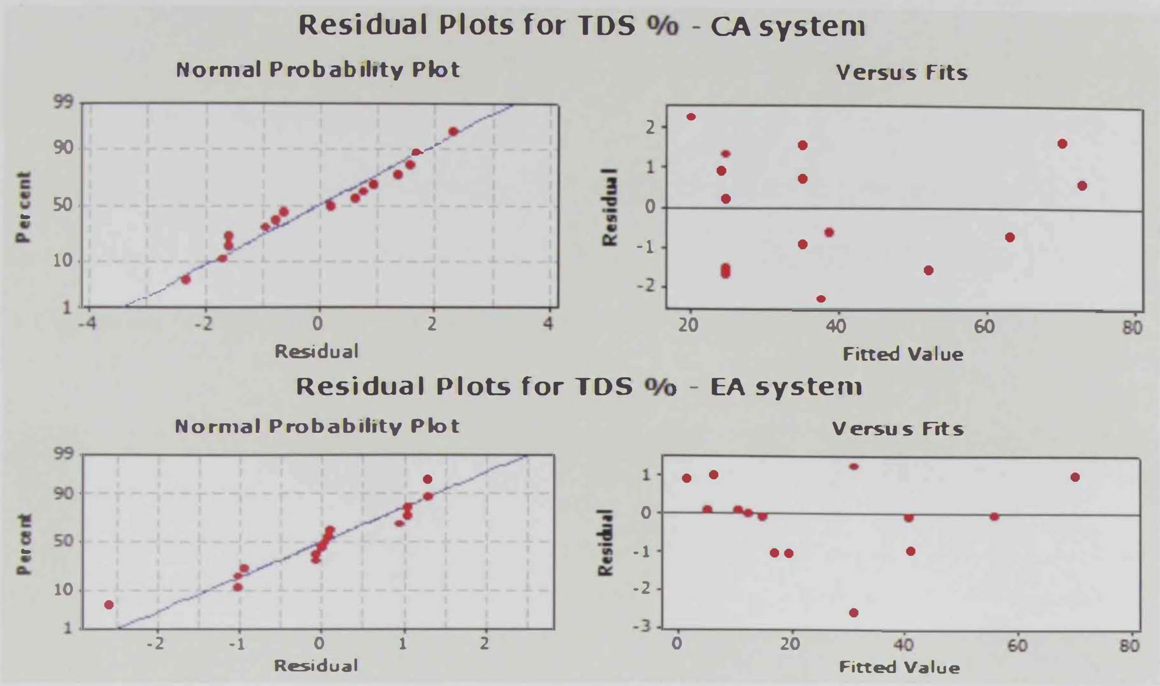


Figure 50: Residual plots for TDS % reduction – CA and EA systems

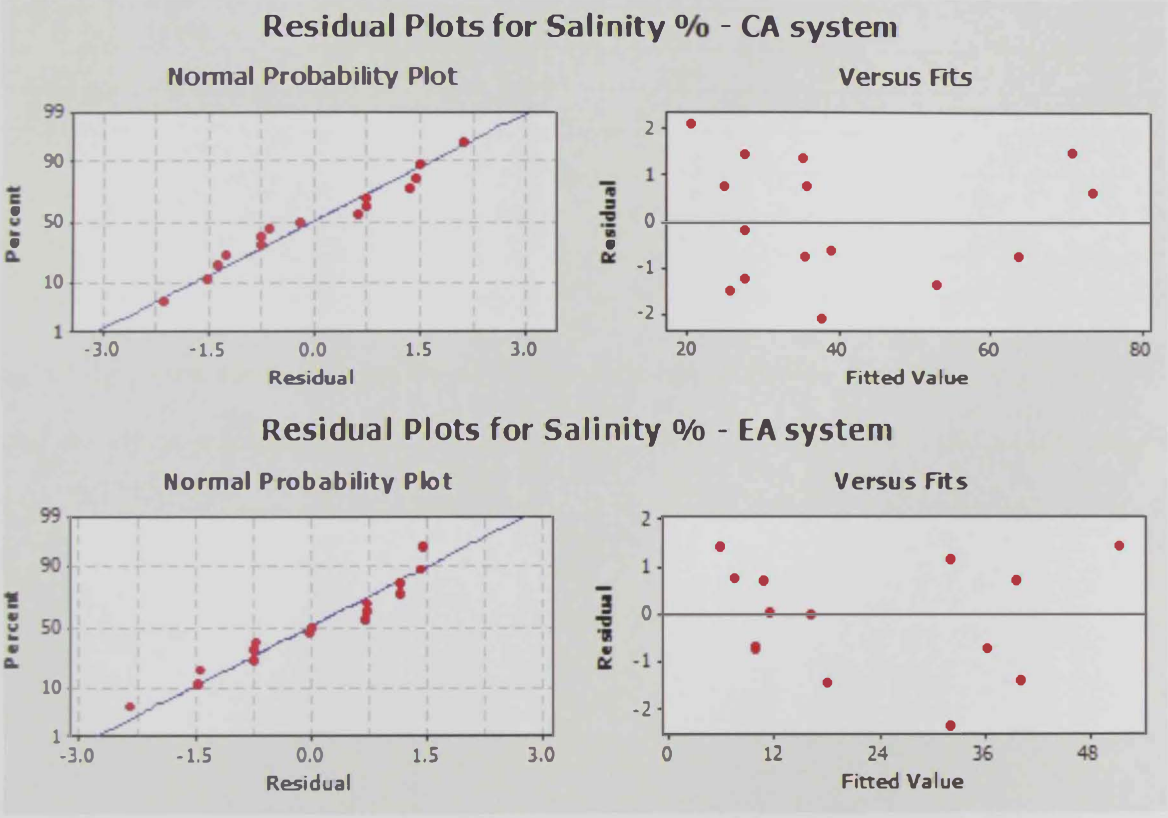


Figure 51: Residual plots for Salinity % reduction - CA and EA systems

4.3. CARBON DIOXIDE CAPTURING

To find the efficiency of CO_2 capturing, area under the curve of the CO_2 captured values with time must be calculated using the graph software.

Moles of CO_2 captured = [Area * Flow rate (L/min)* (1 mole CO_2/ 22.4 L)]* (10/100) of CO_2

Moles of CO_2 IN = [flow rate (L/ min) * Time (min) * (1 mole CO_2/ 22.4 L) * 0.1 of CO_2]

CO_2 Capturing efficiency (%) = moles of CO_2 captured / moles of CO_2 IN

Table 22: CO_2 capturing efficiency (%)

RO	Area	Total CO_2 IN (mole)	CO_2 Captured (mole)	CO_2 Capturing efficiency (%)
1	11227	10.45	6.52	62.37
2	11227	10.45	6.52	62.37
3	9212.5	10.45	5.35	51.18
4	9864.5	10.45	5.72	54.80
5	5945.4	10.45	3.45	33.03
6	11142.5	10.45	6.47	61.90
7	11698	10.45	6.79	64.99
8	4063.5	10.45	2.36	22.58
9	11700.5	10.45	6.79	65
10	4476	10.45	2.59	24.87
11	13129	10.45	7.62	72.94
12	15111	10.45	8.76	83.95
13	11900.5	10.45	6.91	66.11
14	9474.25	10.45	5.49	52.63
15	4184.25	10.45	2.43	23.25

Fig. 52 shows that the perfect conditions for capturing carbon dioxide from air were 9.5, 35 and 284 A/m^2 for pH, temperature and current density, respectively; the highest CO_2 capture efficiency was 84%.

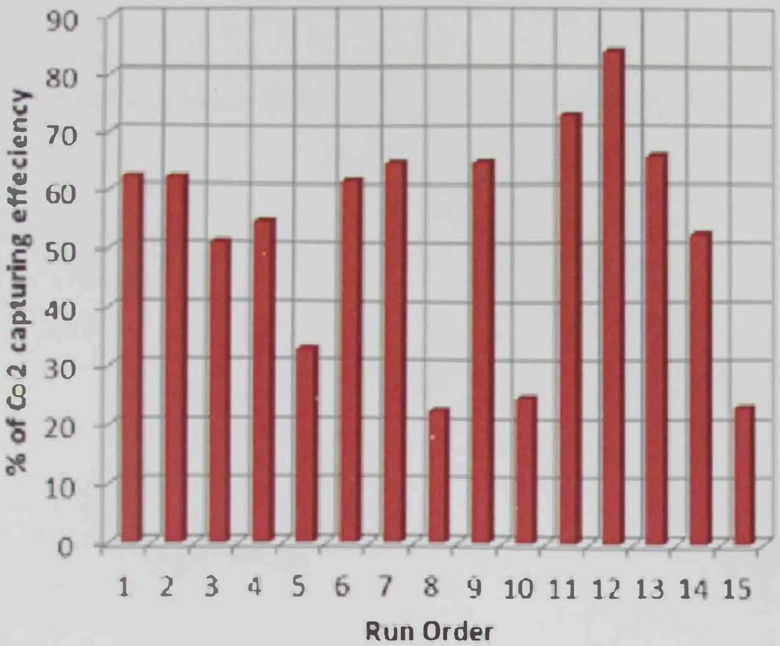


Figure 52: % of CO_2 capturing effeciency vs. Run order

The CO_2 capture has no correlation with any of the independent variables (Table 23).

The analysis was done using coded units.

Table 23: Estimated Regression Coefficients for CO_2 Capturing efficiency (%)

Term	Coef	SE Coef	T	P
Constant	27.5801	1.698	16.246	0.000
pH	15.8754	1.040	15.270	0.000
Temp	1.2953	1.040	1.246	0.268
CD	6.7073	1.040	6.452	0.001
pH*pH	20.7935	1.530	13.588	0.000
Temp*Temp	4.6442	1.530	3.035	0.029
CD*CD	-2.4613	1.530	-1.608	0.169
pH*Temp	3.3247	1.470	2.261	0.073
pH*CD	1.8762	1.470	1.276	0.258
Temp*CD	-0.3185	1.470	-0.217	0.837

R-Sq = 60.60% R-Sq(pred) = 0.00% R-Sq(adj) = 0.00%

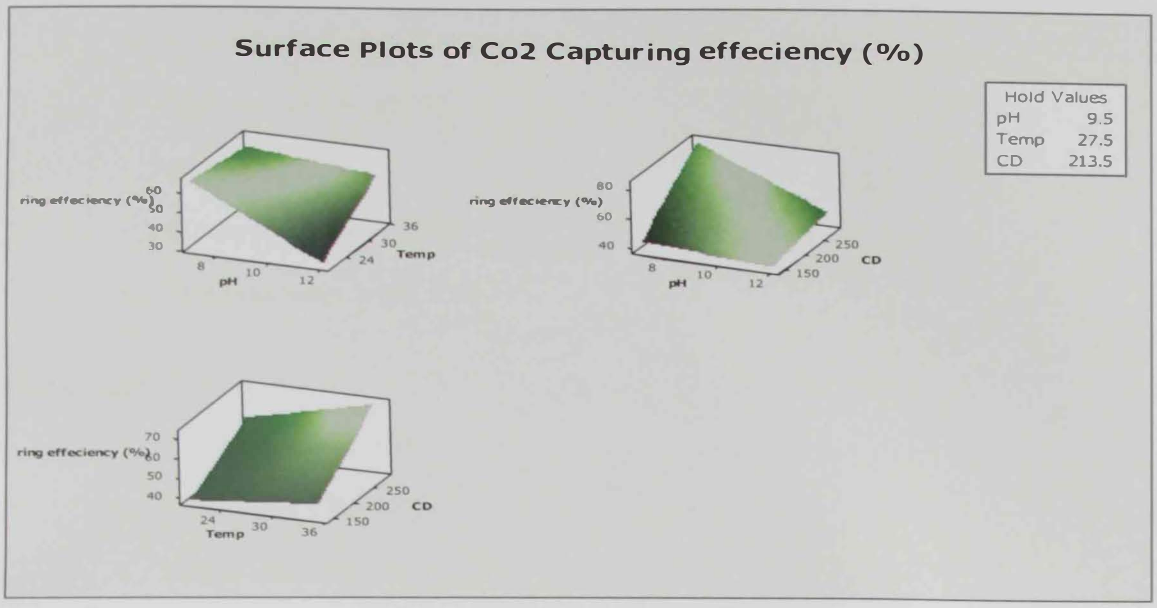


Figure 53: Correlations between pH, temperature and current density of CO_2 capturing efficiency % reduction in CA system

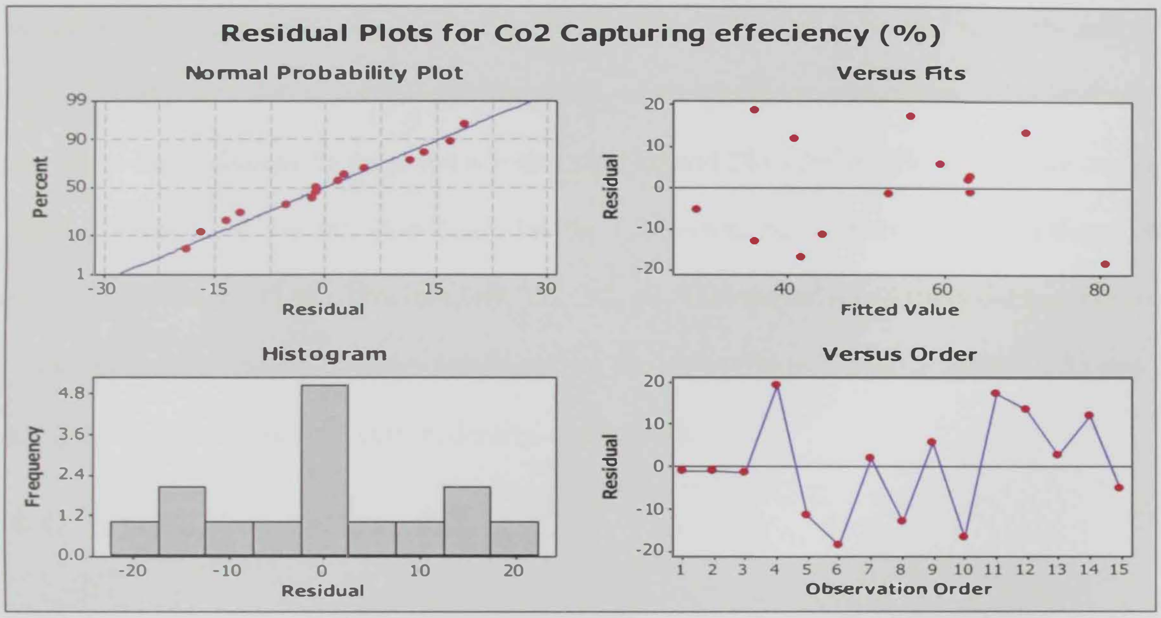


Figure 54: Residual plots for CO_2 Capturing efficiency (%)

From the aforementioned discussion, it could be concluded that:

For EA system:

- COD reduction = fn (pH, T, CD)
- TH reduction = fn (pH, T)
- EC = fn (pH, CD)
- Salinity reduction = fn (pH)
- TDS reduction = fn (pH, CD)

For CA system:

- TH reduction = fn (pH)
- EC = fn (pH, CD)
- Salinity reduction = fn (pH, CD)
- TDS reduction = fn (pH, CD)

To conclude, the best treatment time had chosen 3 hours for both systems because it yielded the highest reduction efficiencies for the EA system (around 47.47%, 47.75%, 69.66%, 36.1%, 71.4% and 53% for COD, TH, EC, pH, TDS and salinity), respectively under specific conditions and the overall optimum conditions for the highest % reduction is under 12, 27.5 and 284 A/m^2 as pH, temperature and current density, respectively. On the other hand, for the CA system, the highest reduction efficiencies are (42%, 75%, 73%,46, 73 and 74% for COD, TH, EC, pH, TDS and salinity), respectively under specific conditions and the overall optimum conditions for the highest % reduction is under 12, 35 and 213.5 A/m^2 as pH, Temperature and current density, respectively.

4.4. IMPACT OF INITIAL PH

To study the performance of the electrocoagulation process, initial pH of the solution is one of the parameters that should be studied (Do and Chen, 1994; Tir and Mostefa, 2008). It is concluded by the researchers (Daneshvar et al.,2006; Yýldýz et al., 2008) that the pH of the reaction solution changes during the electrocoagulation process and the final pH of the effluent actually affects the overall treatment performance. When the initial pH value is less than 4 (acidic), the effluent pH increases, while it tends to decrease when the initial pH value is higher than 8 (basic), and the pH of the effluent changes only slightly when the initial pH value is in the neutral range (around 6–8) (Kabdaşl1 et al., 2012). The value of the pH was detected that the pH of the processed industrial wastewater increased when the pH of the effluent between (4-7) that is because of the hydrogen evolution at cathodes by Vik et al. (1984) and because of the release of CO_2 from industrial wastewater owing to H_2 bubble disturbance by Chen (2004) In addition, the chemical dissolution of aluminium gives rise to the pH increase which could be explained by the excess of hydroxyl ions produced at the cathode and by the liberation of OH- due to the occurrence of a partial exchange of Cl^- with OH- in $Al(OH)^3$ (Feng et al., 2007). Fig 55 and 56 show that the effect of pH on COD and TH reduction efficiencies in CA and EA systems are 7 and 12, 12 and 12, respectively.

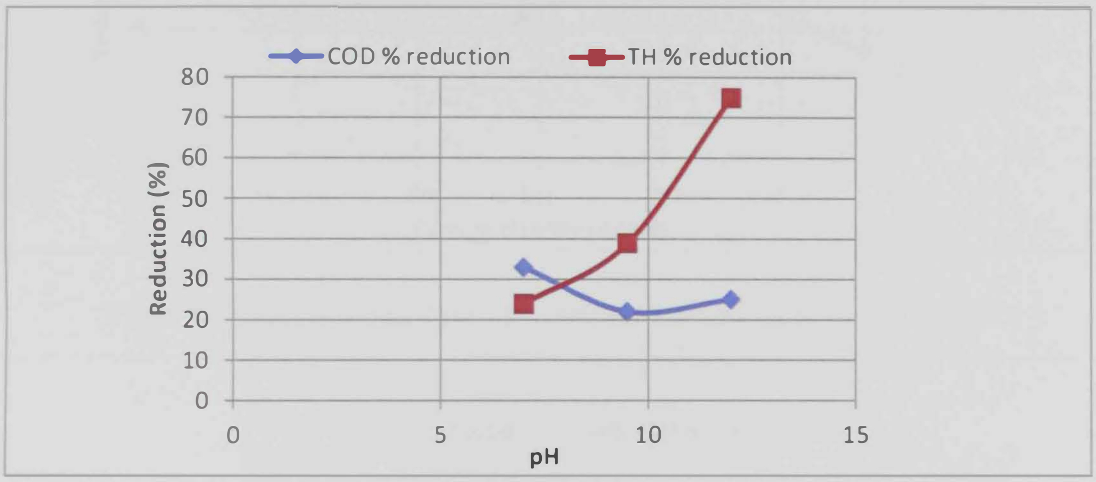


Figure 55: Impact of initial pH for COD and TH % reduction – CA system

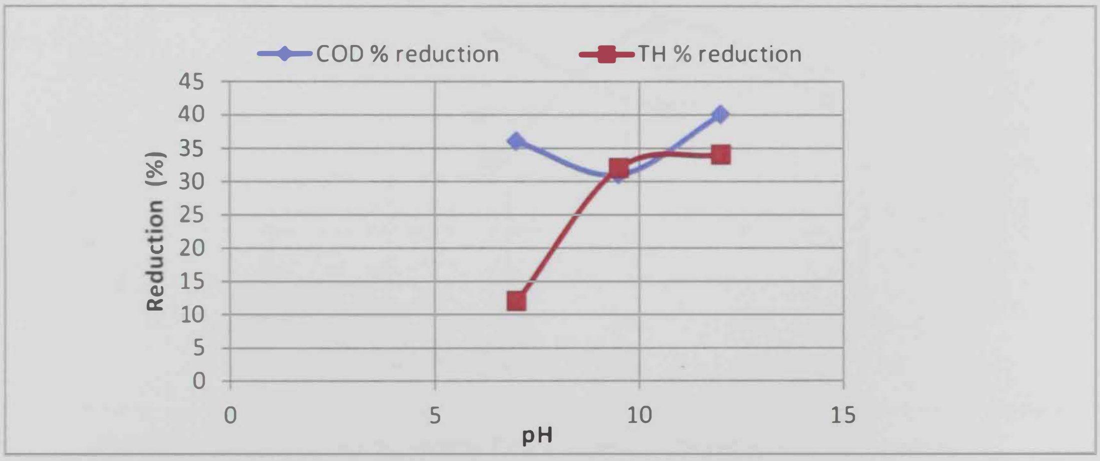


Figure 56: Impact of initial pH for COD and TH % reduction – EA system

4.5. IMPACT OF CURRENT DENSITY

Depicts the effect of current density on COD and TH reduction efficiencies in CA and EA systems are “213.5 and 143 A/m^2 “and “284 and 213 A/m^2”, respectively is required for good efficiencies (Fig. 57 and 58).

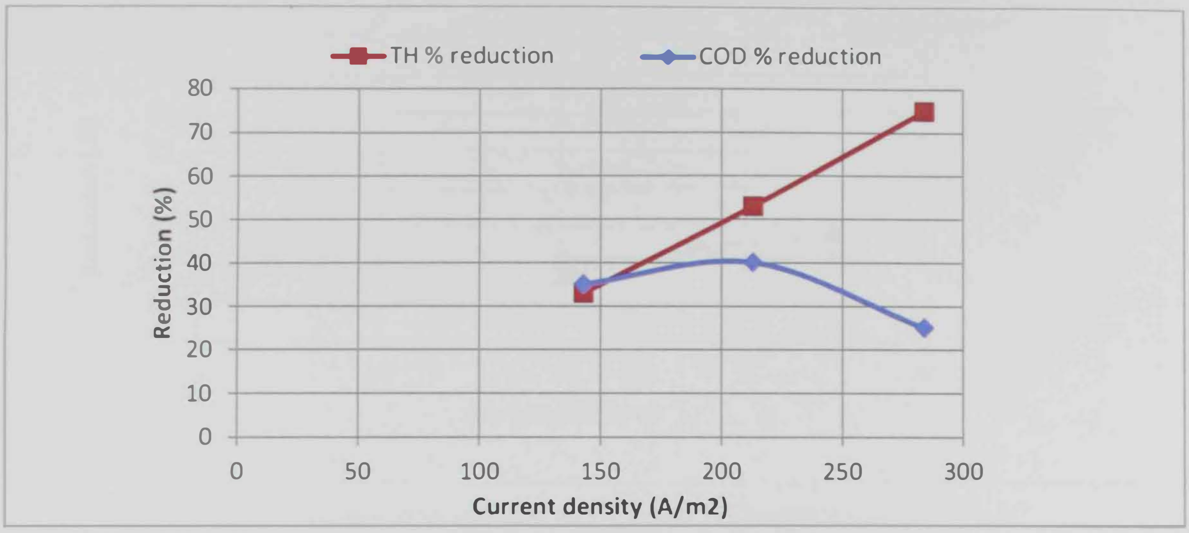


Figure 57: Impact of current density for COD and TH % reduction – CA system

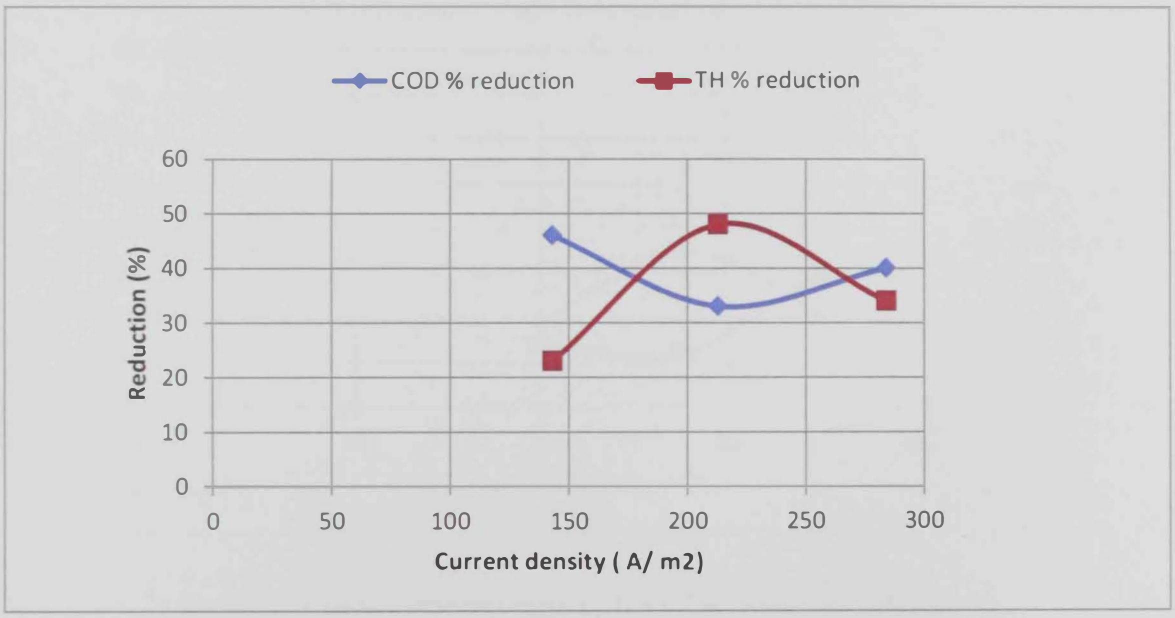


Figure 58: Impact of current density for COD and TH % reduction – EA system

4.6. IMPACT OF TEMPERATURE

Fig 59 shows that there is no effective relation when changing the temperatures on the COD, TH and EC responses in CA system. However, In EA systems the impact of temperatures on COD and TH reduction efficiencies are 27.5 and 35 °C as shown in Fig. 60.

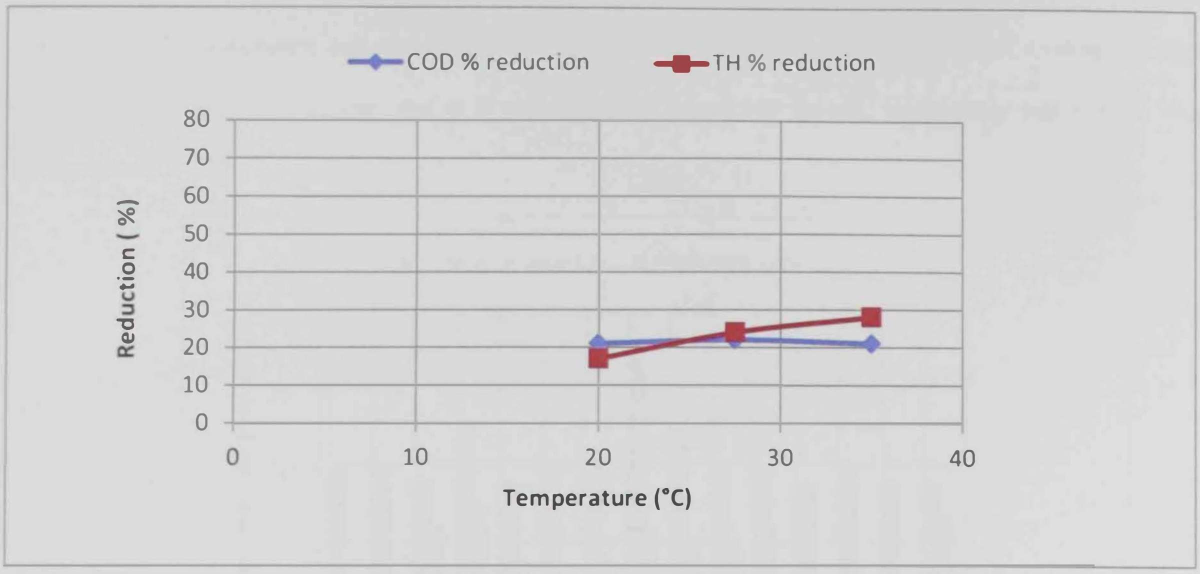


Figure 59: Impact of temperature for COD and TH % reduction – CA system

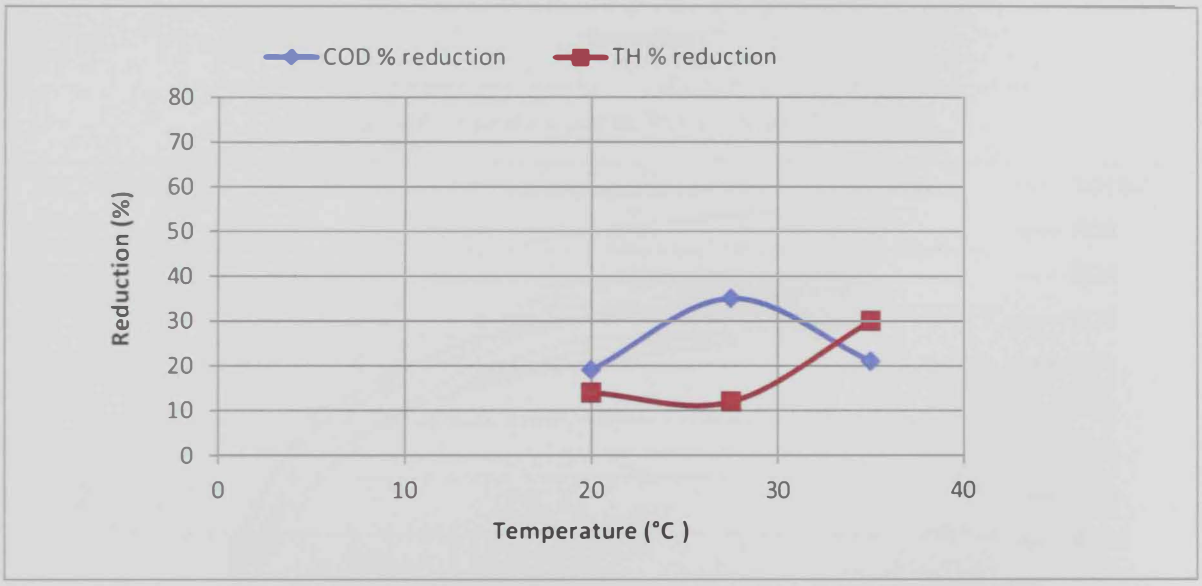


Figure 60: Impact of temperature for COD and TH % reduction – EA system

4.7. SLURRY WASTE CHARACTERISTICS SUCH AS FILTERABILITY AND SETTLING TESTS

4.7.1 Filterability test

As shown in Fig.61 the highest filterability rate in CA system is 17 ml/min and it is under condition 9.5, 20, 143 A/m^2 as pH, temperature and current density respectively. On the other hand, In EA system the highest filterability rater is 7.5 ml/min and it is under 12, 27.5 and 143 as pH, temperature and current density respectively

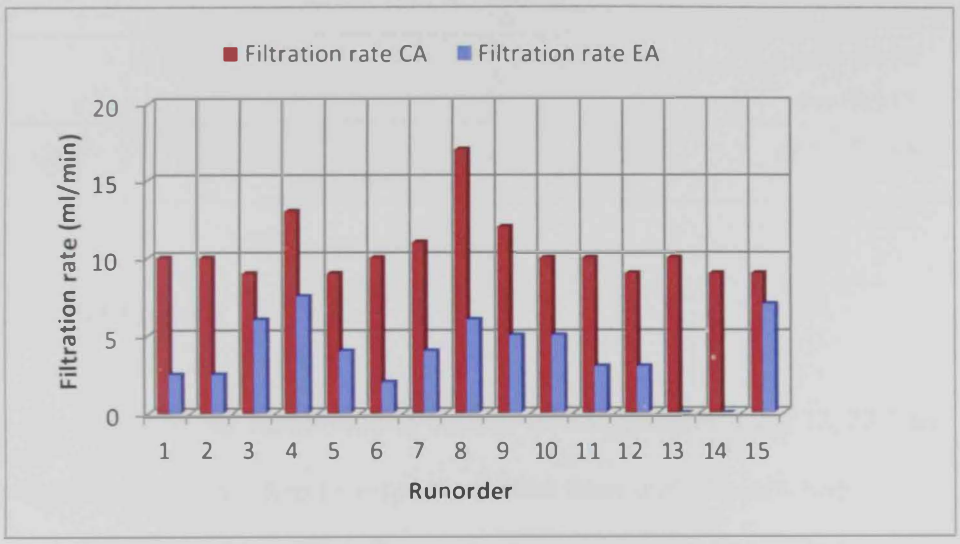


Figure 61: Filtration rate vs. RO in CA and EA systems

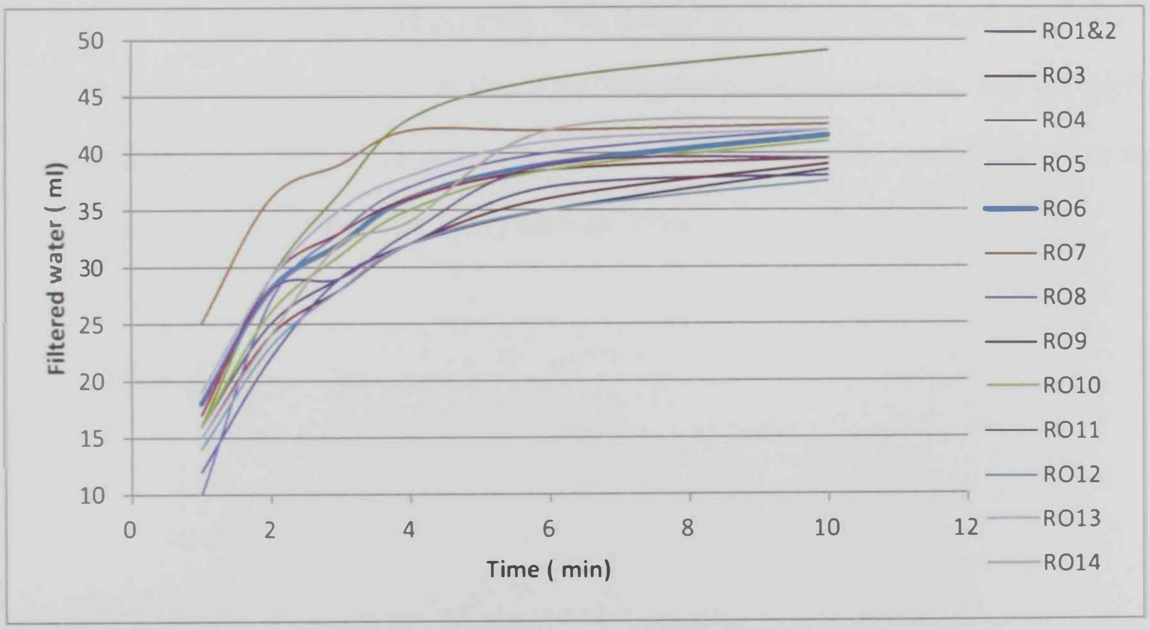


Figure 62: Filterability test- CA system

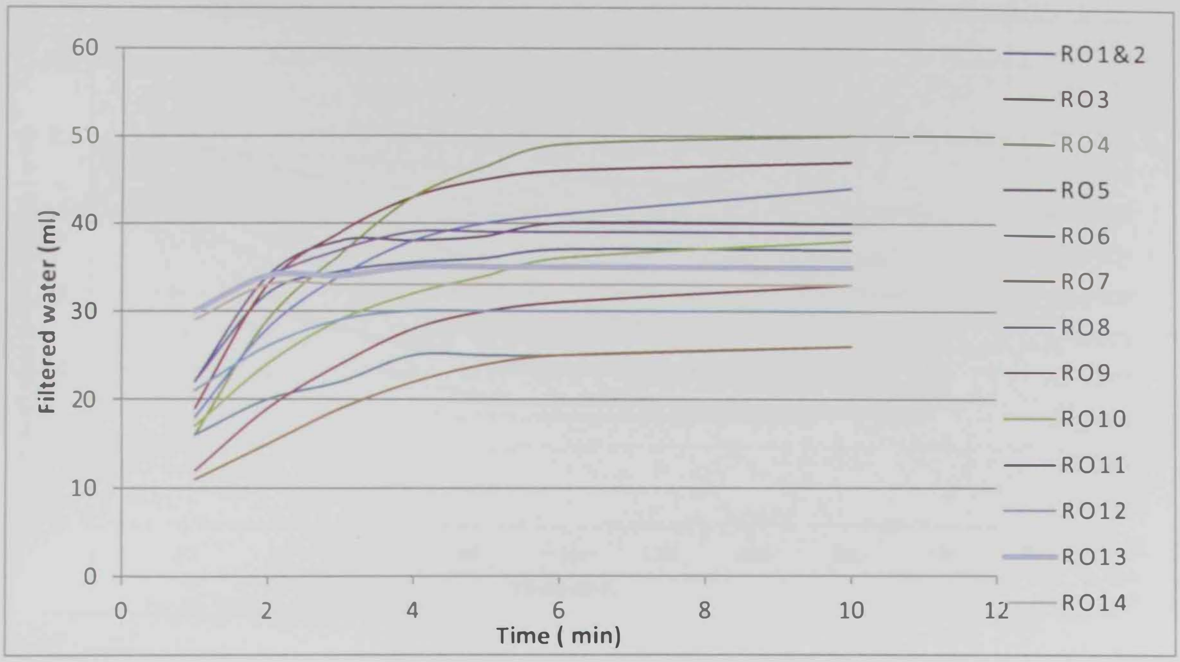


Figure 63: Filterability test - EA system

4.7.2. Settling test

As shown in Fig. 64 and 65 the fastest settling velocity in CA system is under 12, 27.5 and 143 A/m^2 as pH, temperature and current density respectively and these particles are huge, heavy, spherical molecules. In EA system the fastest settling velocity is under 12, 35 and 213.5 A/m^2 as pH, temperature and current density respectively. The slowest settling particles, which sometimes cannot be settled accurately or properly, are tiny, light, irregularly shaped molecules. And for anything in between, here is a general guide as to what characteristics increase the rate of thickening such as: spherical or near-spherical particles, heavy particles, dilute slurries and concentration.

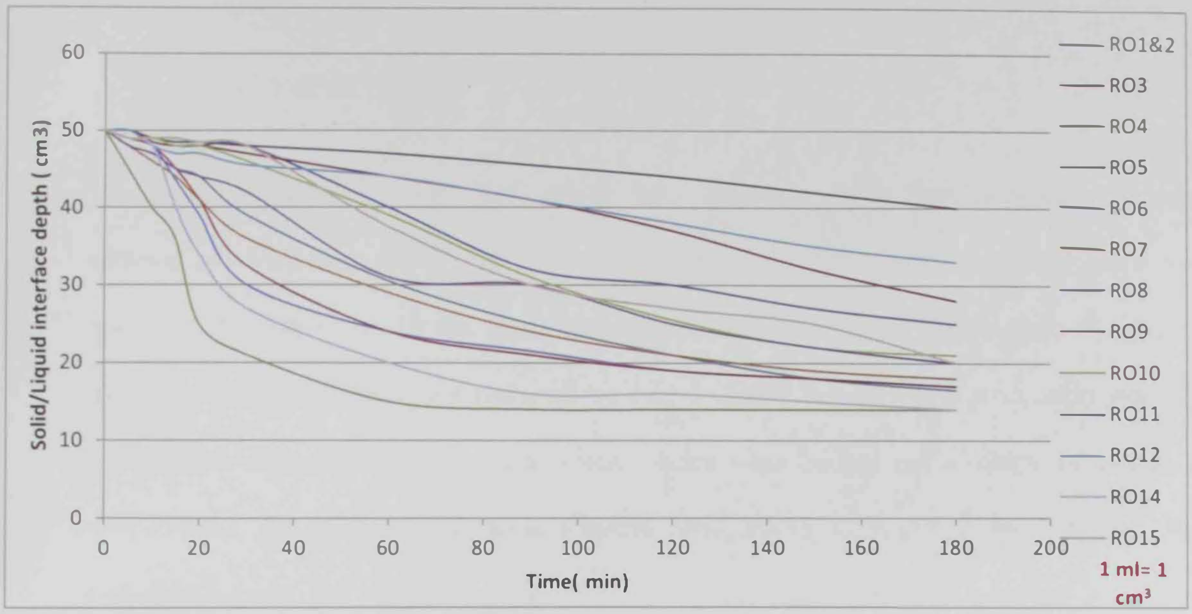


Figure 64: Sludge settling velocity test – CA system

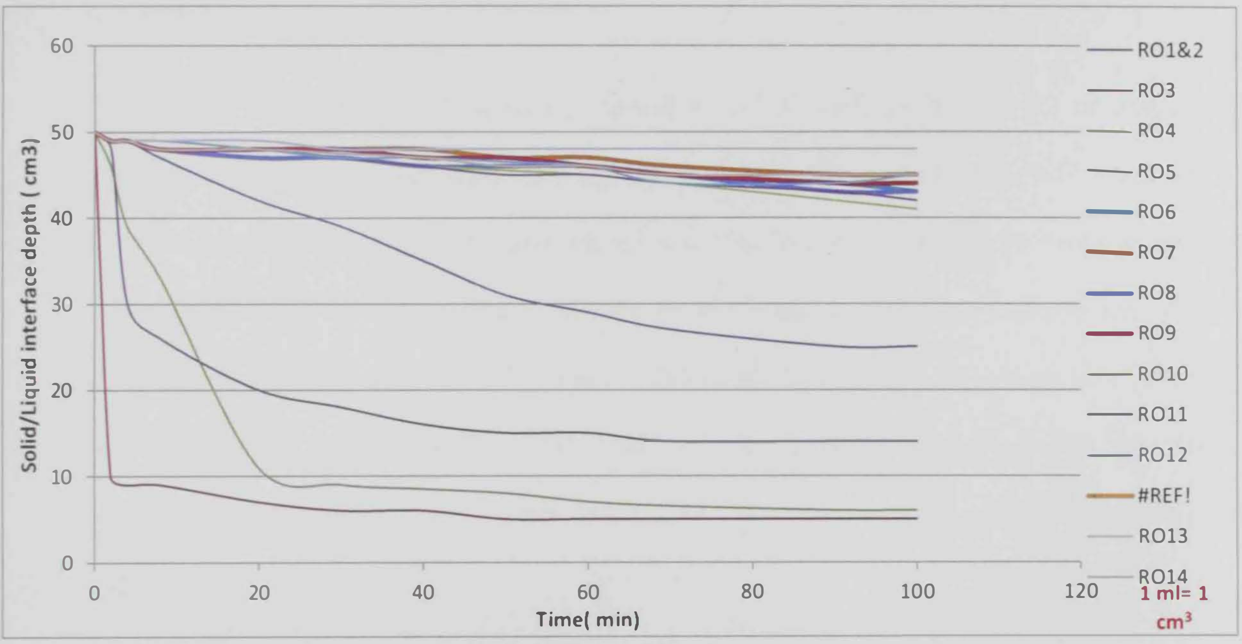


Figure 65: Sludge settling velocity test - EA system

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

Wastewater treatment by electrocoagulation is an environmentally friendly process that requires no addition of chemicals, yields high quality effluent, and requires short treatment times and simple operation. The objectives of this thesis were to evaluate the potential use of electrocoagulation in the treatment of carbide slurry; a wastewater generated during the acetylene production process. Several experiments using an electrochemical batch reactor were carried out at different current densities, temperatures, and pH ranging between 140-290 A/m^2, 20-35 °C, and 7-12, respectively. The pure air (EA system) and the 10% of carbon dioxide (CA system) were used to ensure good mixing and solution homogeneity. Below is a summary of the study's major findings:

EA system

The highest TH reduction (48%) were obtained at 213.5 A/m^2, 35 °C, and 12 of current density, temperature, and pH, respectively. The highest COD reduction was (47%) at 143 A/m^2, 35 °C, and 9.5of current density, temperature, and pH, respectively. In addition, the highest reduction of salinity (53%) and TDS (71%) were recorded while the electrochemical reactor operated at current density, pH and temperature of 213.5 A/m^2, 35 °C, and 12, 284 A/m^2, 27.5 °C, and 12, respectively. Furthermore, statistical analysis showed that COD, TH, TDS, and salinity reduction were significantly affected and function of pH, temperature, and current density, pH and temperature, pH and current density, and pH, respectively.

CA system

The highest COD reduction (41%) was obtained at 143 A/m^2, 35 °C, and 9.5 of current density, temperature, and pH, respectively. The maximum TH reduction (75%) was reported while 284 A/m^2, 27.5 °C, and 12 of current density, temperature, and pH, respectively were implemented. In addition, the highest reduction of salinity (74%) and TDS (74%) were recorded while the electrochemical reactor operated at current density, pH and temperature of 213.5 A/m^2, 35 °C, and 12, respectively. The highest CO_2 capture (84%) was obtained at 284 A/m^2, 35 °C, and 9.5 of current density, temperature, and pH, respectively Moreover, statistical analysis showed that TH, TDS, and salinity reduction were significantly affected and function of pH, current density, and pH, and pH and current density, respectively.

Finally, it could be summarized that the quality of the treated wastewater as well as the generated by-products could be enhanced through controlling the operating conditions in the electrochemical reactor. Electrocoagulation process can enhance the reduction efficiency of COD, TH, electrical conductivity, salinity, TDS and, at the same time, contribute to carbon dioxide capture. Overall, this research study showed that electrocoagulation is environmentally compatible and reliable technique for the management of carbide slurry wastewater.

5.2. RECOMMENDATIONS

Based on the experimental results obtained in the present study, the following future studies are recommended:

1. Evaluate the continuous operation of an electrocoagulation reactor for the treatment of carbide slurry at the obtained optimum conditions.
2. Carry out numerical modeling for the rate of reduction of COD, TH, TDS and salinity at different operating conditions
3. Expand the study into a pilot-scale to evaluate its performance at different operating conditions.

REFERENCES

- Abuzaid N.S., Bukhari A.A., and Al-Hamouz Z.M.(1998). Removal of bentonite causing turbidity by electrocoagulation. Journal of Environmental Science and Health, Part A 33 (7), 1341-1358.
- American Public Health Association, American Water Works Association, Water
- Environment Federation. (1999): "Standard Methods for the Examination of Water and Wastewater", 20th edition.
- APHA, AWWWA, WPCF (1998). Standard method for the examination of water and wastewater, 20th Edition, Washington DC.
- Aylesworth-Spink, S. Walkerton Affects Today's Drinking Water System. http://www.suite101.com/content/walkerton-effects-todays-drinking-water-systema96164. 2009, 02 28. (Accessed 09 2010)
- Bani-Melhem, K. and Elektorowicz, M. (2010). Development of a Novel Submerged Membrane Electro-Bioreactor (SMEBR): Performance for Fouling Reduction. Environmental Science and Technology. 44(9): 3298-3304. doi: 10.1021/es902145g.
- Barkley, N.P., Farrell, C.W. and Gardner-Clayson, T.W., (1993). Alternating current electrocoagulation for superfund sit.0e remediation. Air Waste 43, 784–789.
- Bratby, J. (2006). Coagulation and Flocculation in Water and Wastewater Treatment.London: IWA Publishing., London, Britain.
- Chen G., Chen X., and Yue P.L. (2000). Electrocoagulation and electroflotation of restaurant wastewater. Journal of Environmental Engineering, 126 (9), 858-863.
- Choua W.L., TaWang C. and Chang S.Y., (2009). Study of COD and turbidity removal from real oxide-CMP wastewater by iron electrocoagulation and the evaluation of specific energy consumption. Journal of Hazardous Materials 168 1200–1207.

- Cosgrove, T. (2010). Colloids Science - Principles, Methods and Applications: John Wiley and Sons.West Sussex, United Kingdom
- Daneshvar, N., Oladegaragoze, A. and Djafarzadeh, N. (2006). Decolorization of basic dye solutions by electrocoagulation: an investigation of the effect of operational parameters. J. Hazard. Mater., 129, 116–122.
- Dooley, J.J. and M.A. Wise, (2003): Retention of CO2 in Geologic Sequestration Formations: Desirable Levels, Economic Considerations, and the Implications for Sequestration R&D. Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies. J. Gale and Y. Kaya (eds). Elsevier Science, Amsterdam pp. 273–278.
- Do, J. S. and Chen, M. L. (1994). Decolorization of dyecontaining solutions by electrocoagulation. J. Appl. Electrochem., 24, 785–790.
- Dubai Municipality Environmental Standards and Allowable Limits of Pollutants on Land, Water and Air Environment (2007).
- El-Naas, M. H.; Al-Marzouqi, A. H. and Chaalal, O., (2010). A combined approach for the management of desalination rejects brine and capture of CO_2. Desalination, 251, 70–74.
- Feng, J. W., Sun, Y. B., Zheng, Z., Zhang, J. B., Li, S. and Tian, Y. C. (2007). Treatment of tannery wastewater by electrocoagulation. J. Environ. Sci., 19, 1409–1415.
- Fenglian Fu. and Wang Qi., (2010). Removal of heavy metal ions from wastewaters. Journal of Environmental Management 92 407 - 418
- Ferreira S.L.C., Bruns R.E. , Ferreira H.S., Matos G.D., David J.M., Brand G.C., da Silva E.G.P., Portugal LA., dos Reis P.S., Souza A.S. and dos Santos W.N.L., (2007). Box-Behnken design: An alternative for the optimization of analytical methods. Analytica Chimica Acta 597(179–186)
- G.E.P. Box, D.W. Behnken, Technometrics 2 (1960) 195.

- Hamad, S., (2008). 'Spatial analysis of groundwater level and hydrochemsitry in the south Al Jabal Al Akhdar area using GIS'. Salzburg University, Salzburg. (Master thesis)
- Hasan, Shadi (2012). Design and Performance of a Pilot Submerged Membrane Electro-Bioreactor (SMEBR) for Wastewater Treatment. PhD thesis, Concordia University.
- Hirzallah, W. (2011). Effectiveness of Electrochemical Treatment of Municipal Sewage. MSc. thesis, Concordia University.
- Holt P.K., Barton G.W. and Mitchell C.A., (2006). The future for electrocoagulation as a localized water treatment technology. In: 6th World Congress of Chemical Engineering Conference Media CD, Melbourne, Australia. Chemosphere 59 (2005) 355–367.
- Holt, P.K., Barton, G.W. and Mitchell C.A., (2001). The role of current in determining pollutant removal in a batch electrocoagulation reactor. In: 6th World Congress of Chemical Engineering Conference Media CD, Melbourne, Australia.
- Huang, H. P.; Shi, Y.; Li, W. and Chang, S. G. (2001). Dual alkali approaches for the capture andseparation of CO_2. Energy. Fuels. 15, 263–268.
- Huijgen, W. J. J. and Comans, R. N. J. (2003). Carbon dioxide sequestration by mineral carbonation – literature review. ECN-C-03-016.
- Kabdaþlý, I., Arslan-Alaton, I., Ölmez-Hancý, T. and Tünay, O. (2012). Electrocoagulation applications for industrial wastewaters: a critical review. Environ. Technol.Reviews, 1 (1), 2-45.
- M.-S. Jo et al. 2008. An analysis of synergistic and antagonistic behavior during BTEX removal in batch system using response surface methodology. Journal of Hazardous Materials 152(3): 1276-1284.
- Malakootian M. and Yousefi N., (2009). The efficiency of electrocoagulation process using aluminum electrodes in removal of hardness from, Iran. J. Environ. Health. Sci. Eng., Vol. 6, No. 2, pp. 131-136.

- Mameri N., Yeddou A.R., Lounici H., Belhocine, D., Grib, H. and Bariou, B., (1998). Defluoridation of septentrional Sahara water of North Africa by electrocoagulation process using bipolar aluminium electrodes. Water Res. 32, 1604–1612.
- Mason R.L, Gunst RF and Hess J.L. (2003). Statistical Design and Analysis of Experiments: With Applications to Engineering and Science: John Wiley & Sons, Inc.
- Matteson M.J., Dobson R.L., Glenn R.W.J., Kukunoor N.S., Waits W.H.I. and Clayfield E.J., (1995). Electrocoagulation and separation of aqueous suspensions of ultrafine particles. Colloids Surf., A 104, 101–109.
- Metcalf and Eddy, Inc., (2003) Wastewater Engineering, Treatment and Reuse, fourth edition New York: McGraw-Hill.
- Mikko Vepsäläinen, (2012). Electrocoagulation in the treatment of industrial waters and wastewaters. PhD thesis, Lappeenranta University of Technology – Finland.
- Mollah, Y.A. Mohammad, Morkovsky Paul, Gomes, A.G., Jewel, Kesmez, M., Parga J., Cocke, L David, (2004). Fundamentals, present and future perspectives of electrocoagulation. Journal of Hazardous Materials B114 199–210.
- Mulligan, C. N., (2002). Environmental biotreatment: technologies for air, water, soil, and waste. Government Institutes, Michigan.
- Ni'am M.F., Othman F., Sohaili J. and Fauzia Z., (2007). Electrocoagulation technique in enhancing COD and suspended solids removal to improve wastewater quality. Water Science & Technology Vol 56 No 7 pp 47–53 Q IWA Publishing.
- Paul A.B., (1996). Proceedings of the 22nd WEDC Conference on Water Quality and Supply, New Delhi, India, 1996, p. 286.
- Pouet, M.F., Grasmick, A., (1995). Urban wastewater treatment by electrocoagulation and flotation. Water Sci. Technol. 31, 275–283.

- Ramesh, R. B., Bhadrinarayana ,N. S., Meera, S. B. K. M. and Anantharaman, N., (2007). treatment of tannery Waste water by electro coagulation, Journal of the University
- Song, C.; Gaffney, A. F. and Fujimoto, K., (2002). CO_2 conversion and utilization: an overview. Edited by American Chemical Society, Washington, DC, ACS Symposium Series 809.112–116.
- Tchabonglous, G., and Metcalf and Eddy. (1979). Wastewater engineering: treatment, disposal and reuse. McGraw-Hill, Newyork.
- Tchobanoglous G. and Schroeder E. (1987). Water quality.
- Tchamango S., Nanseu-Njiki P., Ngameni E., Hadjiev D. and Darchen A.(2010). Treatment of dairy effluents by electrocoagulation using aluminium electrodes. Science of the Total Environment 408 947–952
- Tir, M. and Moulai-Mostefa, N. (2008). Optimization of oil removal from oily wastewater by electrocoagulation using response surface method. J. Hazard. Mater., 158, 107–115.
- Varank, G., Erkan, H., Yazýcý, S., Demir, A. and Engin, G., (2014). Electrocoagulation of Tannery Wastewater using Monopolar Electrodes:Process Optimization by Response Surface Methodology. Int. J. Environ. Res., 8(1):165-180, Winter, ISSN: 1735-6865.
- Vik A., Carlson D.A., Eikum A.S. Gjessing, Water Res. 18 (11) (1984) 1355.
- Vik, E. A., Carlson, D. A., Eikum, A. S. and Gjessing, E. T. (1984). Electrocoagulation of potable water. Water Res., 18, 1355–1360.
- World Health Organization, (2008), “Guidelines for drinking-water quality”. Third edition.
- Yoshida, M.; Fujita, M.; Ishii, T. and Ihara, M., 2003. A novel methodology for the synthesis of cyclic carbonates based on the palladium - catalyzed ascade reaction of 4-methoxycarbonyloxy-2-butyn-1-ols with phenols, involving a novel carbon dioxide elimination-fixation process. J. Am. Chem. Soc., 125, 4874–4881.

- Yýldýz, Y. S., Koparal, A. S. and Keskinler, B. (2008). Effect of initial pH and supporting electrolyte on the treatment of water containing high concentration of humic substances by electrocoagulation. Chem. Eng. J., 138, 63– 72.
- Zeta Potential of colloids in water and wastewater. (1985). American Society for Testing and Materials (ASTM Standard D 4187-82).

Websites:

- http://www.freedrinkingwater.com/water-education2/74-alkalinity-water.htm
- http://ga.water.usgs.gov/edu/phdiagram.html
- http://water.epa.gov/type/rsl/monitoring/vms59.cfm
- www.epa.gov
- http://www.sigmaplot.com/products/sigmaplot/sif.php
- http://download.cnet.com/Graph/3000-2053_4-10063417.html)
- www.wikipedia.com

APPENDIX

10% CO_2 - CA SYSTEM

Table 24: Combination of experiments obtained from Response Surface Method – CA system

pH	Temp	CD	COD %	TH %	EC %	pH %	TDS %	Salinity %	Co2 Capturing effeciency (%)	RunOrder
9.5	27.5	213.5	21.69	38.17	24.85	38.86	24.85	29.05	62.37	1
9.5	27.5	213.5	22.09	39.33	23.10	37.01	23.10	27.37	62.37	2
12	35	213.5	41.16	52.94	72.99	41.54	73.84	74.39	51.18	3
12	27.5	143	34.82	32.88	49.12	40.87	50.55	51.45	54.80	4
12	27.5	284	25.25	75.00	70.39	41.00	71.99	72.50	33.03	5
7	27.5	284	22.89	23.77	34.67	24.40	36.69	36.62	61.90	6
7	20	213.5	20.96	16.67	37.00	28.95	37.99	38.30	64.99	7
9.5	20	143	23.17	17.29	21.85	40.04	22.19	22.44	22.58	8
7	35	213.5	21.33	28.95	34.76	18.76	35.83	36.36	65.00	9
9.5	35	143	33.61	9.07	24.11	36.12	25.00	25.55	24.87	10
9.5	20	284	25.35	19.68	35.73	46.17	34.10	34.62	72.94	11
9.5	35	284	23.91	43.83	33.94	42.95	35.14	35.44	83.95	12
9.5	27.5	213.5	18.94	43.51	24.93	42.64	26.03	26.32	66.11	13
7	27.5	143	16.61	33.21	22.61	18.14	23.01	24.08	52.63	14
12	20	213.5	24.38	59.57	60.73	44.17	62.34	63.02	23.25	15

100% Air – EA System

Table 25 Combination of experiments obtained from Response Surface Method – EA system

pH	Temp	CD	COD %	TH %	EC %	pH %	TDS %	Salinity %	TSS %	RunOrder
9.5	27.5	213.5	31.21	31.84	32.90	20.41	32.10	33.41	126.18	1
9.5	27.5	213.5	31.21	31.84	32.90	20.41	32.10	33.41	126.18	2
12	35	213.5	33.26	47.75	53.88	11.95	55.67	53.01	400.00	3
12	27.5	143	45.76	23.52	38.33	36.08	40.38	35.72	1260.81	4
12	27.5	284	40.64	33.71	69.67	12.99	71.41	38.72	432.93	5
7	27.5	284	35.59	12.06	11.51	-5.03	10.34	8.08	373.48	6
7	20	213.5	18.68	13.69	11.82	-18.15	12.01	16.39	508.43	7
9.5	20	143	41.64	12.08	4.10	17.93	7.06	11.47	571.30	8
7	35	213.5	21.98	30.86	4.33	-11.38	2.09	8.97	133.33	9
9.5	35	143	47.47	22.56	4.67	16.95	5.17	9.00	310.00	10
9.5	20	284	30.96	20.54	14.39	11.03	14.73	11.28	420.24	11
9.5	35	284	44.91	20.58	19.43	11.02	18.49	16.01	279.67	12
9.5	27.5	213.5	29.42	28.98	28.64	18.74	28.19	29.90	84.86	13
7	27.5	143	43.32	11.81	12.92	-10.62	15.93	7.01	541.37	14
12	20	213.5	31.21	31.84	32.90	20.41	32.10	33.41	126.18	15

APPENDIX

10% CO_2 - CA SYSTEM

Table 24: Combination of experiments obtained from Response Surface Method – CA system

pH	Temp	CD	COD %	TH %	EC %	pH %	TDS %	Salinity %	Co2 Capturing effeciency (%)	RunOrder
9.5	27.5	213.5	21.69	38.17	24.85	38.86	24.85	29.05	62.37	1
9.5	27.5	213.5	22.09	39.33	23.10	37.01	23.10	27.37	62.37	2
12	35	213.5	41.16	52.94	72.99	41.54	73.84	74.39	51.18	3
12	27.5	143	34.82	32.88	49.12	40.87	50.55	51.45	54.80	4
12	27.5	284	25.25	75.00	70.39	41.00	71.99	72.50	33.03	5
7	27.5	284	22.89	23.77	34.67	24.40	36.69	36.62	61.90	6
7	20	213.5	20.96	16.67	37.00	28.95	37.99	38.30	64.99	7
9.5	20	143	23.17	17.29	21.85	40.04	22.19	22.44	22.58	8
7	35	213.5	21.33	28.95	34.76	18.76	35.83	36.36	65.00	9
9.5	35	143	33.61	9.07	24.11	36.12	25.00	25.55	24.87	10
9.5	20	284	25.35	19.68	35.73	46.17	34.10	34.62	72.94	11
9.5	35	284	23.91	43.83	33.94	42.95	35.14	35.44	83.95	12
9.5	27.5	213.5	18.94	43.51	24.93	42.64	26.03	26.32	66.11	13
7	27.5	143	16.61	33.21	22.61	18.14	23.01	24.08	52.63	14
12	20	213.5	24.38	59.57	60.73	44.17	62.34	63.02	23.25	15

100% Air – EA System

Table 25 Combination of experiments obtained from Response Surface Method – EA system

pH	Temp	CD	COD %	TH %	EC %	pH %	TDS %	Salinity %	TSS %	RunOrder
9.5	27.5	213.5	31.21	31.84	32.90	20.41	32.10	33.41	126.18	1
9.5	27.5	213.5	31.21	31.84	32.90	20.41	32.10	33.41	126.18	2
12	35	213.5	33.26	47.75	53.88	11.95	55.67	53.01	400.00	3
12	27.5	143	45.76	23.52	38.33	36.08	40.38	35.72	1260.81	4
12	27.5	284	40.64	33.71	69.67	12.99	71.41	38.72	432.93	5
7	27.5	284	35.59	12.06	11.51	-5.03	10.34	8.08	373.48	6
7	20	213.5	18.68	13.69	11.82	-18.15	12.01	16.39	508.43	7
9.5	20	143	41.64	12.08	4.10	17.93	7.06	11.47	571.30	8
7	35	213.5	21.98	30.86	4.33	-11.38	2.09	8.97	133.33	9
9.5	35	143	47.47	22.56	4.67	16.95	5.17	9.00	310.00	10
9.5	20	284	30.96	20.54	14.39	11.03	14.73	11.28	420.24	11
9.5	35	284	44.91	20.58	19.43	11.02	18.49	16.01	279.67	12
9.5	27.5	213.5	29.42	28.98	28.64	18.74	28.19	29.90	84.86	13
7	27.5	143	43.32	11.81	12.92	-10.62	15.93	7.01	541.37	14
12	20	213.5	31.21	31.84	32.90	20.41	32.10	33.41	126.18	15

Table 26: Filterability test - CA system

	(ml)												
Time (min)	RO1&2&13	RO3	RO4	RO5	RO6	RO7	RO8	RO9	RO10	RO11	RO12	RO14	RO15
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	12	15	16	16	18	25	10	17	16	18	14	15	17
2	22	24	29	25	28	36	27	29	26	28	23	24	26
3	29	28	36.5	29	32	39	33	33	31	29	28	32	32
4	32	32	43	32	36	42	37	36	35	33	32	34	34
6	37	36	46.5	35	39	42	40	38.5	38.5	39	35	42	40
10	38	39	49	38.5	41.5	42.5	42	39.5	41	39.5	37.5	43	40.5
15	39	40	50	39	41.5	42.5	42	40	41.5	40	39	43.5	41
25	39	40.5	50	39	42	42.5	42	40	41.5	40	39	43.5	41
40	40	41	50	39.5	42	42.5	42	40	42	40	39	43.5	41
60	40	41	50	39.5	42	43	42	40	42	40.5	39	43.5	41
120	40	41	50	40	42	43	42	40	42	41	39	43.5	41.5

Table 27: Filterability test - EA system

	(ml)												
Time (min)	RO1&2&13	RO3	RO4	RO5	RO6	RO7	RO8	RO9	RO10	RO11	RO12	RO14	RO15
1	22	19	16	22	16	11	18	12	17	30	21	29	23
2	32	33	29	34	20	15	28	19	24	34	26	33	37
3	34.5	39	36.5	38	22	19	34	24	29	37	29	33	44
4	35.5	43	43	38	25	22	38	28	32	39	30	33	47
5	36	45	46.5	38.5	25	24	40	30	34	39	30	33	47.5
6	37	46	49	40	25	25	41	31	36	39	30	33	48
10	37	47	50	40	26	26	44	33	38	39	30	33	48
15	37	47	50	40	26.5	26.5	44	33.5	38.5	39.5	30	33.5	48
20	37	47	50	41	26.5	26.5	44	34	39	39.5	30	34	48
25	37	47.5	50	41	26.5	27	44	34	39	39.5	30	34	48
30	37	48	50	41	27	27	44	34	39	39.5	30	34	48
35	37	48	50	41	27	27	44	34	39	39.5	30	35	48
60	41	49	50	43	30	29	46	35	40	43.5	33	37	49

Table 28: Settling test- CA system

Settling Test /Time(min)	RO1&2&13	RO3	RO4	RO5	RO6	RO7	RO8	RO9	RO10	RO11	RO12	RO14	RO15
0	50	50	50	50	50	50	50	50	50	50	50	50	50
5	49	50	45	50	48	48	49	49	49	48	50	49	49
10	49	48.5	40	49	47	46	48	48	49	47	48	48	49
15	48	48	36	48.5	45	44	43.5	45	48	45	47	40	49
20	48	48	25	48.5	44	41	39	41	48	44	47	34	48.5
30	48	47	21	48	39	36	30	32.5	46	42	45.5	27	48
60	40	44	15	47	30.5	29	24	24	39	31	44	20	37.5
90	32	41	14	45.5	25	24	21.5	21	31	30	41	16	30
120	30	37	14	44	21	21	19	19	25.5	25	38	16	27
150	27	32	14	42	18	19	18	18	22	22	35	15	25
180	25	28	14	40	16.5	18	17	17	21	20	33	14	20

Table 29: Settling test - EA system

Settling Test / Time(min)	RO1&2&13	RO3	RO4	RO5	RO6	RO7	RO8	RO9	RO10	RO11	RO12	RO14	RO15
0	50	50	50	50	50	50	50	50	50	50	50	50	50
2	49	10	46	48	49	49	49	49	49	49	49	49	48
4	49	9	39	30	49	49	49	49	49	49	49	49	35
8	47	9	33	26	48	48	48	48	48	49	49	48	25
20	42	7	11	20	48	48	47	48	48	48	48	48	13
30	39	6	9	18	48	48	47	48	47	47	47	47.5	7
40	35	6	8.5	16	47	48	46	47	46	46	47	47	6
50	31	5	8	15	47	47	46	47	45.5	45	46.5	46	6
60	29	5	7	15	46	47	46	46	45	45	46	46	6
70	27	5	6.5	14	45	46	45	45	44	44	44	45	6
90	25	5	6	14	44	45	43	44	42	43	44	45	5
100	25	5	6	14	43	45	43	44	41	42	45	45	5

Equations

- **COD % prediction**

CA system

$$\text{COD\%prediction} = 79.0635 + (2.85807 \ast \text{pH}) + (4.85305 \ast \text{Temp}) + (0.0912371 \ast \text{CD}) + (0.253755 \ast \text{pH} \ast \text{pH}) + (0.0769938 \ast \text{Temp} \ast \text{Temp}) + (0.000505326 \ast \text{CD} \ast \text{CD})(0.192027 \ast \text{pH} \ast \text{Temp}) + (-0.023903 \ast \text{pH} \ast \text{CD}) + (-0.00395793 \ast \text{Temp} \ast \text{CD}) \qquad (13)$$

EA system

$$\text{COD \% prediction} = 104.174 + (7.57144 \ast \text{pH}) + (1.95355 \ast \text{Temp}) + (-1.35462 \ast \text{CD} + (-0.46004 \ast \text{pH} \ast \text{pH}) + (-0.0525408 \ast \text{Temp} \ast \text{Temp}) + (0.00273409 \ast \text{CD} \ast \text{CD}) + (0.0633361 \ast \text{pH} \ast \text{Temp}) + (0.00371123 \ast \text{pH} \ast \text{CD}) + (0.00384104 \ast \text{Temp} \ast \text{CD}) \quad (14)$$

- **TH % prediction**

CA system

$$\text{TH \% prediction} = 35.6857 + (-30.3439 \ast \text{pH}) + (9.81282 \ast \text{Temp}) + (-0.308475 \ast \text{CD}) + (1.39027 \ast \text{pH} \ast \text{pH}) + (-0.18953 \ast \text{Temp} \ast \text{Temp}) + (0.00160502 \ast \text{CD} \ast \text{CD}) + (0.225497 \ast \text{pH} \ast \text{Temp}) + (0.0759712 \ast \text{pH} \ast \text{CD}) + (0.0145515 \ast \text{Temp} \ast \text{CD}) \quad (15)$$

EA system

$$\text{TH \% prediction} = -138.775 + (-1.24342 \ast \text{pH}) + (2.47195 \ast \text{Temp}) + (1.05014 \ast \text{CD}) + (0.198955 \ast \text{pH} \ast \text{pH}) + (-0.00167985 \ast \text{Temp} \ast \text{Temp}) + (-0.00238506 \ast \text{CD} \ast \text{CD}) + (-0.0700795 \ast \text{pH} \ast \text{Temp}) + (0.0141054 \ast \text{pH} \ast \text{CD}) + (-0.00493592 \ast \text{Temp} \ast \text{CD}) \quad (16)$$

- **EC, TDS and Salinity % prediction CA – EA systems**

CA system

- **EC % Prediction** $= 379.366 + (-65.1747 * \mathrm{pH}) + (-7.41074 * \mathrm{Temp}) + (0.136185 * \mathrm{CD}) + (3.34902 * \mathrm{pH} * \mathrm{pH}) + (0.109236 * \mathrm{Temp} * \mathrm{Temp}) + (0.000256986 * \mathrm{CD} * \mathrm{CD}) + (0.193193 * \mathrm{pH} * \mathrm{Temp}) + (0.0116621 * \mathrm{pH} * \mathrm{CD}) + (-0.00144138 * \mathrm{Temp} * \mathrm{CD})$ (17)

- **TDS % Prediction** $= 392.192 + (-67.8192 * \mathrm{pH}) + (-7.20666 * \mathrm{Temp}) + (0.105369 * \mathrm{CD}) + (3.51735 * \mathrm{pH} * \mathrm{pH}) + (0.104087 * \mathrm{Temp} * \mathrm{Temp}) + (-0.000232996 * \mathrm{CD} * \mathrm{CD}) + (0.181961 * \mathrm{pH} * \mathrm{Temp}) + (0.0105892 * \mathrm{pH} * \mathrm{CD}) + (-0.000359972 * \mathrm{Temp} * \mathrm{CD})$ (18)

- **Salinity % Prediction** $= 346.693 + (-64.0109 * \mathrm{pH}) + (-5.92414 * \mathrm{Temp}) + (0.222031 * \mathrm{CD}) + (3.32695 * \mathrm{pH} * \mathrm{pH}) + (0.0825628 * \mathrm{Temp} * \mathrm{Temp}) + (-0.000495216 * \mathrm{CD} * \mathrm{CD}) + (0.177315 * \mathrm{pH} * \mathrm{Temp}) + (0.0106453 * \mathrm{pH} * \mathrm{CD}) + (-0.000602336 * \mathrm{Temp} * \mathrm{CD})$ (19)

EA system

- **EC % Prediction** $= 1.16129 + (-37.5086 * \mathrm{pH}) + (9.25688 * \mathrm{Temp}) + (0.278019 * \mathrm{CD}) + (1.55833 * \mathrm{pH} * \mathrm{pH}) + (-0.214608 * \mathrm{Temp} * \mathrm{Temp}) + (-0.00157846 * \mathrm{CD} * \mathrm{CD}) + (0.232915 * \mathrm{pH} * \mathrm{Temp}) + (0.0441919 * \mathrm{pH} * \mathrm{CD}) + (0.00258707 * \mathrm{Temp} * \mathrm{CD})$ (20)

- **TDS % Prediction** $= 51.6959 + (-40.9896 * \mathrm{pH}) + (8.5681 * \mathrm{Temp}) + (0.0705068 * \mathrm{CD}) + (1.5923 * \mathrm{pH} * \mathrm{pH}) + (-0.221323 * \mathrm{Temp} * \mathrm{Temp}) + (-0.00128797 * \mathrm{CD} * \mathrm{CD}) + (0.313191 * \mathrm{pH} * \mathrm{Temp}) + (0.0491014 * \mathrm{pH} * \mathrm{CD}) + (0.00314466 * \mathrm{Temp} * \mathrm{CD})$ (21)
- **Salinity % Prediction** $= -87.3589 + (-14.7764 * \mathrm{pH}) + (3.20269 * \mathrm{Temp}) + (1.0482 * \mathrm{CD}) + (0.677126 * \mathrm{pH} * \mathrm{pH}) + (-0.115748 * \mathrm{Temp} * \mathrm{Temp}) + (-0.0027307 * \mathrm{CD} * \mathrm{CD}) + (0.267045 * \mathrm{pH} * \mathrm{Temp}) + (0.0041579 * \mathrm{pH} * \mathrm{CD}) + (0.0034985 * \mathrm{Temp} * \mathrm{CD})$ (22)

Graphs

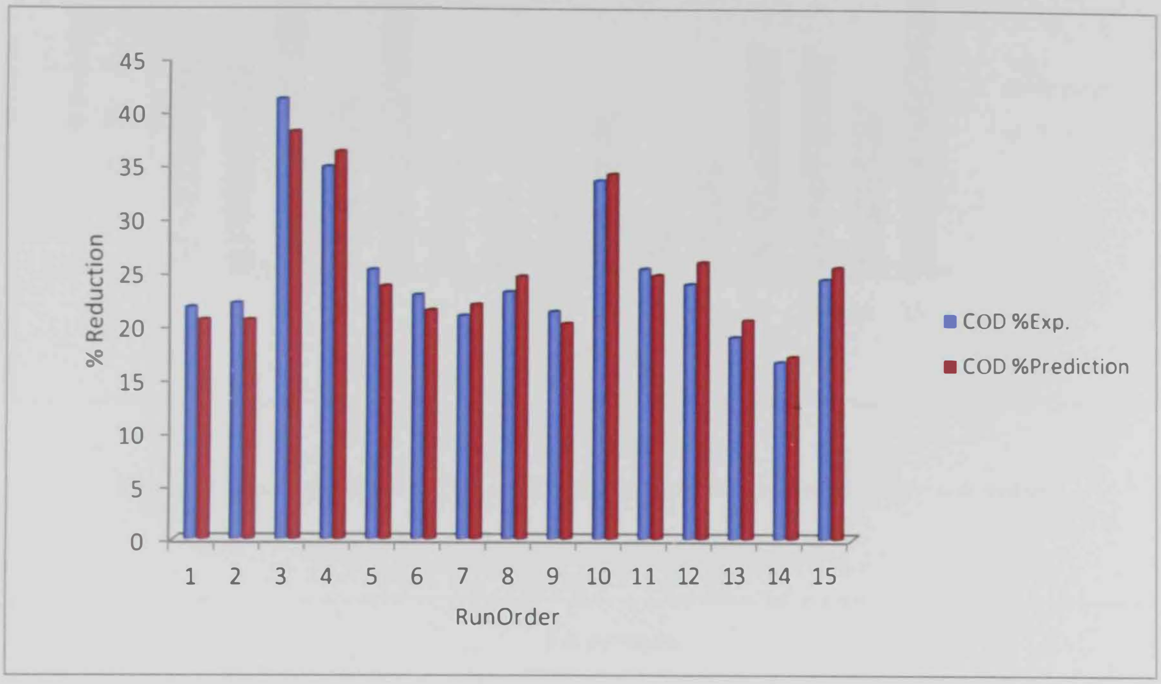


Figure 66: Run-order verses COD % reduction experimentally and prediction – CA system

Figure 67: Run-order verses COD % reduction experimentally and prediction – EA system

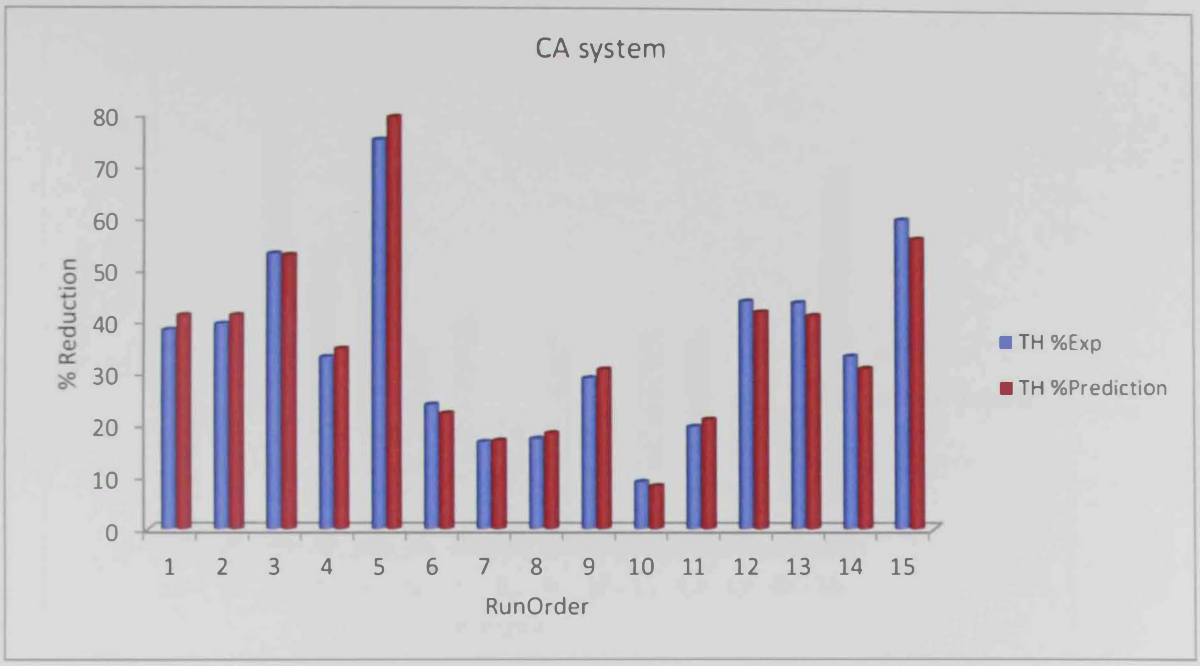


Figure 68: Run-order verses TH %reduction experimentally and prediction – CA system

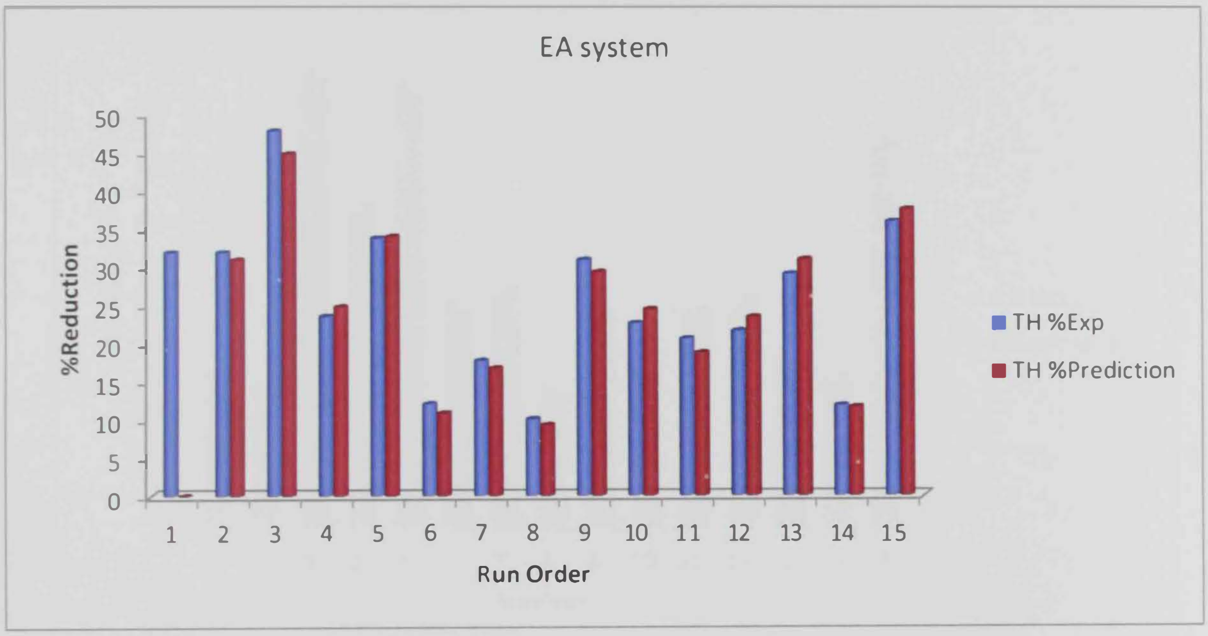


Figure 70 Run-order verses TH % reduction experimentally and prediction – EA system

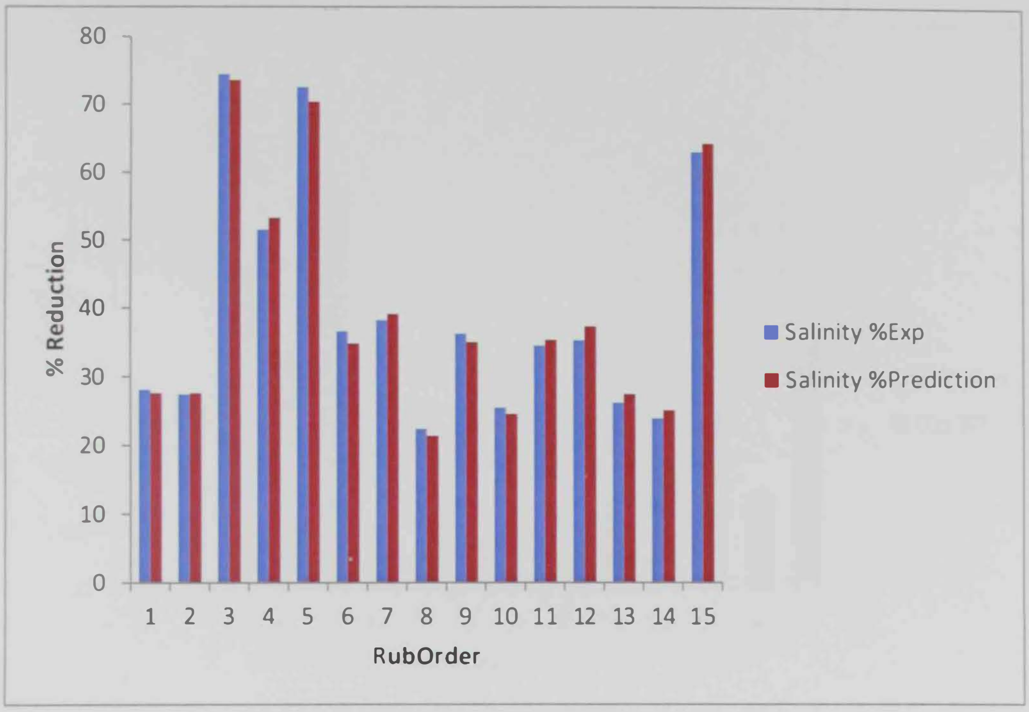


Figure 73: Run-order verses Salinity % reduction experimentally and prediction – CA system

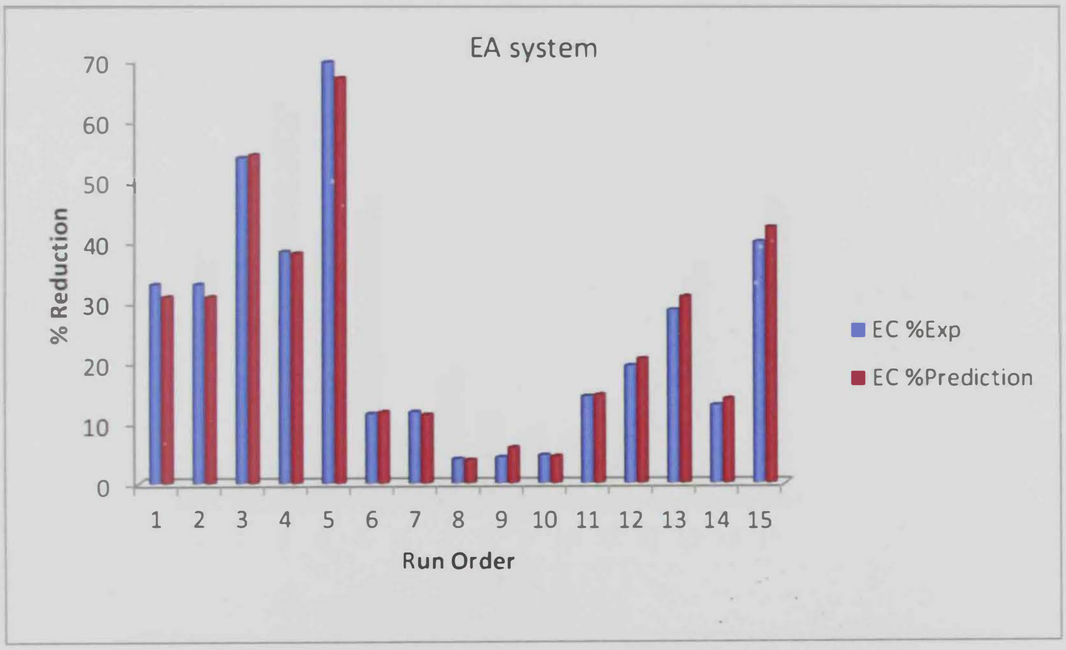


Figure 74: Run-order verses % EC reduction experimentally and prediction – EA system

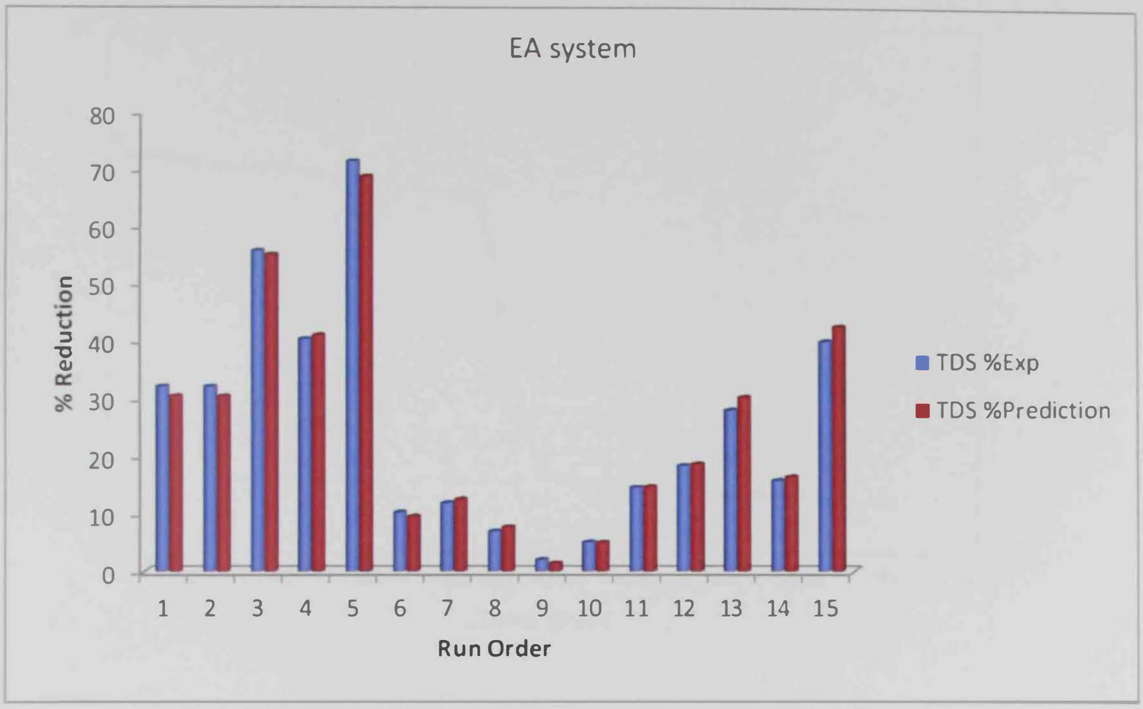


Figure 75: Run-order verses TDS% reduction experimentally and prediction – EA system

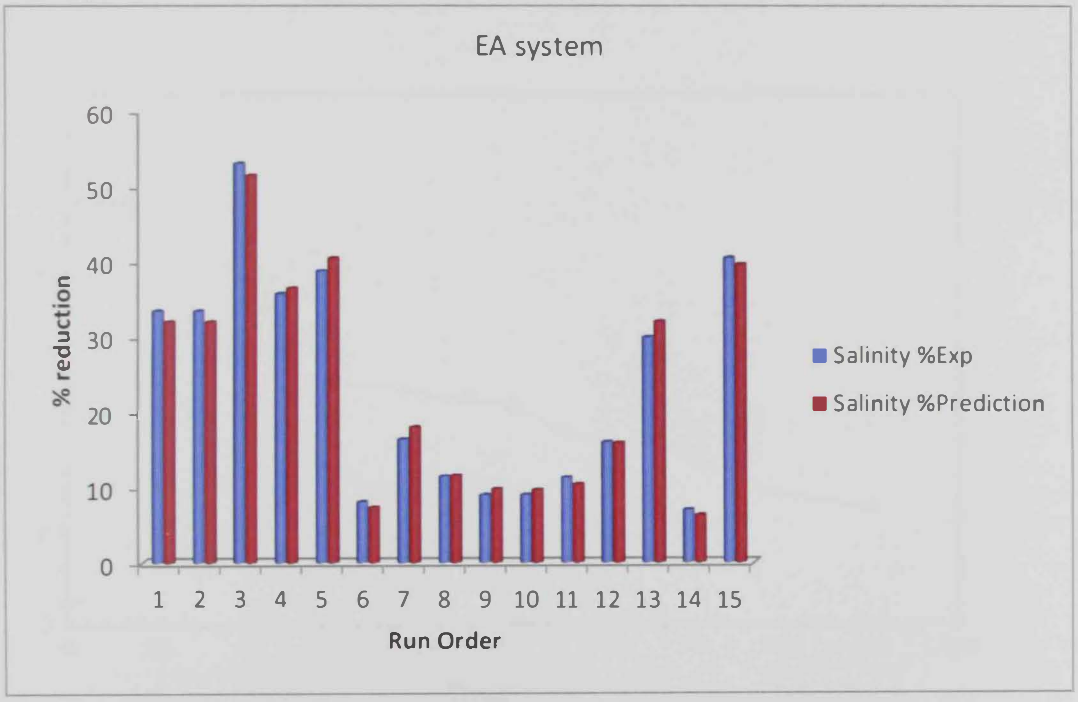


Figure 76: Run-order verses Salinity % reduction experimentally and prediction – EA system

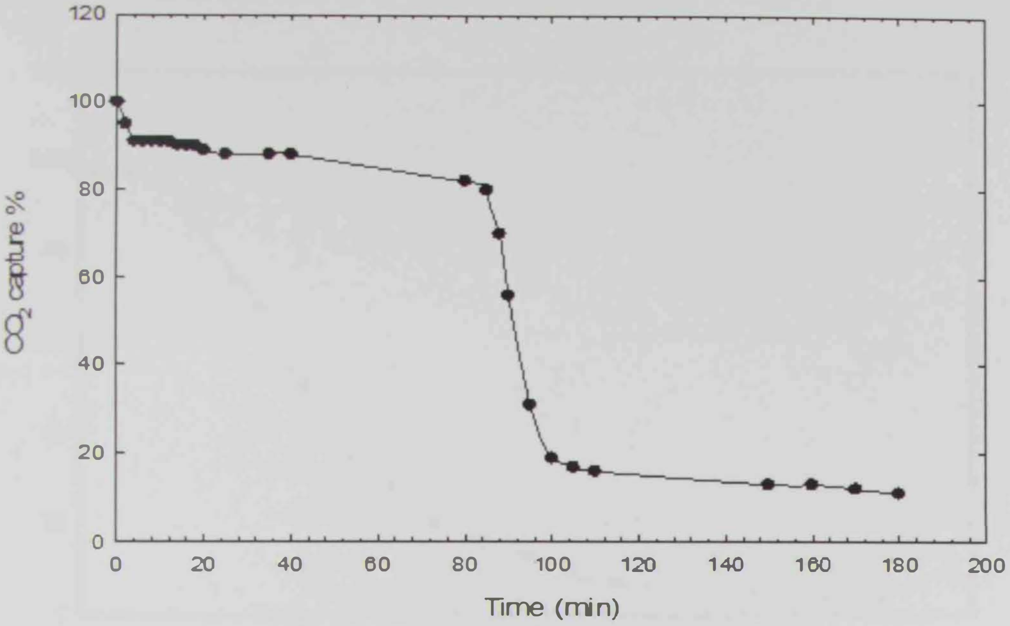


Figure 77: CO_2 variation in CA system at pH 12, Temperature 35 °C and current density 213.5 A/m^2- RO3

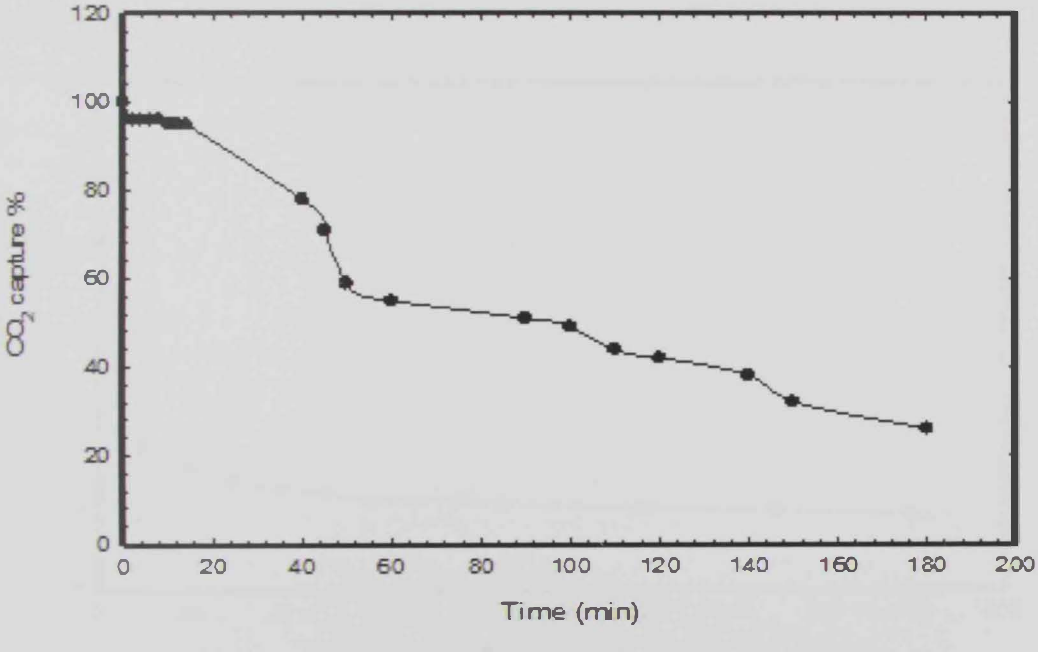


Figure 78: CO_2 variation in CA system at pH 12, Temperature 27.5 °C and current density 143 A/m^2 -RO4

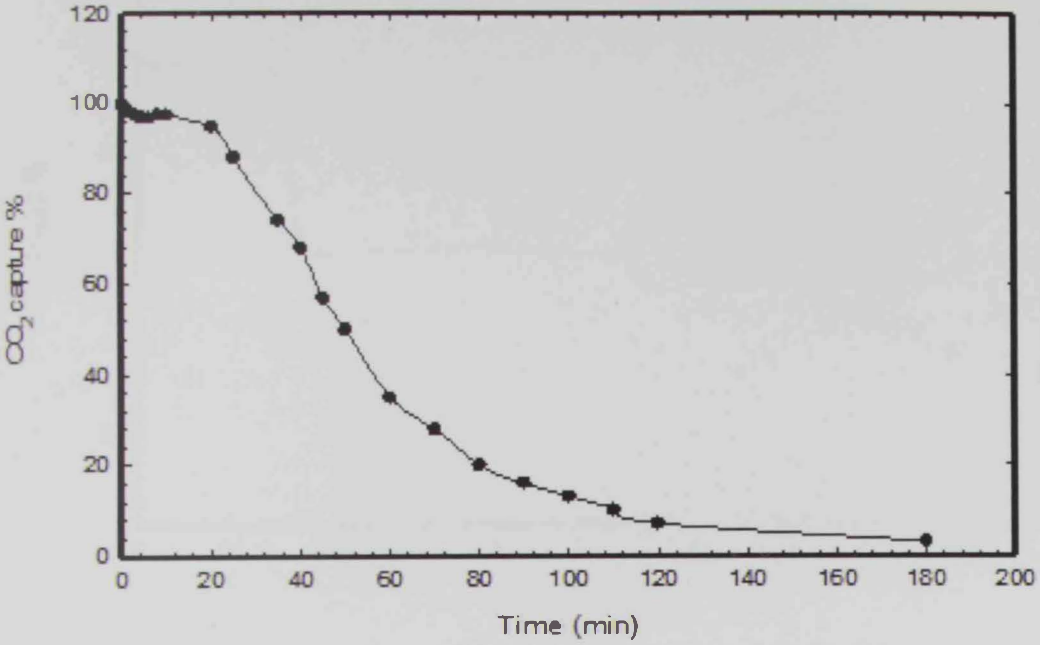


Figure 79: CO_2 variation in CA system at PH 12, Temperature 27.5 °C and current density 284 A/m^2- RO5

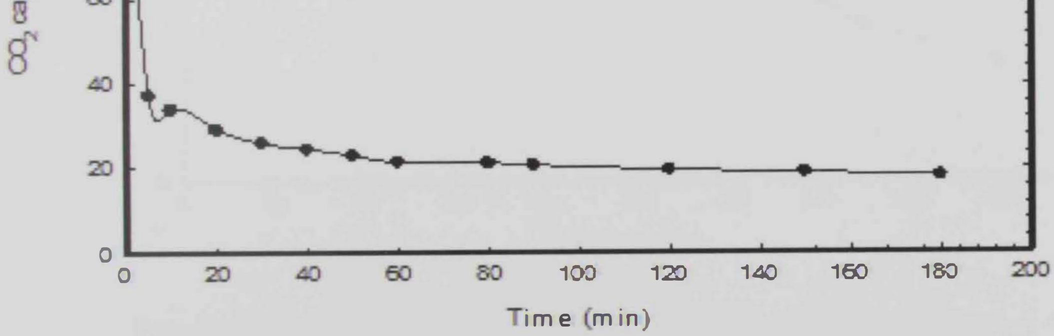


Figure 80: CO_2 variation in CA system at pH 12, Temperature 20 °C and current density 213.5 A/m^2 –RO15

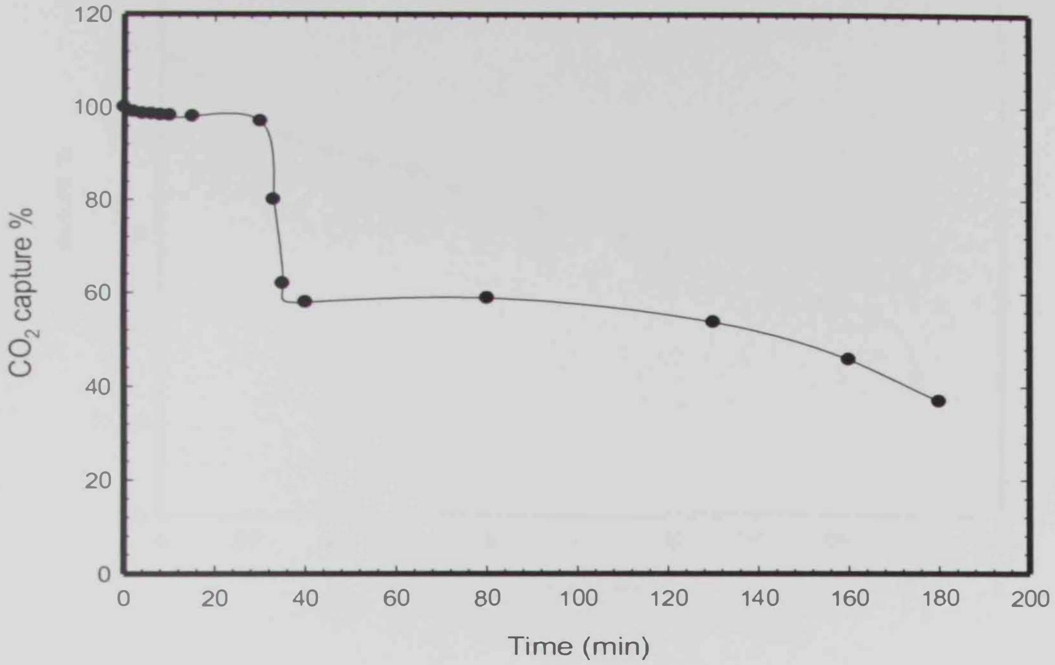


Figure 81: CO_2 variation in CA system at pH 7, Temperature 27.5 °C and current density 284 A/m^2 – RO6

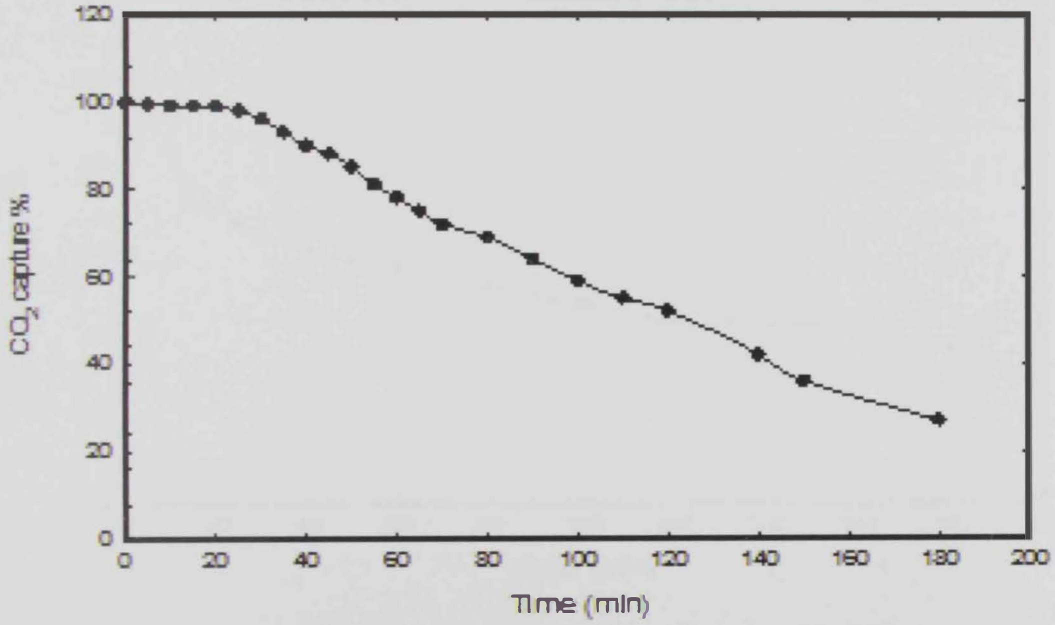


Figure 82: CO_2 variation in CA system AT PH 7, Temperature 20 °C and current density 213.5 A/m^2- RO7

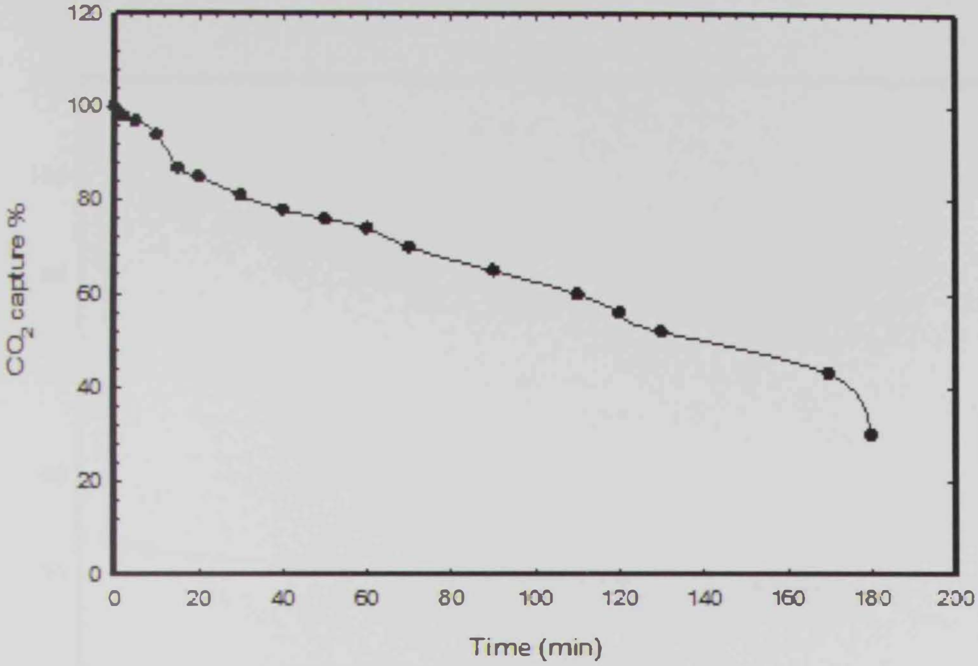


Figure 83: CO_2 variation in CA system AT PH 7, Temperature 35 °C and current density 213.5 A/m^2- RO9

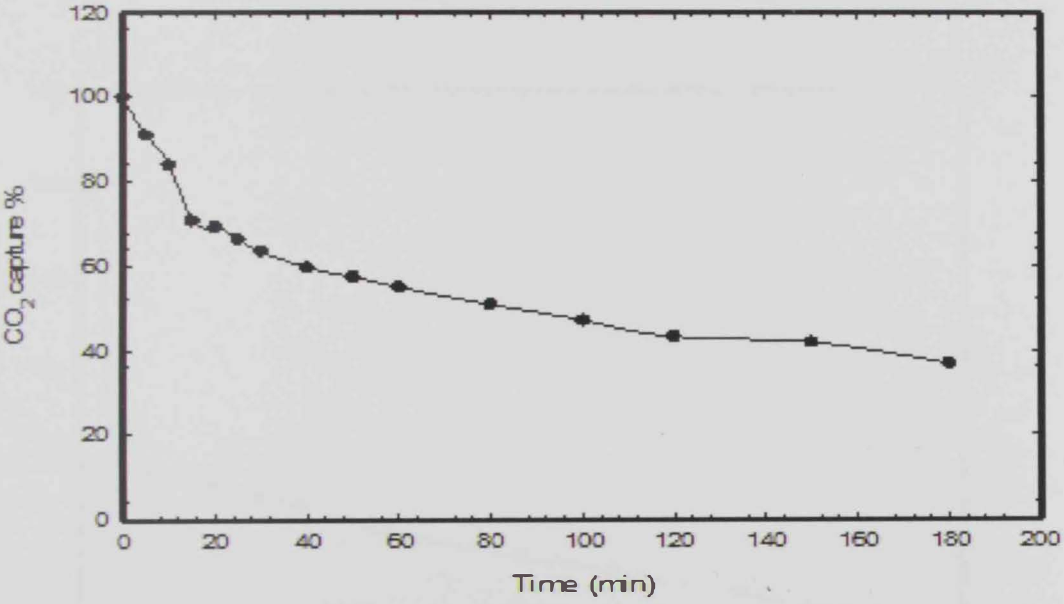


Figure 84: CO_2 variation in CA system at pH 7, Temperature 27.5 ^{O}C and current density 143 A/m^2- RO14

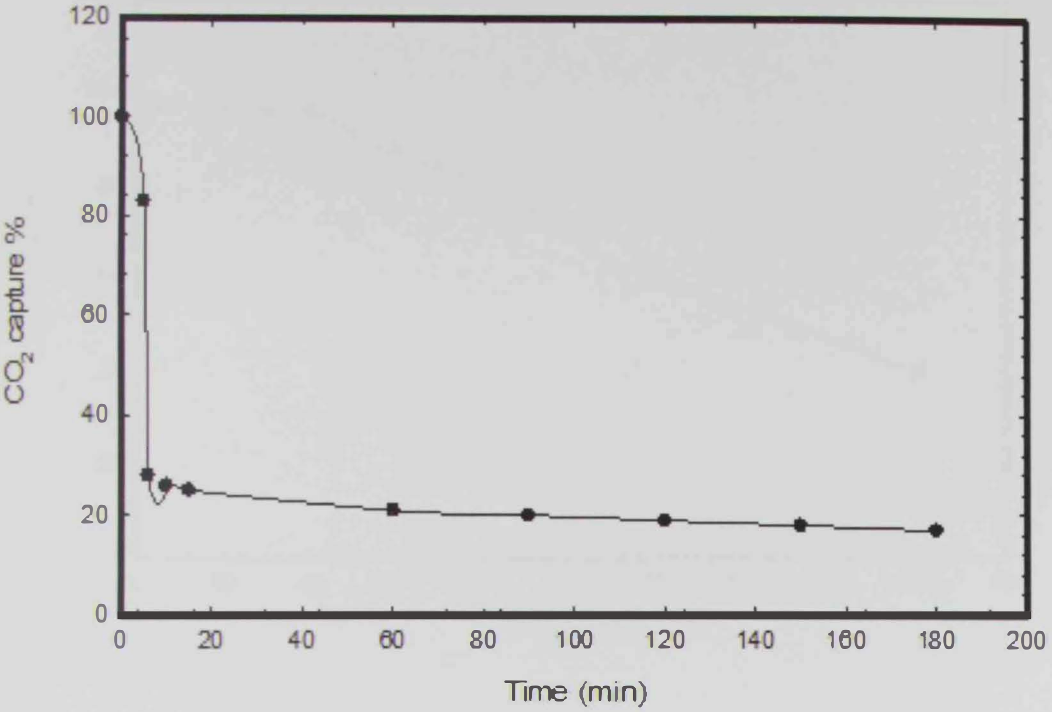


Figure 85: CO$_2$ variation in CA system at pH 9.5, temperature 20 ^{0}C and current density 143 A/m^2- RO8

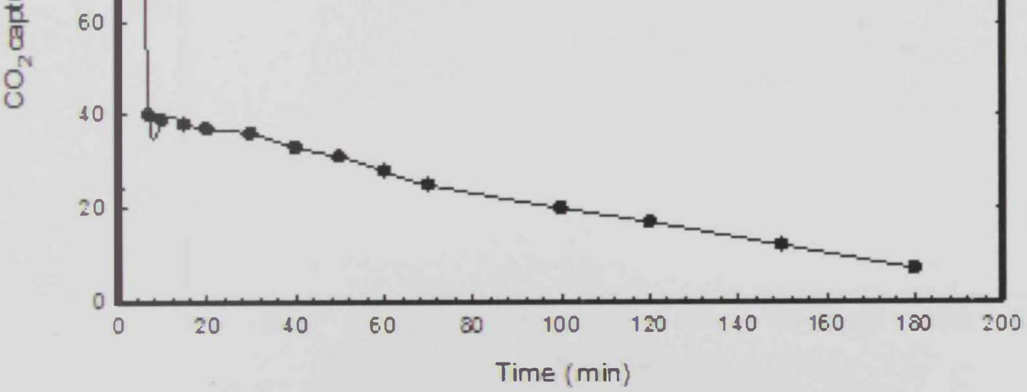


Figure 86: CO$_2$ variation in CA system at pH 9.5, Temperature 35 ^{o}C and current density 143 A/m^2 –RO10

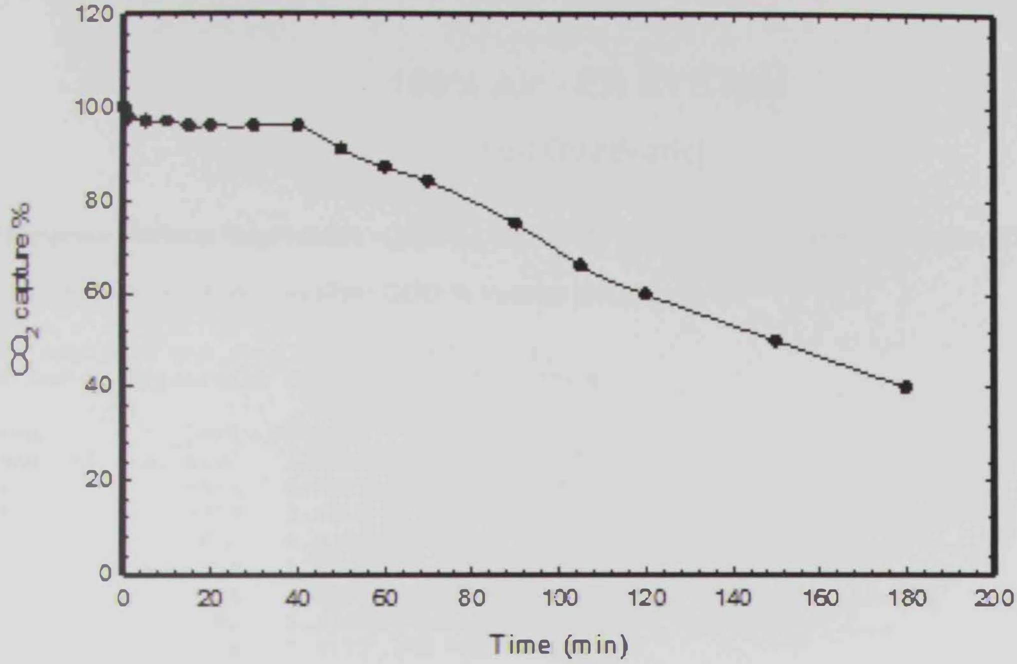


Figure 87: CO2 variation in CA system AT pH 9.5, Temperature 20 °C and current density 284 A/m^2-RO11

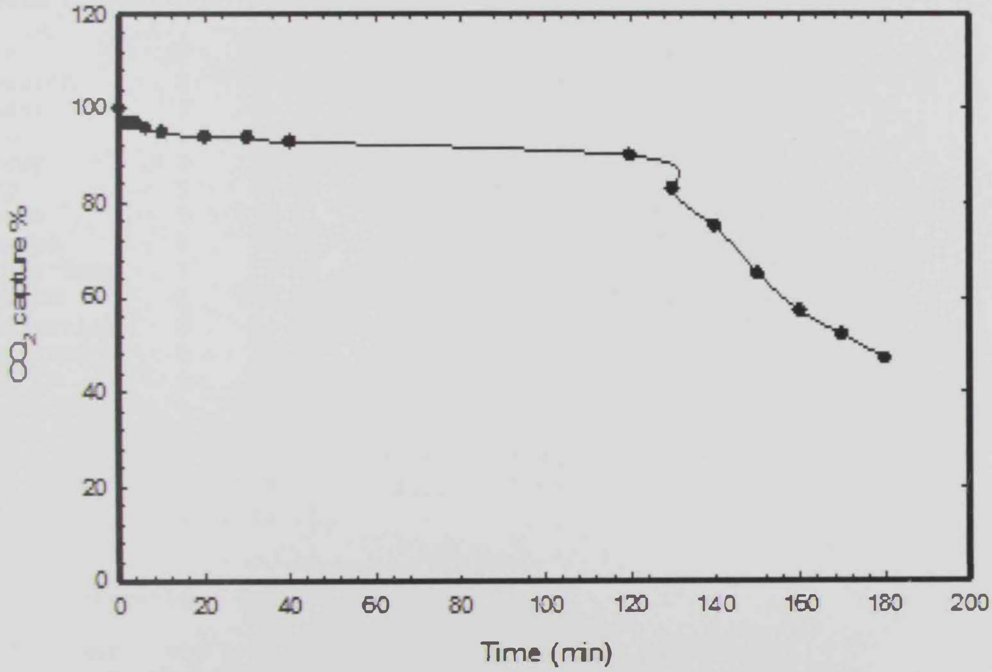


Figure 88: CO$_2$ variation in CA system at pH 9.5, Temperature 27.5 °C and current density 284 A/m^2- RO12

Response Surface Method Regression

100% Air - EA SYSTEM

[Full Quadratic]

Response Surface Regression: COD %; TH %; EC %; pH %; ... versus pH; Temp; CD

Response Surface Regression: COD % versus pH; Temp; CD

```
The analysis was done using coded units.
Estimated Regression Coefficients for COD %

Term           Coef  SE Coef       T      P
Constant    30.6130   1.5213  20.122  0.000
pH           3.4119   0.9316   3.662  0.015
Temp         3.6417   0.9316   3.909  0.011
CD          -3.2626   0.9316  -3.502  0.017
pH*pH       -2.8753   1.3713  -2.097  0.090
Temp*Temp   -2.9554   1.3713  -2.155  0.084
CD*CD       13.5891   1.3713   9.910  0.000
pH*Temp      1.1876   1.3175   0.901  0.409
pH*CD        0.6541   1.3175   0.496  0.641
Temp*CD      2.0310   1.3175   1.541  0.184


S = 2.63504    PRESS = 526.184
R-Sq = 96.94%  R-Sq(pred) = 53.58%  R-Sq(adj) = 91.42%


Analysis of Variance for COD %

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression       9  1098.85  1098.85  122.094  17.58  0.003
  Linear         3   284.39   284.39   94.795  13.65  0.008
    pH           1    93.13    93.13   93.130  13.41  0.015
    Temp         1   106.10   106.10  106.097  15.28  0.011
    CD           1    85.16    85.16   85.159  12.26  0.017
  Square         3   790.61   790.61  263.536  37.95  0.001
    pH*pH        1    49.32    30.52   30.525   4.40  0.090
    Temp*Temp    1    59.45    32.25   32.250   4.64  0.084
    CD*CD        1   681.83   681.83  681.834  98.20  0.000
  Interaction    3    23.85    23.85    7.951   1.15  0.416
    pH*Temp      1     5.64     5.64    5.641   0.81  0.409
    pH*CD        1     1.71     1.71    1.711   0.25  0.641
    Temp*CD      1    16.50    16.50   16.499   2.38  0.184
Residual Error   5    34.72    34.72    6.943
  Lack-of-Fit    3    32.59    32.59   10.862  10.20  0.091
  Pure Error     2     2.13     2.13    1.065
Total           14  1133.56


Unusual Observations for COD %

Obs  StdOrder   COD %     Fit  SE Fit  Residual  St Resid
  9         9  20.981  23.825   2.282    -2.844    -2.16 R
 15        15  26.209  23.365   2.282     2.844     2.16 R

R denotes an observation with a large standardized residual.
```

```
Estimated Regression Coefficients for COD % using data in uncoded units

Term              Coef
Constant       104.174
pH             7.57144
Temp           1.95355
CD            -1.35462
pH*pH        -0.460040
Temp*Temp   -0.0525408
CD*CD       0.00273409
pH*Temp      0.0633361
pH*CD       0.00371123
Temp*CD     0.00384104
```

Response Surface Regression: TH % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for TH %

Term          Coef  SE Coef       T      P
Constant   30.8867    1.906  16.204  0.000
pH          9.0526    1.167   7.755  0.001
Temp        4.9499    1.167   4.241  0.008
CD          2.1138    1.167   1.811  0.130
pH*pH       1.2435    1.718   0.724  0.502
Temp*Temp  -0.0945    1.718  -0.055  0.958
CD*CD     -11.8544    1.718  -6.899  0.001
pH*Temp    -1.3140    1.651  -0.796  0.462
pH*CD       2.4861    1.651   1.506  0.192
Temp*CD    -2.6099    1.651  -1.581  0.175


S = 3.30158    PRESS = 796.720
R-Sq = 96.46%  R-Sq(pred) = 48.21%  R-Sq(adj) = 90.08%


Analysis of Variance for TH %

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression       9  1483.99  1483.99  164.888  15.13  0.004
  Linear         3   887.35   887.35  295.784  27.14  0.002
    pH           1   655.60   655.60  655.595  60.14  0.001
    Temp         1   196.01   196.01  196.013  17.98  0.008
    CD           1    35.75    35.75   35.745   3.28  0.130
  Square         3   537.76   537.76  179.254  16.44  0.005
    pH*pH        1    16.42     5.71    5.709   0.52  0.502
    Temp*Temp    1     2.48     0.03    0.033   0.00  0.958
    CD*CD        1   518.86   518.86  518.865  47.60  0.001
  Interaction    3    58.87    58.87   19.625   1.80  0.264
    pH*Temp      1     6.91     6.91    6.906   0.63  0.462
    pH*CD        1    24.72    24.72   24.722   2.27  0.192
    Temp*CD      1    27.25    27.25   27.246   2.50  0.175
Residual Error   5    54.50    54.50   10.900
  Lack-of-Fit    3    49.02    49.02   16.342   5.97  0.147
  Pure Error     2     5.48     5.48    2.739
Total           14  1538.49


Estimated Regression Coefficients for TH % using data in uncoded units
```

```
Term              Coef
Constant      -138.775
pH            -1.24342
Temp           2.47195
CD             1.05014
pH*pH         0.198955
Temp*Temp  -0.00167985
CD*CD      -0.00238506
pH*Temp     -0.0700795
pH*CD        0.0141054
Temp*CD    -0.00493592
```

Response Surface Regression: EC % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for EC %

Term          Coef  SE Coef       T      P
Constant    30.813    2.028  15.192  0.000
pH          19.849    1.242  15.981  0.000
Temp         1.639    1.242   1.319  0.244
CD           6.696    1.242   5.391  0.003
pH*pH        9.740    1.828   5.327  0.003
Temp*Temp  -12.072    1.828  -6.603  0.001
CD*CD       -7.845    1.828  -4.291  0.008
pH*Temp      4.367    1.757   2.486  0.055
pH*CD        7.789    1.757   4.434  0.007
Temp*CD      1.368    1.757   0.779  0.471


S = 3.51313     PRESS = 628.761
R-Sq = 98.79%  R-Sq(pred) = 87.67%  R-Sq(adj) = 96.61%


Analysis of Variance for EC %

Source          DF   Seq SS   Adj SS   Adj MS       F      P
Regression       9  5039.52  5039.52   559.95   45.37  0.000
  Linear         3  3532.17  3532.17  1177.39   95.40  0.000
    pH           1  3151.97  3151.97  3151.97  255.38  0.000
    Temp         1    21.48    21.48    21.48    1.74  0.244
    CD           1   358.72   358.72   358.72   29.07  0.003
  Square         3  1180.91  1180.91   393.64   31.89  0.001
    pH*pH        1   465.15   350.25   350.25   28.38  0.003
    Temp*Temp    1   488.50   538.06   538.06   43.60  0.001
    CD*CD        1   227.26   227.26   227.26   18.41  0.008
  Interaction    3   326.44   326.44   108.81    8.82  0.019
    pH*Temp      1    76.29    76.29    76.29    6.18  0.055
    pH*CD        1   242.66   242.66   242.66   19.66  0.007
    Temp*CD      1     7.48     7.48     7.48    0.61  0.471
Residual Error   5    61.71    61.71    12.34
  Lack-of-Fit    3    35.63    35.63    11.88    0.91  0.561
  Pure Error     2    26.08    26.08    13.04
Total           14  5101.23


Estimated Regression Coefficients for EC % using data in uncoded units

Term            Coef
Constant     1.16129
pH          -37.5086
Temp         9.25688
CD          0.278019
```

```
pH*pH          1.55833
Temp*Temp    -0.214608
CD*CD      -0.00157846
pH*Temp       0.232915
pH*CD        0.0441919
Temp*CD     0.00258707
```

Response Surface Regression: pH % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for pH %

Term           Coef  SE Coef        T      P
Constant    19.8506   0.8931   22.227  0.000
pH          16.0248   0.5469   29.301  0.000
Temp        -0.3340   0.5469   -0.611  0.568
CD          -3.6655   0.5469   -6.702  0.001
pH*pH      -12.3860   0.8050  -15.386  0.000
Temp*Temp   -6.2560   0.8050   -7.771  0.001
CD*CD        0.6391   0.8050    0.794  0.463
pH*Temp     -4.3077   0.7734   -5.570  0.003
pH*CD       -7.2717   0.7734   -9.402  0.000
Temp*CD      0.2427   0.7734    0.314  0.766


S = 1.54686    PRESS = 165.786
R-Sq = 99.62%  R-Sq(pred) = 94.73%  R-Sq(adj) = 98.94%


Analysis of Variance for pH %

Source          DF   Seq SS   Adj SS   Adj MS       F      P
Regression       9  3134.12  3134.12   348.24  145.54  0.000
  Linear         3  2162.73  2162.73   720.91  301.29  0.000
    pH           1  2054.35  2054.35  2054.35  858.56  0.000
    Temp         1     0.89     0.89     0.89    0.37  0.568
    CD           1   107.49   107.49   107.49   44.92  0.001
  Square         3   685.41   685.41   228.47   95.48  0.000
    pH*pH        1   536.24   566.45   566.45  236.73  0.000
    Temp*Temp    1   147.66   144.51   144.51   60.39  0.001
    CD*CD        1     1.51     1.51     1.51    0.63  0.463
  Interaction    3   285.97   285.97    95.32   39.84  0.001
    pH*Temp      1    74.23    74.23    74.23   31.02  0.003
    pH*CD        1   211.51   211.51   211.51   88.40  0.000
    Temp*CD      1     0.24     0.24     0.24    0.10  0.766
Residual Error   5    11.96    11.96     2.39
  Lack-of-Fit    3    10.10    10.10     3.37    3.61  0.224
  Pure Error     2     1.86     1.86     0.93
Total           14  3146.08



Estimated Regression Coefficients for pH % using data in uncoded units

Term              Coef
Constant      -426.829
pH             59.1900
Temp           8.15707
CD            0.272434
pH*pH         -1.98176
Temp*Temp    -0.111219
```

```
CD*CD       0.000128578
pH*Temp       -0.229744
pH*CD        -0.0412581
Temp*CD     0.000458980
```

Response Surface Regression: TDS % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for TDS %

Term            Coef  SE Coef       T      P
Constant     30.4660    2.111  14.433  0.000
pH           20.9001    1.293  16.169  0.000
Temp          0.3153    1.293   0.244  0.817
CD            5.1806    1.293   4.008  0.010
pH*pH         9.9519    1.903   5.230  0.003
Temp*Temp   -12.4494    1.903  -6.543  0.001
CD*CD        -6.4015    1.903  -3.364  0.020
pH*Temp       5.8723    1.828   3.212  0.024
pH*CD         8.6541    1.828   4.734  0.005
Temp*CD       1.6627    1.828   0.910  0.405


S = 3.65611    PRESS = 848.315
R-Sq = 98.76%  R-Sq(pred) = 84.24%  R-Sq(adj) = 96.52%


Analysis of Variance for TDS %

Source          DF   Seq SS   Adj SS   Adj MS       F      P
Regression       9  5317.49  5317.49   590.83   44.20  0.000
  Linear         3  3710.01  3710.01  1236.67   92.52  0.000
    pH           1  3494.51  3494.51  3494.51  261.42  0.000
    Temp         1     0.80     0.80     0.80    0.06  0.817
    CD           1   214.71   214.71   214.71   16.06  0.010
  Square         3  1158.91  1158.91   386.30   28.90  0.001
    pH*pH        1   476.57   365.69   365.69   27.36  0.003
    Temp*Temp    1   531.03   572.26   572.26   42.81  0.001
    CD*CD        1   151.31   151.31   151.31   11.32  0.020
  Interaction    3   448.57   448.57   149.52   11.19  0.012
    pH*Temp      1   137.94   137.94   137.94   10.32  0.024
    pH*CD        1   299.57   299.57   299.57   22.41  0.005
    Temp*CD      1    11.06    11.06    11.06    0.83  0.405
Residual Error   5    66.84    66.84    13.37
  Lack-of-Fit    3    50.76    50.76    16.92    2.10  0.338
  Pure Error     2    16.08    16.08     8.04
Total           14  5384.33




Estimated Regression Coefficients for TDS % using data in uncoded units

Term               Coef
Constant        51.6959
pH             -40.9896
Temp            8.56810
CD            0.0705068
pH*pH           1.59230
Temp*Temp     -0.221323
CD*CD       -0.00128797
pH*Temp        0.313191
```

```
pH*CD        0.0491014
Temp*CD     0.00314466
```

Response Surface Regression: Salinity % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for Salinity %

Term            Coef  SE Coef        T      P
Constant     31.9734   1.3496   23.690  0.000
pH           15.8011   0.8265   19.119  0.000
Temp          0.9030   0.8265    1.093  0.324
CD            1.2617   0.8265    1.527  0.187
pH*pH         4.2320   1.2165    3.479  0.018
Temp*Temp    -6.5108   1.2165   -5.352  0.003
CD*CD       -13.5723   1.2165  -11.156  0.000
pH*Temp       5.0071   1.1688    4.284  0.008
pH*CD         0.7328   1.1688    0.627  0.558
Temp*CD       1.8498   1.1688    1.583  0.174


S = 2.33763     PRESS = 267.176
R-Sq = 99.11%  R-Sq(pred) = 91.30%  R-Sq(adj) = 97.51%


Analysis of Variance for Salinity %

Source          DF   Seq SS   Adj SS   Adj MS       F      P
Regression       9  3043.81  3043.81   338.20   61.89  0.000
  Linear         3  2016.66  2016.66   672.22  123.02  0.000
    pH           1  1997.40  1997.40  1997.40  365.52  0.000
    Temp         1     6.52     6.52     6.52    1.19  0.324
    CD           1    12.74    12.74    12.74    2.33  0.187
  Square         3   911.03   911.03   303.68   55.57  0.000
    pH*pH        1   119.88    66.13    66.13   12.10  0.018
    Temp*Temp    1   111.01   156.52   156.52   28.64  0.003
    CD*CD        1   680.15   680.15   680.15  124.47  0.000
  Interaction    3   116.12   116.12    38.71    7.08  0.030
    pH*Temp      1   100.28   100.28   100.28   18.35  0.008
    pH*CD        1     2.15     2.15     2.15    0.39  0.558
    Temp*CD      1    13.69    13.69    13.69    2.50  0.174
Residual Error   5    27.32    27.32     5.46
  Lack-of-Fit    3    14.96    14.96     4.99    0.81  0.595
  Pure Error     2    12.36    12.36     6.18
Total           14  3071.13


Estimated Regression Coefficients for Salinity % using data in uncoded units

Term              Coef
Constant      -87.3589
pH            -14.7764
Temp           3.20269
CD             1.04820
pH*pH         0.677126
Temp*Temp    -0.115748
CD*CD      -0.00273070
pH*Temp       0.267045
pH*CD       0.00415790
Temp*CD     0.00349850
```

Response Surface Regression: TSS % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for TSS %

Term          Coef  SE Coef       T      P
Constant    112.41   114.12   0.985  0.370
pH           82.91    69.88   1.186  0.289
Temp        -62.89    69.88  -0.900  0.409
CD         -147.14    69.88  -2.106  0.089
pH*pH       218.21   102.86   2.121  0.087
Temp*Temp   -38.63   102.86  -0.376  0.723
CD*CD       321.53   102.86   3.126  0.026
pH*Temp     162.23    98.83   1.642  0.162
pH*CD      -165.00    98.83  -1.670  0.156
Temp*CD      30.18    98.83   0.305  0.772


S = 197.656    PRESS = 3109797
R-Sq = 83.94%  R-Sq(pred) = 0.00%  R-Sq(adj) = 55.02%


Analysis of Variance for TSS %

Source          DF   Seq SS   Adj SS  Adj MS       F      P
Regression       9  1020656  1020656  113406    2.90  0.127
  Linear         3   259850   259850   86617    2.22  0.204
    pH           1    54996    54996   54996    1.41  0.289
    Temp         1    31643    31643   31643    0.81  0.409
    CD           1   173211   173211  173211    4.43  0.089
  Square         3   542992   542992  180997    4.63  0.066
    pH*pH        1   146368   175813  175813    4.50  0.087
    Temp*Temp    1    14914     5511    5511    0.14  0.723
    CD*CD        1   381710   381710  381710    9.77  0.026
  Interaction    3   217814   217814   72605    1.86  0.254
    pH*Temp      1   105272   105272  105272    2.69  0.162
    pH*CD        1   108898   108898  108898    2.79  0.156
    Temp*CD      1     3644     3644    3644    0.09  0.772
Residual Error   5   195340   195340   39068
  Lack-of-Fit    3   194202   194202   64734  113.77  0.009
  Pure Error     2     1138     1138     569
Total           14  1215996


Unusual Observations for TSS %

Obs  StdOrder     TSS %       Fit   SE Fit  Residual  St Resid
  4         4  1260.806  1047.202  171.175   213.604      2.16 R
  6         6   373.485   587.089  171.175  -213.604     -2.16 R

R denotes an observation with a large standardized residual.

Estimated Regression Coefficients for TSS % using data in uncoded units

Term             Coef
Constant      6750.59
pH           -668.261
Temp         -64.9925
CD           -22.3861
pH*pH         34.9138
Temp*Temp   -0.686834
CD*CD       0.0646903
pH*Temp       8.65218
pH*CD       -0.936163
Temp*CD     0.0570820
```

Response Surface Regression

10% CO_2 - CA SYSTEM

[Full Quadratic]

Response Surface Regression: COD %; TH %; EC %; pH %; ... versus pH; Temp; CD

Response Surface Regression: COD % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for COD %

Term           Coef  SE Coef       T      P
Constant     20.542    5.011   4.099  0.009
pH            5.352    3.069   1.744  0.142
Temp          2.706    3.069   0.882  0.418
CD           -2.038    3.069  -0.664  0.536
pH*pH         1.586    4.517   0.351  0.740
Temp*Temp     4.331    4.517   0.959  0.382
CD*CD         2.512    4.517   0.556  0.602
pH*Temp       3.601    4.340   0.830  0.445
pH*CD        -4.213    4.340  -0.971  0.376
Temp*CD      -2.093    4.340  -0.482  0.650


S = 8.67995     PRESS = 3248.08
R-Sq = 59.47%  R-Sq(pred) = 0.00%  R-Sq(adj) = 0.00%


Analysis of Variance for COD %

Source          DF   Seq SS   Adj SS   Adj MS     F      P
Regression       9  552.709  552.709   61.412  0.82  0.629
  Linear         3  320.965  320.965  106.988  1.42  0.341
    pH           1  229.136  229.136  229.136  3.04  0.142
    Temp         1   58.595   58.595   58.595  0.78  0.418
    CD           1   33.234   33.234   33.234  0.44  0.536
  Square         3   91.377   91.377   30.459  0.40  0.757
    pH*pH        1    4.495    9.287    9.287  0.12  0.740
    Temp*Temp    1   63.591   69.256   69.256  0.92  0.382
    CD*CD        1   23.291   23.291   23.291  0.31  0.602
  Interaction    3  140.367  140.367   46.789  0.62  0.631
    pH*Temp      1   51.855   51.855   51.855  0.69  0.445
    pH*CD        1   70.994   70.994   70.994  0.94  0.376
    Temp*CD      1   17.519   17.519   17.519  0.23  0.650
Residual Error   5  376.708  376.708   75.342
  Lack-of-Fit    3  174.581  174.581   58.194  0.58  0.685
  Pure Error     2  202.127  202.127  101.064
Total           14  929.417



Estimated Regression Coefficients for COD % using data in uncoded units

Term            Coef
Constant     79.0635
pH          -2.85807
Temp        -4.85305
```

```
CD             0.0912371
pH*pH           0.253755
Temp*Temp      0.0769938
CD*CD        0.000505326
pH*Temp         0.192027
pH*CD         -0.0239030
Temp*CD      -0.00395793
```

Response Surface Regression: TH % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for TH %

Term          Coef  SE Coef       T      P
Constant    41.004    6.993   5.864  0.002
pH          15.225    4.282   3.555  0.016
Temp         2.649    4.282   0.619  0.563
CD           9.029    4.282   2.108  0.089
pH*pH        8.689    6.303   1.379  0.227
Temp*Temp  -10.661    6.303  -1.691  0.152
CD*CD       -7.977    6.303  -1.266  0.261
pH*Temp     -4.228    6.056  -0.698  0.516
pH*CD       13.390    6.056   2.211  0.078
Temp*CD      7.694    6.056   1.270  0.260


S = 12.1120    PRESS = 11078.1
R-Sq = 86.18%  R-Sq(pred) = 0.00%  R-Sq(adj) = 61.30%


Analysis of Variance for TH %

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression       9  4572.96  4572.96   508.11   3.46  0.092
  Linear         3  2562.70  2562.70   854.23   5.82  0.044
    pH           1  1854.38  1854.38  1854.38  12.64  0.016
    Temp         1    56.13    56.13    56.13   0.38  0.563
    CD           1   652.19   652.19   652.19   4.45  0.089
  Square         3   984.80   984.80   328.27   2.24  0.202
    pH*pH        1   374.87   278.78   278.78   1.90  0.227
    Temp*Temp    1   374.96   419.66   419.66   2.86  0.152
    CD*CD        1   234.97   234.97   234.97   1.60  0.261
  Interaction    3  1025.46  1025.46   341.82   2.33  0.191
    pH*Temp      1    71.51    71.51    71.51   0.49  0.516
    pH*CD        1   717.16   717.16   717.16   4.89  0.078
    Temp*CD      1   236.80   236.80   236.80   1.61  0.260
Residual Error   5   733.50   733.50   146.70
  Lack-of-Fit    3   685.65   685.65   228.55   9.55  0.096
  Pure Error     2    47.85    47.85    23.93
Total           14  5306.46


Unusual Observations for TH %

Obs  StdOrder    TH %     Fit  SE Fit  Residual  St Resid
  9         9  17.949  30.684  10.489   -12.735     -2.10 R
 15        15  68.571  55.836  10.489    12.735      2.10 R

R denotes an observation with a large standardized residual.


Estimated Regression Coefficients for TH % using data in uncoded units
```

```
Term              Coef
Constant       35.6857
pH            -30.3439
Temp           9.81282
CD           -0.308475
pH*pH          1.39027
Temp*Temp    -0.189530
CD*CD      -0.00160502
pH*Temp      -0.225497
pH*CD        0.0759712
Temp*CD      0.0145515
```

Response Surface Regression: EC % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for EC %

Term          Coef  SE Coef       T      P
Constant   24.2947    1.737  13.986  0.000
pH         15.6484    1.064  14.711  0.000
Temp        0.9365    1.064   0.880  0.419
CD          6.8811    1.064   6.469  0.001
pH*pH      20.9314    1.566  13.368  0.000
Temp*Temp   6.1445    1.566   3.924  0.011
CD*CD      -1.2773    1.566  -0.816  0.452
pH*Temp     3.6224    1.504   2.408  0.061
pH*CD       2.0554    1.504   1.366  0.230
Temp*CD    -0.7621    1.504  -0.507  0.634


S = 3.00860     PRESS = 694.628
R-Sq = 98.92%  R-Sq(pred) = 83.44%  R-Sq(adj) = 96.98%


Analysis of Variance for EC %

Source          DF   Seq SS   Adj SS   Adj MS       F      P
Regression       9  4149.04  4149.04   461.00   50.93  0.000
  Linear         3  2344.78  2344.78   781.59   86.35  0.000
    pH           1  1958.97  1958.97  1958.97  216.42  0.000
    Temp         1     7.02     7.02     7.02    0.78  0.419
    CD           1   378.79   378.79   378.79   41.85  0.001
  Square         3  1732.55  1732.55   577.52   63.80  0.000
    pH*pH        1  1581.77  1617.68  1617.68  178.72  0.000
    Temp*Temp    1   144.76   139.40   139.40   15.40  0.011
    CD*CD        1     6.02     6.02     6.02    0.67  0.452
  Interaction    3    71.71    71.71    23.90    2.64  0.161
    pH*Temp      1    52.49    52.49    52.49    5.80  0.061
    pH*CD        1    16.90    16.90    16.90    1.87  0.230
    Temp*CD      1     2.32     2.32     2.32    0.26  0.634
Residual Error   5    45.26    45.26     9.05
  Lack-of-Fit    3    43.11    43.11    14.37   13.39  0.070
  Pure Error     2     2.15     2.15     1.07
Total           14  4194.30


Unusual Observations for EC %

Obs  StdOrder    EC %     Fit  SE Fit  Residual  St Resid
  8         8  23.855  20.582   2.606     3.273     2.18 R
 12        12  32.945  36.217   2.606    -3.273    -2.18 R

R denotes an observation with a large standardized residual.
```

```
Estimated Regression Coefficients for EC % using data in uncoded units

Term               Coef
Constant        379.366
pH             -65.1747
Temp           -7.41074
CD             0.136185
pH*pH           3.34902
Temp*Temp      0.109236
CD*CD      -2.56986E-04
pH*Temp        0.193193
pH*CD         0.0116621
Temp*CD     -0.00144138
```

Response Surface Regression: pH % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for pH %

Term          Coef  SE Coef       T      P
Constant   39.5021   1.6201  24.383  0.000
pH          9.6644   0.9921   9.742  0.000
Temp       -2.4969   0.9921  -2.517  0.053
CD          2.4187   0.9921   2.438  0.059
pH*pH      -8.1807   1.4603  -5.602  0.003
Temp*Temp   2.0327   1.4603   1.392  0.223
CD*CD      -0.2162   1.4603  -0.148  0.888
pH*Temp     1.8913   1.4030   1.348  0.235
pH*CD      -1.5323   1.4030  -1.092  0.325
Temp*CD     0.1752   1.4030   0.125  0.906


S = 2.80602    PRESS = 221.162
R-Sq = 96.67%  R-Sq(pred) = 81.27%  R-Sq(adj) = 90.66%


Analysis of Variance for pH %

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression       9  1141.31  1141.31  126.812  16.11  0.003
  Linear         3   843.88   843.88  281.293  35.73  0.001
    pH           1   747.20   747.20  747.203  94.90  0.000
    Temp         1    49.88    49.88   49.876   6.33  0.053
    CD           1    46.80    46.80   46.801   5.94  0.059
  Square         3   273.61   273.61   91.203  11.58  0.011
    pH*pH        1   257.84   247.10  247.105  31.38  0.003
    Temp*Temp    1    15.60    15.26   15.256   1.94  0.223
    CD*CD        1     0.17     0.17    0.173   0.02  0.888
  Interaction    3    23.82    23.82    7.941   1.01  0.462
    pH*Temp      1    14.31    14.31   14.308   1.82  0.235
    pH*CD        1     9.39     9.39    9.391   1.19  0.325
    Temp*CD      1     0.12     0.12    0.123   0.02  0.906
Residual Error   5    39.37    39.37    7.874
  Lack-of-Fit    3     9.64     9.64    3.214   0.22  0.879
  Pure Error     2    29.73    29.73   14.863
Total           14  1180.68


Estimated Regression Coefficients for pH % using data in uncoded units

Term               Coef
```

```
Constant       -77.5113
pH              27.8173
Temp            -3.34942
CD               0.126358
pH*pH           -1.30891
Temp*Temp        0.0361365
CD*CD         -4.34901E-05
pH*Temp          0.100870
pH*CD          -0.00869365
Temp*CD        0.000331278
```

Response Surface Regression: TDS % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for TDS %

Term           Coef  SE Coef       T      P
Constant    24.6614    1.769  13.940  0.000
pH          15.6882    1.083  14.482  0.000
Temp         1.2744    1.083   1.176  0.292
CD           6.8088    1.083   6.285  0.001
pH*pH       21.9835    1.595  13.786  0.000
Temp*Temp    5.8549    1.595   3.672  0.014
CD*CD       -1.1580    1.595  -0.726  0.500
pH*Temp      3.4118    1.532   2.227  0.076
pH*CD        1.8663    1.532   1.218  0.277
Temp*CD     -0.1903    1.532  -0.124  0.906


S = 3.06409     PRESS = 691.241
R-Sq = 98.92%  R-Sq(pred) = 84.10%  R-Sq(adj) = 96.98%


Analysis of Variance for TDS %

Source          DF   Seq SS   Adj SS   Adj MS       F      P
Regression       9  4299.20  4299.20   477.69   50.88  0.000
  Linear         3  2352.81  2352.81   784.27   83.53  0.000
    pH           1  1968.95  1968.95  1968.95  209.72  0.000
    Temp         1    12.99    12.99    12.99    1.38  0.292
    CD           1   370.87   370.87   370.87   39.50  0.001
  Square         3  1885.75  1885.75   628.58   66.95  0.000
    pH*pH        1  1749.57  1784.39  1784.39  190.06  0.000
    Temp*Temp    1   131.23   126.57   126.57   13.48  0.014
    CD*CD        1     4.95     4.95     4.95    0.53  0.500
  Interaction    3    60.64    60.64    20.21    2.15  0.212
    pH*Temp      1    46.56    46.56    46.56    4.96  0.076
    pH*CD        1    13.93    13.93    13.93    1.48  0.277
    Temp*CD      1     0.14     0.14     0.14    0.02  0.906
Residual Error   5    46.94    46.94     9.39
  Lack-of-Fit    3    42.59    42.59    14.20    6.52  0.136
  Pure Error     2     4.35     4.35     2.18
Total           14  4346.15


Unusual Observations for TDS %

Obs  StdOrder   TDS %     Fit  SE Fit  Residual  St Resid
  8         8  24.192  21.085   2.654     3.108    2.03 R
 12        12  34.144  37.251   2.654    -3.108   -2.03 R

R denotes an observation with a large standardized residual.
```

```
Estimated Regression Coefficients for TDS % using data in uncoded units

Term                Coef
Constant         392.192
pH              -67.8192
Temp            -7.2
0666
CD              0.105369
pH*pH            3.51735
Temp*Temp       0.104087
CD*CD       -2.32996E-04
pH*Temp         0.181961
pH*CD          0.0105892
Temp*CD     -3.59972E-04
```

Response Surface Regression: Salinity % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for Salinity %
```

Term	Coef	SE Coef	T	P
Constant	27.5801	1.698	16.246	0.000
pH	15.8754	1.040	15.270	0.000
Temp	1.2953	1.040	1.246	0.268
CD	6.7073	1.040	6.452	0.001
pH*pH	20.7935	1.530	13.588	0.000
Temp*Temp	4.6442	1.530	3.035	0.029
CD*CD	-2.4613	1.530	-1.608	0.169
pH*Temp	3.3247	1.470	2.261	0.073
pH*CD	1.8762	1.470	1.276	0.258
Temp*CD	-0.3185	1.470	-0.217	0.837

```
S = 2.94049    PRESS = 639.438
R-Sq = 98.97%  R-Sq(pred) = 84.74%  R-Sq(adj) = 97.11%


Analysis of Variance for Salinity %

Source          DF   Seq SS   Adj SS   Adj MS       F      P


Regression       9  4147.47  4147.47   460.83   53.30  0.000
  Linear         3  2389.56  2389.56   796.52   92.12  0.000
    pH           1  2016.24  2016.24  2016.24  233.19  0.000
    Temp         1    13.42    13.42    13.42    1.55  0.268
    CD           1   359.90   359.90   359.90   41.62  0.001
  Square         3  1699.20  1699.20   566.40   65.51  0.000
    pH*pH        1  1590.06  1596.44  1596.44  184.63  0.000
    Temp*Temp    1    86.78    79.64    79.64    9.21  0.029
    CD*CD        1    22.37    22.37    22.37    2.59  0.169
  Interaction    3    58.70    58.70    19.57    2.26  0.199
    pH*Temp      1    44.21    44.21    44.21    5.11  0.073
    pH*CD        1    14.08    14.08    14.08    1.63  0.258
    Temp*CD      1     0.41     0.41     0.41    0.05  0.837
Residual Error   5    43.23    43.23     8.65
  Lack-of-Fit    3    39.43    39.43    13.14    6.91  0.129
  Pure Error     2     3.80     3.80     1.90
```

```
Total          14  4190.70


Unusual Observations for Salinity %

Obs  StdOrder  Salinity %     Fit  SE Fit  Residual  St Resid
  8         8      24.444  21.442   2.547     3.003      2.04 R
 12        12      34.444  37.447   2.547    -3.003     -2.04 R

R denotes an observation with a large standardized residual.


Estimated Regression Coefficients for Salinity % using data in uncoded units

Term                Coef
Constant         346.693
pH              -64.0109
Temp            -5.92414
CD              0.222031
pH*pH            3.32695
Temp*Temp      0.0825628
CD*CD       -4.95216E-04
pH*Temp         0.177315
pH*CD          0.0106453
Temp*CD     -6.02336E-04
```

Response Surface Regression: TSS % versus pH; Temp; CD

```
The analysis was done using coded units.

Estimated Regression Coefficients for TSS %

Term          Coef  SE Coef       T      P
Constant    383.33    70.02   5.475  0.003
pH           25.00    42.88   0.583  0.585
Temp        -31.25    42.88  -0.729  0.499
CD           18.75    42.88   0.437  0.680
pH*pH       -79.17    63.12  -1.254  0.265
Temp*Temp  -116.67    63.12  -1.848  0.124
CD*CD      -116.67    63.12  -1.848  0.124
pH*Temp     -12.50    60.64  -0.206  0.845
pH*CD        62.50    60.64   1.031  0.350
Temp*CD      50.00    60.64   0.825  0.447


S = 121.278    PRESS = 1153750
R-Sq = 67.07%  R-Sq(pred) = 0.00%  R-Sq(adj) = 7.80%


Analysis of Variance for TSS %

Source          DF  Seq SS  Adj SS   Adj MS     F      P
Regression       9  149792  149792  16643.5  1.13  0.471
  Linear         3   15625   15625   5208.3  0.35  0.789
    pH           1    5000    5000   5000.0  0.34  0.585
    Temp         1    7812    7813   7812.5  0.53  0.499
    CD           1    2812    2812   2812.5  0.19  0.680
  Square         3  107917  107917  35972.2  2.45  0.179
    pH*pH        1   14583   23141  23141.0  1.57  0.265
    Temp*Temp    1   43077   50256  50256.4  3.42  0.124
    CD*CD        1   50256   50256  50256.4  3.42  0.124
  Interaction    3   26250   26250   8750.0  0.59  0.645
    pH*Temp      1     625     625    625.0  0.04  0.845
    pH*CD        1   15625   15625  15625.0  1.06  0.350
```

```
    Temp*CD       1   10000   10000  10000.0   0.68  0.447
Residual Error    5   73542   73542  14708.3
  Lack-of-Fit     3   71875   71875  23958.3  28.75  0.034
  Pure Error      2    1667    1667    833.3
Total            14  223333


Estimated Regression Coefficients for TSS % using data in uncoded units

Term              Coef
Constant      -2335.23
pH             193.291
Temp           96.0516
CD             4.31966
pH*pH         -12.6667
Temp*Temp     -2.07407
CD*CD       -0.0234730
pH*Temp      -0.666667
pH*CD         0.354610
Temp*CD      0.0945626
```

ملخص

تواجه دولة الإمارات العربية المتحدة قضايا ندرة المياه بسبب النمو السريع للسكان فضلاً عن التطورات الصناعية الكبيرة في السنوات الأخيرة. ولذلك فقد نظرت حكومة دولة الإمارات العربية المتحدة لمعالجة المياه العادمة كبديل عملي من أجل زيادة احتياطي المياه. مياه الصرف الصناعية تحتوي على العديد من الملوثات التي تشكل مخاطر جدية على الموارد المائية مثل المياه السطحية (البحيرات، والأنهار، والمحيطات) والمياه الجوفية. وقد استخدمت العديد من التقنيات على نطاق واسع لمعالجة مياه الصرف الصحي لتحسين نوعية النفايات السائلة التي يمكن تصريفها بأمان أو إعادة استخدامها لتطبيقات أخرى مثل التبريد والزراعة. ومن الأمثلة على الأساليب الفيزيائية والبيولوجية مثل عملية الحمأة المنشطة (ASP)، المفاعلات الحيوية الغشائية (MBRs)، الأراضي الرطبة، الامتزاز، والتبادل الأيوني.

إن الهدف من هذه الأطروحة هو تقييم إمكانية استخدام التخثيرالكهربائي (Electrocoagulation Process) في علاج كربيد الطين (Carbide Slurry)، وهي المياه العادمة الناتجة من تحضير وانتاج مادة الأسيتيلين. أجريت عدة تجارب باستخدام كثافة تيار كهربائي تتراوح ما بين 140-290 A/m^2. تم استخدام نوعين من الغازات مثل الهواء النقي (EA system) و10٪ من ثاني أكسيد الكربون (CA system) لضمان الخلط الجيد والتجانس. واستخدمت ألواح الألومنيوم المتصلة بإمدادات الكهرباء (DC power supply). يتم جمع عينات من مياه الصرف الصحي المعالجة ويتم تحليلها بعد مدة أقصاها 3 ساعات.

تم استخدام منهجية استجابة السطح (RSM) لتصميم مصفوفة من التجارب من أجل تحسين الظروف لعملية المعالجة وتحسين جودة المنتج. تصميم مربع بينكين (BBD) هو أداة لتحسين متعدد المتغيرات. يمكن أن نستخلص إلى أن نوعية مياه الصرف الصحي المعالجة وكذلك الناتجة عن المنتجات يمكن تعزيزها من خلال التحكم في ظروف التشغيل في المفاعل الكهروكيميائية وكانت أعلى كفاءة لنظام الهواء النقي (EA system) 47.5%، 47.8%، 69.7%، 36.1%، 71.4%و 53% لكل من COD، TH، EC، درجة الحموضة، الملوحة وTDS ، على التوالي في ظل ظروف معينة، والظروف المثلى الشاملة لإعطاء أعلى نسبة للتخلص من الملوثات كانت عند درجة حموضة 12، درجة حرارة 27.5 °C و كثافة تيار كهربائي 284 A/m^2. ومن زاوية أخرى وعند استخدام نظام 10% من ثاني أكسيد الكربون (CA system) ، كانت أعلى نسبة تخفيض للملوثات هي 42%، 75%، 73%، 46%، 73% و74% ل COD، TH، EC، ودرجة الحموضة، الملوحة و TDS، على التوالي في ظل ظروف معينة، و الظروف المثلى الشاملة لإعطاء أعلى نسبة نت التخلص من الملوثات كانت عند درجة حموضة 12 و درجة حرارة 35 °C وكثافة تيار كهربائي 213A/m^2.. وكانت أعلى نسبة كفاءة لالتقاط ثاني أكسيد الكربون هي84%.

UAEU College of Engineering

جامعة الإمارات العربية المتحدة
United Arab Emirates University

جامعة الامارات العربية المتحدة

كلية الهندسة

معالجة المياه الناتجة عن الصناعة عن طريق عملية التخثير الكهربائي

شيرين وجيه سليم حسن

رسالة مقدمة لاستكمال متطلبات الحصول على درجة الماجستير في هندسة موارد المياه

باشراف البروفيسور مفتاح النعاس

يونيو 2014