HEAVY METAL REMOVAL FROM WASTEWATER USING NOVEL ADSORBENT

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Heavy Metal Removal from Wastewater Using Novel Adsorbent

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ABSTRACT

Heavy metals, when in abundance, can be very toxic to the medium in which it is dissolved. Adsorption has been used as a suitable water treatment process to remove heavy metals. Many studies have been conducted to remove these heavy metals by using different materials. Different materials have different chemical constitutes, hence, a material that is very effective in removing one heavy metal may prove to have a poor efficiency in adsorbing, or removing, another metal. For this research, palm leaves were used as the adsorbent to remove Copper, Chromium, and Zinc from wastewater. The synthetic wastewater was produced in the laboratory to conduct the experiments. Batch tests were conducted to obtain the optimal materials and conditions combinations. The fixed bed column experiments were then followed, as they simulate the filtration process which is the most commonly used in treatment plants for adsorption. Batch tests were conducted to assess the performance of copper removal via adsorption. Different conditions were tested for and included pH, Co, and adsorbent dosage. Results have used Freundlich and Langmuir equations to fit the experimental data so that kinetics of the process can be obtained. It was also shown that Freundlich isotherm was better able to fit the linearized data points than Langmuir with Copper and Zinc, however, neither isotherm was very successful with Chromium. It was concluded that each metal has its own optimal condition that is not fitted with the other metals, although, all conditions produced positive results. Desorption tests confirmed the reusability of the metals and the adsorbent as recovery was sufficient in some places more than others. Further investigations may need to be performed to obtain results on different parameters, adsorbent particle size, contact time, agitation speed, and temperature, etc.

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

Industrial wastewater contains high levels of heavy metals that may pollute the water once it is discharged to the nature. These metals include arsenic, chromium, copper, zinc, aluminum, cadmium, lead, iron, nickel, mercury, and silver Heavy metals are elements that have more than five times the specific gravity than that of water. They are one of the most toxic types of water pollutants. At least 20 metals are considered to be toxic, and approximately half of these metals are emitted to the environment in quantities that are hazardous to the environment, in addition to the human health. [1]

In Dubai, many industries are located in the free zone region of Jebel Ali. These industries include metals, textile, paper, dairy processing, pharmaceutical, oilfield and refinery, soft drinks, bakeries, rubber, and power. Each of these industries disposes high levels of different metals, which in aggregate and in combination, pollutes the coastal water bodies. Due to these limitations, and regulations brought about by governmental agencies, technologies are needed to remove these metals.

Some of the treatment processes that have been used to remove heavy metals from wastewater include precipitation with coagulation and flocculation, ion exchange, complexation of dry biomass and adsorption [2]. However, there are limitations: Precipitation produces large quantities of heavy metals rich waste sludge; ion exchange and biomass methods are costly and cannot be readily applied to large scale applications [2]. Adsorption as a process, employed due to its low cost and applicability on large scales. Adsorption is commonly being done using activated carbon, which adsorbs dissolved organic substances in the water treatment [3]. Although activated carbon has its advantageous, such as its effectiveness in removing colours and its applicability on wide variety of organic compounds, it has limitations that prevent it from treating highly soluble organics, and high concentrations or organic and inorganic compounds. In addition to these, cost of operation is high. [3]. Other adsorbents that have been used include synthetic polymers and silica-based substances [4] [5]. However, these materials are more costly compared to activated carbon. Hence, there is a perceived necessity and growing interest in finding adsorbents that are more cost-effective and produce fewer limitations including high temperatures and pressures. Therefore, finding suitable materials and operating conditions are essential to addressing the concerns of heavy metal pollution.

1.2 THESIS OBJECTIVES

The overall objective of this research is to remove heavy metals from wastewater using novel, biological and cheap materials. The specific objectives of the project are:

- To find an effective suitable material for removing heavy metal
- To determine the optimal operating conditions
- To evaluate the feasibility of using palm leaf as locally available absorbent material.

1.3 SCOPE

The scope of this thesis is to test wastewater for the removal of copper, chromium, and zinc using cheap and readily available adsorbents. The wastewater was artificially prepared in the lab. The water is tested for one metal at a time, where other materials were added at a later stage to test for changes in the results. The experiments were performed in the laboratory scale, and consist of batch and column tests. Water quality analyses of the heavy metals were done using HACH DR5000 spectrophotometer due to lack of availability of Atomic Adsorption Spectrophotometer (AA). However, an additional test was performed using both machines to evaluate the relationship between the results originating from the two testing equipments. These results helped to assess the reliability of the results. Column tests were performed on the conditions that provided the best results during the batch tests. The best condition was then deduced from the column test. In addition to evaluating the adsorption capability of the adsorbent on the metals, the recovery ability was also tested and evaluated to determine the reusability of both the adsorbent and the metals. This is an additional benefit as this reduces the need for extracting metals from the environment to be used in the industrial process.

The scope of this work does not include studying the chemical constituents of the adsorbents to determine the chemical reactions involved during the process. Further research into the matter is not part of the scope.

1.4 STRUCTURE OF THE THESIS

The thesis report is divided into the following chapters:

Chapter One presents the background of the thesis research and the necessity of this project.

Chapter Two presents the literature review of studies conducted by other researches, in which this research was referred to. It consists of background of the theory of the topics involved, providing a background on the uses and applications. The chapter emphasizes the advantages of using adsorption and low cost materials in terms of cost, time, and efficiency and illustrates the applications of using it on wastewater.

Chapter Three presents the methodology employed to achieve the objectives of the thesis. It discusses the experiments that were conducted. It consists of procedures, methods, equipment, apparatus, and other relevant information that was used for conducting the experiments.

Chapter Four presents the results that were obtained during the experimentations. It consists of discussion of the results obtained, and presents favorable and unfavorable scenarios for the best experiment results. The chapter emphasizes on obtaining optimal conditions that lead to the best conditions for the most efficient adsorption, as well as fitting the experimental data with both Freundlich and Langmuir Adsorption Isotherms. It also presents the results obtained from recovering the metals from the adsorbents, which allows the process to be more environmentally friendly.

Chapter Five presents a conclusion to the thesis. It provides observations, conclusions and recommendations. It highlights the outcomes that were obtained from the thesis research.

Appendix A provides figures and data that were not included in the context of the report, but may be used for supporting some content. The section also illustrates the full figures and tables that were conducted and used for the manufacturing of the report. The appendix is divided into 3 subsections: A.1 represents results obtained from the batch tests. It also includes the adsorption isotherms obtained for each metal; A.2 represents results obtained from the column tests; and A.3 represents results obtained from desorption tests.

CHAPTER 2 LITERATURE REVIEW

2.1 GENERAL

Many methods have been used by researchers to obtain the most optimal and cost effective method to remove soluble solids from wastewater. Of these solids, metals have received a lot of attention due to their harmful and toxic effect when present in abundance. At least 20 metals are considered to be toxic, and approximately half of this number is emitted to the environment in quantities that are hazardous to the environment in addition to the human health [6]. The most abundant metal existing in wastewater is Chromium and is considered the most dangerous metal due to it being mutagenic and carcinogenic [7]. Other metals in high quantities include magnesium, calcium, copper, aluminum, nickel, zinc, and arsenic. Some of the methods employed, or studied, include precipitation, filtration, coagulation, ion-exchange, magnetic fields, fluidized bed reactor, ion flotation, flue gas purification, and adsorption [8]. These methods have their advantages; however, to choose the suitable method, the disadvantages need to be compared. Precipitation, for example, cannot be used when low concentrations of heavy metal ions are present in large volumes of water. Flocculation or coagulation needs to accompany precipitation, which usually results in large volumes of sediments containing heavy metal ions forming. Also, small concentrations of the metals are still dissolved in the water after the process has been complete, hence, resulting in it as an unsuitable method for this research [9]. Other methods are either time consuming, expensive, or cannot be applied on large volumes of waste. Adsorption, however, is a cost effective, relatively quick method of removing heavy metals from water regardless of the concentration of the metals or the volume of water that it is dissolved in. Different materials may be used as adsorbents which collect, or adsorb, the heavy metals from the wastewater. Of those investigated in prior research include cashew nut shells [10], olive cake [11], date pits and fruits [12] [1], tea factory waste [6], maize cobs [13], and wood saw dust [14], to name a few. Waste products and other natural products are readily used as adsorbates, hence, allowing for an inexpensive and feasible method of removing solids from wastewater [14]. The problem lies in obtaining the optimal adsorbent and corresponding conditions that effectively remove a large percentage of a known metal. Table 2.1 illustrates the type of adsorbate or metals that have been previously investigated, the type of test conducted (batch or column), the adsorbent material, the experimental conditions, the procedure, and the result obtained.

Table 2.1: Experiments Conducted by Researchers

Heavy Metal	Adsorbent	Type of Test	Experimental Variable	Experimental Conditions	Result	Ref
Zn	Tea Factory Waste	Batch Test	pH values, adsorbent dose, contact time, initial conc, temp	Room temperature (30±1 C) in 100cm3 conical flasks.	Max adsorption capacity of Zn (II) per gram adsorbent was 8.9±0.08 mg. Contact time Percent removal decreased with increase in initial concentration	[6]
Pb, Cd, Fe, Sr	Date Pits	Steam pyrolysis in batch mode	adsorbent dosage, pH, contact time, temp	One step steam pyrolysis in a batch mode.	Percent Removal:Pb^{2+} – 66%.Cd^{2+} – 93%,Fe^{3+} – 35%,Sr^{2+} – 69%.	[12]
Al	Date pits BDH activated Carbons	Batch test	Effect of pH low and high initial conc		DP activated carbon more capable of absorbing Al than BDH in low concentration (due to pH) At low initial conc and low pH – uptake of Al from DP was 0.305 mg/g; from BDH – 0.021mg/g	[15]

Table 2.1: Experiments Conducted by Researchers (continued)

Heavy Metal	Adsorbent	Type of Test	Experimental Variable	Experimental Conditions	Result	Ref
Fe, Mn	Maize Cobs	Fixed Bed Column	Initial conc	Cst temp (22 C), cst speed (800rpm); Atomic Adsorption spectrophotometer; fixed adsorbant;50 ml metal soln; pH 5.5 for 3 days; Contact time for 100 min	Max adsorption capacity at 2.3 mg Mn/g maize cob, and 2.5 Fe. Percent removal – initial conc 1 to 40 mg/L – 79% to 37% (Mn), 80 to 39% (Fe).	[13]
Pb	Natural porous medium (red pozzolan)	Batch and Column test	pH, total Pb conc	0.5g of solid phase suspended with 50 mL of 0.1 mol.L NaCl soln at fixed Pb conc. Magnetic stirring for 24 hrs; Column – (10 cm L, 3 mm D). NO3- used as tracer.	Batch Percent Removal - 38.8% Pb2+, 55.5% PbCl, 5.3% PbCl2 aq irrespective of pH and total lead conc; Conc of hydrolysis prod of lead always negligible. Column –lead breakthrough at 0.1 mol/L NaCl soln at pH4, with total conc of 2.2x10-4 mol/L.	[16]
Cu, Zn, Cd,	Wood saw dust	Batch	adsorbent conc	Cst temp (23C), pH (4), conc of metal, and contact time (3 hrs).	Percentage removal : 76% Cu, 37% Zn, 31% Cd Adsorption increased with increase of sawdust	[14]

The experiments previously performed have been employed on wastewater from industries and treatment plants, in addition to artificially wastewater produced in the lab. Adsorption behaves differently when different suspended solids are dissolved in water, hence, different values may be obtained for the same conditions with one metal dissolved, multiple metals, or other inorganic and organic solids [14]. Hence, studying the effect of adsorption in one condition does not necessarily provide measures for other conditions. But using a consistent system (here with a consistent wastewater) allows us to eliminate the other sources of uncertainties and study the removal mechanisms.

Batch tests and column tests were conducted extensively by previous researchers to test the efficiency of the adsorbent on the adsorbate, testing various experimental conditions. Batch tests are a cheap and easy way to determine if the material employed, and the conditions used, are successful in producing significantly positive results. Once the results are plotted on a figure, isotherms such as Freundlich and Langmuir are used to determine the regression, and hence, the accuracy of the method employed is also determined [2]. Column tests were less likely used due to their longer experimental duration, however, the results obtained from these tests are highly reliable as they mimic real life situations on a smaller scale [17].

2.2 ADSORPTION – THE PROCESS

Adsorption is a process that collects, or adsorbs, dissolved substances in water to the surface of the materials being used, or adsorbent. Adsorption has not been readily used to treat wastewater, but as the demands for better water quality become more rigorous, extensive research have been conducted on the process of adsorption to provide better quality and reduced toxicity of water. Adsorption with activated carbon was the most sought-on process, where the carbon was used as a “polishing process” to remove a fraction of the existing dissolved substances in the water after treatment [2]. In addition, some adsorption processes require high temperatures and pressures to allow for the process to work with activated carbon.

Adsorption has been used for centuries. It is thought that the idea was first conceived in ancient times. However, first results or observations weren’t documented until the late 1700's. At that time, adsorption was used to test the ability of charcoals and clays to uptake gases. With more research, by 1814 it was concluded by de Saussure, that all types of gases can be taken up by porous substances such as asbestos, cork, sea-foam, in addition to charcoal. By the early 1900's, the Freundlich equation was developed but was not theoretically justified. The adsorption isotherm is known as Freundlich equation, due to Freundlich's emphasis on the importance of the equation, which developed its extended use, although it was believed the equation was developed in the empirical form a decade earlier by Boedecker. Other equations were also developed and included Langmuir, Euckena, and Polanyi. Langmuir's equation was originally developed for monolayer adsorption. It is this equation that is considered as the practical equation that corresponding to an ideal and localized monolayer. Branauer, Emmett, and Teller (BET) proposed the multilayer isotherm. The BET equation uses the same assumptions as Langmuir, and assumes that Langmuir's equation applies to every adsorption layer. It was the BET theory that was the initial endeavor at creating a universal theory of physical attraction. The Langmuir and BET theories and equations are the most widely used equations for monolayer and multilayer adsorption [18] [19] [20] [21].

Different types of materials have been used to test the effect on adsorbing, or collecting, dissolved organics and inorganics in water. Over the years, tests have been performed on domestic wastewater, industrial wastewater, seawater, and drinking water among other types of water sources. Each of these types of water has different types of dissolved substances depending on the location, source and use of the water, in addition to the codes and thresholds of the government. Purification and treatment processes also yield varying results based on the methods used, and the wastewater itself. In the case of heavy metals dissolved in water, industrial wastewater yields the most amounts of dissolved metals. The type and quantity of each metal varies within different industries.

Adsorbents previously used usually require a chemical process for its production. This is usually accompanied by a complex or time-consuming process or one that results in a lot of waste or bi-products. Other adsorbents that have been used require organic materials such as nuts [22], leaves, shells [23], bark [24], pits [25] [12], wood [14], etc, to be heated to high temperatures and undergo rigorous processes for them to form an activated carbon [2]. However, the process of forming activated carbon is often time-consuming and. Adsorbents that readily exist in the environment and have proved to be effective have not been used until recently. Many of the recently used adsorbents are natural waste products that can be found in the environment or as a bi-product from other processes. Simple but thorough washing, drying, and grinding of the materials are the basic processes of the preparation of effective adsorbents. Also, these materials have been proven to be more effective in removing heavy metals compared to the more renowned activated carbon.

In the case of organic substances and activated carbon, interactions known as "specific adsorptions" occur between the surfaces of the adsorbent and the different functional groups of the adsorbate. An attraction occurs between the adsorbate and the adsorbent primarily due to one or more of the following phenomena: (1) exchange adsorption – electrical attraction, (2) physical/ideal adsorption – Van Der Waal force attraction, (3) chemical adsorption – chemical reactions. Also, the solubility of the substance in water plays an important role in adsorption, since the more hydrophobic the substance is in water, the higher its ability to be adsorbed, and the more hydrophilic it is, the lower its ability. This is due to the effect the soluble substances have on the surface tension of the water: the more substances are dissolved and soluble in the liquid solution, the more the alterations to the surface tension of the liquid solution. Adsorbents that have active surfaces, such as activated carbon, will result in reduced surface tension upon the substances' movement to the surface. The movement results in a diminution of effort to increase surface area that is proportional to the amount of adsorbate at the surface. Moreover, hydrophobic impurities in the water reduce the tension at the surface of water. [21]

The equilibrium reached in adsorption is illustrated by plotting the amount of solute, or metals in the case, adsorbed per unit weight of the adsorbent, q_e, against the concentration of the solute still remaining in the solution, C. This develops an adsorption isotherm. There are two most used equations for water and wastewater treatment: Langmuir and Freundlich. The capacity of the adsorbents determines the amount of heavy metal that was adsorbed onto the adsorbent, and can be determined through the following mass balance equation

$$q_e = \frac{(C_o - C_e)V}{m} \qquad (1)$$

Where q_e represents the adsorbent concentration after equilibrium (mg absorbent/g absorbent), V represents the total volume of the solute solution (in L), C_o represents the initial concentration of the solute (in mg/L), C_e the residual equilibrium concentration of the solute after adsorption (in mg/L), and, m represents the weight of the adsorbents used (in g)

Langmuir's Adsorption Isotherm may be used for monolayer adsorption onto a surface containing a finite number of identical sites, and assumes uniform energies of adsorption on the surface, in addition to no transmigration of the adsorbate in the plane of the surface [19]. The Langmuir isotherm model determines the maximum capacity of the adsorbent from complete monolayer coverage of the adsorbent surface. Langmuir's isotherm non-linear equation is

$$q_e = \frac{q_o b C_e}{1 + b C_e} \qquad (2)$$

Where q_e represents the amount adsorbed at equilibrium time (in mg/g), q_o and b are Langmuir constants that depend on the maximum monolayer adsorption capacity and adsorption equilibrium constant that relates to the energy of adsorption respectively. They can be calculated from the $\frac{1}{q_e}$ vs $\frac{1}{C}$ figure, where q_o is $\frac{1}{\text{intercept}}$, and b is equal to the intercept $\times \frac{1}{\text{slope}}$.

Freundlich Adsroption Isotherm may also be used for heterogenous surface energies and is commonly used to compare powder carbon in the treatment of water. The isotherm portrays that the ratio of the quantity of the solute adsorbed on a known mass of adsorbent to the concentration of the solute in the solution differs at different concentrations. Langmuir's energy term, b, varies here as a function of q_e due to variations in the heat of adsorption. The Freundlich equation is as follows:

$$q_e = K_f C^{1/n} \qquad (3)$$

Where K_f and n are constants, with K_f being the Freundlich constant defining the adsorption coefficient that indicates the relative adsorption capacity of the adsorbent of the bonding energy, and is proportional to $RT_n be^{\Delta H/RT}$, and with n >1.

Data obtained are fitted into the logarithmic equation:

$$\mathrm{Logq_e} = \mathrm{LogK_f} + \frac{1}{\mathrm{nLogC}} \qquad (4)$$

With an intercept of K_f and a straight lined-slope of $\frac{1}{n}$, where K_f roughly indicates the adsorption capacity, and $\frac{1}{n}$ the adsorption intensity [19].

These equations can be easily linearized and used to fit the experimental data through a linear regression. There are other isotherm models but Langmuir and Freundlich's are considered to be the most commonly used ones especially for monolayer and noncompetitive adsorption processes. The isotherms are useful in exemplifying the competence of the adsorbent in adsorbing the adsorbates from the water. They also present an interpretation of the practical reliance of capability on the concentration of the adsorbate. An effective adsorbent will represent a steep isotherm, hence, a spiked increase in the isotherm to the ultimate capacity at increasing concentration represents an elevated effectual capacity at the concentration level. These isotherms relate to the equilibrium condition, although most treatment applications do not offer adequate conditions and time for the equilibrium to be properly reached [26].

The rate of adsorption is important for equilibrium to be reached, and consists of three steps: (1) film diffusion - the adsorbate is transported through a surface layer to the outer surface of the adsorbent, (2) pore diffusion – the adsorbate is diffused through the pores of the adsorbent, and (3) adsorption of the adsorbate on the inner planes bounding pore and capillary spaces [27].

2.2.1 Sorption

As was previously stated, adsorption is one of the cheapest methods to effectively remove heavy metals from wastewater. However, depending on the conditions used to remove the metals, mostly the pH, other forms of removal may occur. One of this is precipitation. Precipitation alone is a costly and time-consuming process that cannot be effectively performed merely on its own. Sorption is a terms used to describe removal of metals not only through adsorption, but also through formation of solutes or precipitates [28]. However, throughout the thesis, the term referred to will be “adsorption” although precipitation may occur for some metals. As the topic in question refers to the overall removal of the heavy metals from the wastewater, it is beyond the scope of this paper to determine how much of the total removed metals have been removed via adsorption, and how much by precipitation.

2.2.2 Activated Carbon

Activated carbon has been used extensively by previous researchers due to its high capacity of removing heavy metals and other organics dissolved in water. Activated carbon is obtained by initially heating the material such as pits or barks at a high enough temperature to allow for water to evaporate completely. The material is then impregnated with an acid, and then carbonated in a furnace at very high temperatures of around 500 C to 900 C [25] [29]. The reside is washed in hot distilled water to achieve the desired pH level, and finally the activated carbon is crushed and sieved to the required diameter. As it is known, the smaller the diameter of the carbon the better it is for adsorption as it allows for a greater surface area to volume ratio. The larger the ratio, the greater the ability of the carbon to attach the dissolved substances, such as heavy metals, in the water to it. Many previous studies and experiments on adsorption have been conducted using activated carbon. The activated carbon has been made from bark, date seed, food and agricultural waste, and other low cost waste materials. However, the problem with activated carbon is the extensive pretreatment required to produce it. In other words, a lot of energy and funding is spent on maintaining specific conditions to produce activated carbon. Very high temperatures are required, in addition to the use of acidic chemicals. Hence, what started off as a cheap waste material ends up as a costly adsorbent after a long process [2]. Therefore, studies have been made to test the effect of adsorption on materials that have not undergone rigorous treatment to form activated carbon. These researches also studied the effect of low cost waste materials that have been washed and completely dried to remove any moisture in the material, and sieved to the desired range of diameters.

2.2.3 Low Cost Materials

Adsorption is a low-cost process as it uses relatively cheap materials. The method to obtain and prepare the materials is effortless and does not require the use of other resources, chemicals, or processes. Low cost material that only requires thorough washing and drying to remove moisture before being sieved is the latest research material being employed for successful adsorption [30]. Evaluation of tree leaves [31], date pits [1], cashew nut [10], hazelnut shells [31], barks [24], agricultural waste [31], maize corn [13], saw dust [14] etc has been done to test adsorption capability on different metals at different conditions. Conditions that are tested for include obtaining optimal pH, contact time, agitation speeds, and initial concentrations of metals and dosage of adsorbent. Different conditions yield different results for different metals and adsorbents. Hence, what may apply for a certain combination of experimental conditions, metals, and adsorbents, may not apply for another.

2.2.4 Palm Tree Leaves

Palm tree leaves (PTL) are readily available in the Middle Eastern Gulf region, the region where the analysis is taking place. Due to their abundance in the region, they are very inexpensive and easily obtained, hence, resulting in their desirability to be used for this research. Palm trees are usually maintained by removing some leaves and branches for landscaping purposes. These braches may fall out themselves naturally; hence using them for experimental purposes yields no cost, no adverse environmental effect, and no hassle in obtaining. Over the course of the year, many trees have their branches and leaves thrown away with no use. These leaves contain various chemical functional groups and include hydroxyl, carboxylic, and phenolic [32]. Adsorption increases as higher number of functional groups are present, hence, PTL proves to be a good candidate to use. This research allows for these unused leaves to be used in an unconventional method of removing heavy metals from wastewater, especially water that has been emitted from industries, as it is this water that contains the most amount of dissolved hazard substances.

2.2.5 Heavy Metals

As mentioned earlier, a metal is classified as a heavy metal when its density is five times that of water. Of these metals, chromium, nickel, copper, cobalt, manganese, mercury, lead, zinc, cadmium, silver, arsenic, and barium are the most abundant found in wastewater. These metals originate from industrial wastewater that is emitted in the neighbouring water bodies. However, because of their toxicity, it is important that they are removed from the wastewater before discharging to water bodies. Of these heavy metals, the ones that were chosen for this research were Chromium, Copper and Zinc, mostly due to their abundance in the wastewater, and also due to their level of toxicity.

2.2.5.1 Chromium

Chromium is the most abundant of all the heavy metals that can be found in wastewater. It is discharged from the wastewater of the steel manufacturing industry, paints industry, leather tannery products, dye and textile industry, paper industry, electroplating, and chrome plated products [17] [33]Chromium exists in two forms: trivalent Cr(III) and hexavalent Cr(VI). Its abundance is harmful to the marine life, vegetation and plants, in addition to humans due to its toxicity [34]. Cr(VI) is also a strong oxidizing agent, as well as a potential carcinogen. Other potential harmful effects on humans due to long term exposure to the metal include liver damage, kidney circulatory damage, nerve tissue damage, and dermatitis. In general, chromium results in very grave harmful effects on human health [34] [35]. Cr (III) is less toxic than Cr(VI) as it only affects plants, not humans. Thus, the total concentration of Chromium in the form of both Cr(VI), Cr(III), in addition to other forms, is regulated to a threshold of 2 mg/L. The reduction of chromium concentration is crucial in order to meet this threshold. Hence, the U.S. Environmental Protection Agency (EPA) regulates a threshold of maximum allowed concentration of the metal allowed to be discharged into water bodies without treatment to be 0.05 mg/L. The US EPA also set the maximum contamination level for chromium to be 0.1 mg/L in drinking water.

2.2.5.2 Copper

Copper is another heavy metal that is found in abundance in wastewater. Most industries use large amounts of copper, where some of these industries that discharge this metal include metal processing, dye and textile, metallurgical, plating, printing circuits, fertilizer, refining [36], and paints [37]. Copper is severely toxic to human health, and may result in liver damage, lung damage [38], severe mucosal irritation and corrosion, central nervous system irritation, in addition to a potential to cause necrotic changes in the liver and kidney [39], widespread capillary damage, hepatic and renal damage, and depression [37]. Authorities have set a tolerance limit of copper discharged at 3 mg/L, but this number drops to 0.05mg/L for drinking water. The Environmental Quality Act (EQA) 1974 set the threshold at 0.2 mg/L for drinking water [37].

2.2.5.3 Zinc

Zinc is another heavy metal that is present in detrimental quantities in wastewater. Zinc is discharged from municipal wastewater treatment plants, metals industries, pulp and paper industries, acid marine drainage, galvanizing plants, and the yarn and fiber production [32]. Zinc is a potentially carcinogenic, as well as having other health effects. According to MSDS for metals, zinc metal is hazardous in the case of skin and eye contact, poses indigestion, and is hazardous if inhaled [40].

2.3 EXPERIMENTAL AND NUMERICAL STUDIES

2.3.1 Batch Tests

Most of the research conducted on adsorption of metals using waste materials underwent batch tests to analysis how the adsorbate and adsorbent perform under various conditions. These conditions include pH levels, initial concentration of metal solution, concentration of adsorbent, temperature, agitation speed, and contact time. All of these conditions produce different results once changed; however, the magnitude and significance of change alters between the different conditions as each has a different effect on the adsorption process. As adsorption is a process which involves reactions between the adsorbate and adsorbent, varying the conditions may improve or exacerbate the rate and amount of adsorption. pH affects adsorption reactions through H^+ and OH_- ions that are emitted into the solution. A more acidic pH releases more H^+ ions that may react with the adsorbent or adsorbate, hence affecting results. Likewise, an alkaline pH solution releases OH^- which may also react with the adsorbent or adsorbate [41]. Hence, it is crucial when performing batch tests to evaluate the process at different pH levels. Unfortunately, a universal pH value cannot, be determined and set due to the different types of adsorbents used and their chemical constitutions. Hence, tests need to be performed to determine the most efficient value of pH. Like pH, contact time is another crucial factor to consider when performing tests. This is also significant as the adsorbents used are organic materials, which may release additional organic materials in the system. Not allowing for enough contact time will not effectively complete the adsorption process, hence, results obtained will be incomprehensible and void. The greater the contact time, the greater the possibility that equilibrium has been reached, and hence, adsorption has reached its potential. Agitation speed is another important criterion to be test, as this either speeds up or slows down adsorption. However, a higher agitation speed does not necessarily mean a higher rate of adsorption. Adsorption is highest at a certain speed that needs to be determined through experimentation. Different initial concentrations of the metal solution evaluate the capacity of the adsorbent in its ability to adsorb and remove the metals from the solution. Usually, the lower the concentration of the metal, the better the adsorption, as there is less adsorbate for the adsorbent to remove. However, some adsorbents perform extremely well in high initial concentrations of adsorbate, and hence, have a higher adsorption capacity. These adsorbents are thus favorable due to their capacity. Also, to test the capacity of the adsorbent, the concentration dosage in the liquid solution needs to be evaluated. If only a small quantity is required to remove a large portion of the adsorbate, then the adsorbent is favorable. Likewise, the more the quantity that is required, the least favourable as its capacity is low. One way to reduce the quantity of adsorbent is to increase the surface area. This can be achieved by using very small diameters of the adsorbent. Larger surface areas are a lot more successful in adsorption, and hence, the same adsorbent may require smaller dosages once ground compared to its larger counterpart.

2.3.2 Column Tests

After batch tests have been completed, optimal conditions are obtained for removal of dissolvents in the water. Column tests can then be performed to provide a real-life treatment process but on a smaller scale. Column tests, also known as bed columns, are used for industrial applications [42]. Also, since the column tests run for a longer period of time, they can show results different from those from the batch tests. Breakthrough time and behaviour is obtained from these tests. For the column tests to take place, previous researchers placed the adsorbent in a pipe where the ends are sealed off with rubber to support the adsorbent. A thin tube is placed on either side of the pipe, where one tube, the inflow, transports the water being tested into the pipe with the aid of a pump, and where the other tube, the outflow, transports the treated water into a basin to be tested and discarded. A pump is required in this case to allow water to flow from the basin and up the tube as the water here flows upwards. Water that has been treated through the tube is collected at regular intervals and tested.

Breakthrough curves are calculated by using the following equation:

$$\mathrm{BV} = \frac{\mathrm{V_s}}{\mathrm{V_p}} \qquad (5)$$

Where, BV is the breakthrough volume

V_s is the total volume of water that has passed through the column at time (t)

V_p is the volume of adsorbents in the column bed.

For IIdia et al , it was assumed that the breathrough capacity of the of the bed is 10% of the influent concentration to obtain the target concentration in the effluent. Hence, the breakthrough capacity can be calculated using the following equation:

$$\mathrm{q_b} = \frac{\mathrm{Q_V t_{10\%} C_o}}{\mathrm{m_c}} \qquad (6)$$

Where q_b represents the breakthrough capacity (mg metal/g adsorbent)

$T_{10\%}$ = the time (min) where the concentration of the effluent is 10% that of the influent

Q_v = the volumetric flow rate at the effluent (L/min)

C_o = the initial concentration of the solute (in mg/L)

M_c = the amount of adsorbent in the column (g). [42]

Ildia et al conducted experiments using GAC and organic polymer resin to remove organic pollutants from wastewater. They studied the adsorption properties of cetyl trimethylammomium bromide (CTAB) as a catonic surfactant. They determined that bed volumes per hour (BV) were approximately 16 hours, and empty bed contact time (EBCT) was 3 minutes [42].

2.3.3 Desorption

Once the column tests have been completed, the desorption batch tests may follow. Desorption tests are performed to evaluate the ability of the adsorbent to recover the metals, hence, allowing for the re-use of the metals. The procedure follows the same as that of the batch tests, however, the adsorbents are those extracted from the column tests.

Blazquez et al studied the effect of sorption, desorption, and regeneration of sugar beet pectin gels on heavy metals. The metals that were used were cadmium, lead, and copper. To determine the performance of the desorption, the following equations were used:

$$\%M_d = \frac{M_d}{M_a} \qquad (7)$$

Where $\%M_d$ corresponds to the desorption performance

M_d is the amount of mass in the solution obtained after desorption tests

And M_a corresponds to the total final amount of metal adsorbed, and is calculated using the following equation

$$M_a = (M_o + M_r) - M_f \qquad (8)$$

Where M_o is the initial concentration of the metal in the solution,

M_r is the residual metal concentration from previous desorption tests, if applicable

And M_f is the final concentration of metal in the solution

The remaining, or residual, amount of metal at the end of desorption experiment is calculated as follows:

$$\frac{M_r}{g} = \frac{M_a - M_d}{g\ \text{biomass}} \qquad (9)$$

Where the residual metal is obtained in per g of adsorbent [43].

CHAPTER 3 METHODOLOGY

3.1 GENERAL

To achieve the objective of finding an effective suitable materials, bench scale experiments were performed to obtain effective heavy metal removal. These tests consisted of batch tests and column tests. The batch tests were conducted to determine the optimal adsorbent and operating condition to adsorb a metal from wastewater.

Batch tests reflect the adsorptive capacity of the metal removal process. Therefore, column tests were used to investigate the applicability of the technology. The column tests have longer durations and simulate the application of this technology in bench scale setup. The optimal three operating conditions from the batch tests were evaluated in the column tests.

3.2 MATERIALS

The materials that were used as the adsorbent were PTL. These leaves were picked from the end of palm tree branches located on the American University of Sharjah campus, in Sharjah, United Arab Emirates. Even though the leaves used in this research were slightly fresh leaves, the research occurred at a small scale and it does not pose a significant effect on the environment. As the biological components of the leaves are expected to be consistent, the experiment can provide reliable results.

After the leaves have been picked, they have been thoroughly washed in water to remove any dust, dirt, and adhesive insoluble materials. They were then washed in distilled water to avoid having any ions from regular water contributing to variations in results. After the leaves were thoroughly washed, they were placed in the oven to dry. The temperature was set at around $90^{o}C$ for around 12 hours to remove any moisture residing in the leaves. Once dried, the leaves were crushed and ground to a sieve size no larger than 0.03 mm in size. These powdered leaves which were covered and stored in a dry air-conditioned room until they were used as adsorbents in the experiments. In the experiments, the leaves were used immediately, where new batches were made whenever necessary. Leaves were not stored for over a week due to their being consumed in the experiments.

The wastewater that was used was artificially prepared in the laboratory. This was due to the fact that the effect of studying each metal alone was required, as having other soluble and insoluble substances in the water would make it difficult to assess the effect of tree leaves on the adsorption behaviour of the metal. Each wastewater sample that was tested had only one metal solution dissolved. The water used to dissolve the metal crystals was distilled water. This was also performed to eliminate the disturbances of other soluble substances located in regular tap or drinking water. Distilled water was used to dissolve metal crystals. $CuSO_4.5H_2O$ was used to obtain copper solution, $K_2Cr_2O_7$ was used to obtain chromium solution and $ZnSO_4.7H_2O$ was used to obtain zinc solution. The amount of metal crystal solids that are required to obtain an initial metal concentration of 2, 6, and 10 mg/L of solution was calculated and used in the tests. The required mass of the metal crystals to obtain these concentrations were calculated and used. The metal crystals were dissolved in 1L distilled water, and shaken until completely dissolved. Selected experiments were done to assess the adsorption in competitive environment with wastewater prepared with all the different metals together.

3.3 BATCH TESTS

Batch experiments were conducted using five bottles for each pH-initial concentration combinations. PTL were placed in the samples in increments of 2.5 g/L dosage ranging from 0 to 10 g/L. Hence, the PTL concentrations were 0, 2.5, 5, 7.5, and 10 g/L. The blank sample was the sample that does not contain any tree leaves. This was tested to measure the concentration of the metal after the sample went through similar experimental conditions to isolate and assess the effect of tree leaves in changing the metal concentrations. The samples were placed in a shaker table (Figure 3.1) and set to an agitation speed of 175 rpm for two hours where it is assumed equilibrium is reached. From the literature, researchers used different shaking time ranging from 30 minutes [22] to 4 hours [6]. For this research, a contact time of 2 hours was chosen to lie in between the range. After shaking is complete, the samples were filtered to prepare for water quality analyses. Once results were obtained, they were plotted on figures to determine the percentage of metal that was removed by the tree leaves.

The first set of experiments conducted were the batch tests, where the effects of altering metal initial concentration, concentration of tree leaves, and solution pH were investigated and evaluated. Each metal was tested separately and optimal conditions were obtained. Another set of batch tests were run to test the effect of having the three metals dissolved together. For the single metal, three pHs were tested (3, 5, 9) in addition to no pH change. Three initial concentrations of the metal were used : 2, 6, and 10 mg/L. As mentioned in the previous paragraph, five samples were obtained for each experimental run. This results in a total of 60 batch tests for each metal solution, amounting to 180 batch tests for all three metals. Another set of experiment was run of all metals dissolved in the solution together to test any alternations in efficiency of results. Four pH's (no change, 3, 5, and 9) were used in tests involving all the metals. These experiments were investigated for all the metals at 2 mg/L each. This test was performed as it slightly imitates real life applications, as in reality the metals are not isolated in the wastewater. The procedure involved followed the same outline as that of the individual metals and where all the constants were kept constant.

To test for the different pH values, the samples had their pHs altered with wither 0.1M HCl or 0.1M NaOH. To allow for consistent pH throughout the preparation of the samples, the samples had the pHs adjusted at intervals whilst on the shaker table. This is due to pH slightly neutralizing during shaking as contact surface with the adsorbent increases. pH did not alter significantly while shaking; hence, they were adjusted twice during the two hour shaking period. Studying the effect of changing agitation speed and contact time of the samples was not part of the scope for this research and was left constant for all the samples.

Figure 3.1: Samples on Shaker Table

3.4 COLUMN TESTS

The column tests were used to represent the process that would occur in the industry but on a smaller scale. The experimental setup was prepared by using a column of 2.25 cm diameter and 20 cm depth filled with the tree leaves. To prepare the column tests, the apparatus was cleaned to remove any insoluble substances that may have been present of the apparatus. This includes the tubes, the column, the stopper, and the bucket in which the water is to be placed. The apparatus was cleaned first with water, or soap and water depending on the degree of dirt, and then washed down thoroughly with distilled water. The equipment was then dried off thoroughly. The column and stoppers were weighed when dried. One stopper was inserted on one end of the column to allow only one open side. The adsorbent, the PTL, was added in the column until it was completely full allowing little room for the stopper at the other end to close the column. Once the column has been stopped at both end, the weight of the now filled column was taken. The mass of the PTL in the column can be determined by subtracting the weight of the column and the stoppers from the mass of the filled column. Once the column has been filled, the tubes are inserted into the stopper on both ends of the column. To allow for this, incisions were made in the stopper to allow for the tube to fit in tightly.

During the column test, untreated wastewater is pumped in a thin tube to the bottom of the column, where it travels through the adsorbent up the column, and discharged through a thin tube Figure 3.2. The pH was measured and recorded at both the influent and effluent.

To ensure that the pH does not change due to the surrounding, it was measured at intervals and adjusted as necessary. The water was allowed to be fed through a tube by the pump (Figure 3.3). The flow of the pump was pre-determined and set. The flow was constant throughout the running on one column test. As is expected, the faster the flow, the faster the breakthrough time is obtained, in addition to the saturation period. The column test flow was set so that the test could be complete within one week. The pump collects water from the influent via the tubes, and carries it through the column, where the water flows through the column and out the tube, where the effluent water is collected at intervals. At different time intervals, treated effluent is collected and tested for water quality analyses to see the amount of each metal that has been removed from the system. These values, once collected, are plotted to determine the breakthrough and saturation times. The breakthrough time was considered as the time when the concentration of the metals in the effluent exceeds 0.0 mg/L, or the threshold permittable amount allowed by governmental or environmental agencies. As the concentration used in the research is relatively low compared to what is seen in real life applications, a breakthrough value of 10% will be used. This value will still remain below the threshold mandated by governmental agencies. The saturation time denotes the time where the concentration of the metals in the effluent equal the concentration of the influent, hence, represents the time when the adsorbent no longer has the ability to remove any of the metals. This is due to adsorption and desorption of the adsorbent occurring at equal rates.

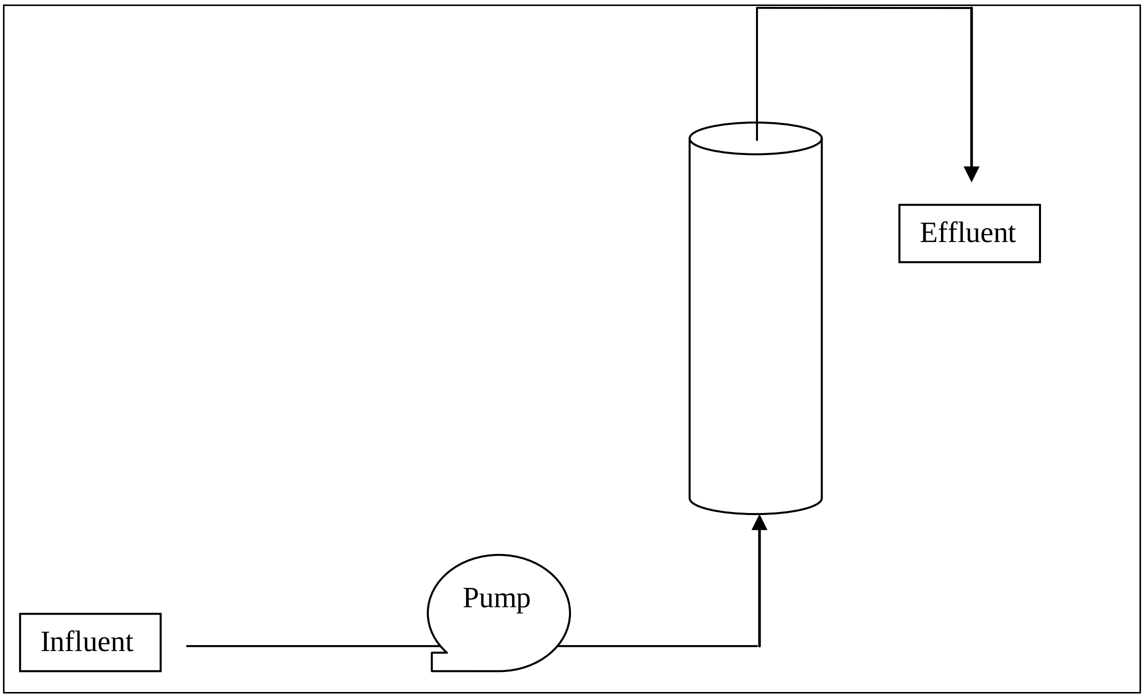


Figure 3.2: Column Test Setup

At intervals, the influent concentration of the metals was also tested for using the spectrophotometer. This is done to ensure that the concentrations of the influent do not change and affect the effluent results, in addition to testing if precipitation of the metals may have occurred and caused variation of results. Hence, obtaining low concentrations of the metal at the effluent does not necessary indicate good adsorption capability of the adsorbent, but that the metals precipitated and were not carried to the column to allow for treatment. Tests were also performed to the influent as new batches of artificial wastewater were constantly manufactured and added to the influent as amount of water reduces. Adding artificial wastewater when supply of water runs low allows for the test to be continuous. As it was expected that concentrations of the influent alter, even if slightly, due to the addition of new water, concentrations were constantly tested for and the average used in the calculations. Column tests results are presented with the removal against the time. To determine this time, samples need to be collected from the column tests at different time intervals and tested for the heavy metal removal. From the data obtained, a figure of the percent metal removed against the time required is plotted and the breakthrough and saturation times are obtained.

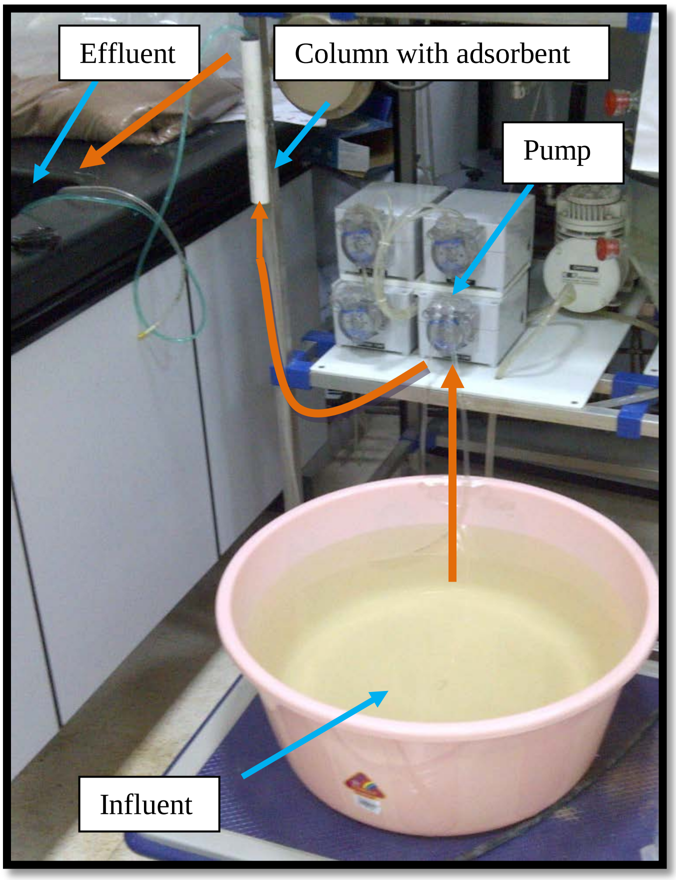


Figure 3.3: Set-up used for Column Test

The column tests were performed three times, once for each pH (5, 9, and no change). Although a pH of 3, 9, and neutral obtained the best results during the batch tests, it is not feasible to have a very low pH of 3 in real applications and in large quantities, hence, a pH of 5 was used instead to allow for better correlation and feasibility with reality. Column tests were prepared with initial concentrations of the metals of 2mg/L.

The figures of the C/Co vs. the number of pore volumes were plotted to determine the breakthrough and exhaustion times. C/Co represents the ratio between the concentrations of the metal at the effluent to that of the influent. The number of pore volumes represents how many total pore volumes are required to adsorb the metals, and is calculated as follows:

$$\#\text{of pore volumes} = \text{Qt}(\text{m}_{\text{after}} - \text{m}_{\text{before}}) \quad (10)$$

Where Q represents the inlet flow of the influent to the column; t the time at each measurement in question; V_c the volume of the column; and μ the porosity of the adsorbents in the column.

The porosity is a representation of the pores in the adsorbent in the column and can be calculated as follows:

$$\mu = \frac{m_{after} - m_{before}}{V_c} * \rho_w \qquad (11)$$

Where m_{after} represents the mass of the adsorbents after the column test has been performed, m_{before} represents the mass before the test, and ρ_w represents the density of water.

Determining the total mass of metal that entered the column is calculated as follows:

$$m = \frac{C_o F t_e}{1000} \qquad (12)$$

Where, C_o = influent metal concentration (mg/L), F = volumetric flow rate (mL/min) and t_e = exhaustion time (min) [44].

The exhaustion time was considered the time where the ratio of C/Co reaches 1, or is close to 1. In some cases, the ratio is less than 1 before the experiment was stopped, hence, the exhaustion time will differ than that shown on the figure. The breakthrough time is the time where C/Co ratio exceeds 10% of the influent, as the concentration used in the influent is the threshold many agencies set, as previously discussed in the literature.

3.5 DESORPTION

The experiments underlined in the previous sections illustrated the methods conducted to remove the metals from the wastewater using the PTL. The already adsorbed metals can be recovered and tree leaves can be regenerated. This method of recovering the adsorbed metals is known as desorption. To do this, the PTL that were placed in the column tests first need to be recovered, where they are allowed to dry to remove any moisture. If the column tests were performed to evaluate the adsorption capacity at different pHs, drying the adsorbent allows for less interference from the pH of the adsorbent. To allow for recovery of the metals, the PTL is recovered from the column test, dried, and stored until needed. In the case of this research, the used adsorbents were not stored for over one week. To prepare the samples, it is first important to known at what pHs do the most recovery occur at. Hence, two samples are initially prepared: one at very acidic pH, and the other at very basic pH. A little of the PTL in dropped in a known amount of distilled water before the pH is adjusted. The samples are agitated from a shaking time of 2 hours. Once the shaking time has expired, the samples are filtered and tested for water quality analyses.

3.6 ADSORPTION ISOTHERMS

The results obtained for the batch tests were then best fitted into both the Langmuir and Freundlich isotherms.

3.6.1 Langmuir Isotherm

Langmuir's isotherm follows the following equation:

$$Q = \frac{abC_e}{1+bC_e} \qquad (13)$$

Where the Q equals $(C_o-C_e)/m$ and represents the adsorption density of the adsorption of the adsorbent, C_e , the concentration of the adsorbate at equilibrium, C_o , the initial concentration of the adsorbate in the solution, m the mass of the adsorbent, and the variables a and b are characteristics of the materials used.

To obtain the isotherm, it is beneficial to plot the figure of C_e vs. Q. This illustrates that as the dosage of the adsorbents increases, the adsorption power of the adsorbent reduces.

3.6.2 Freundlich Isotherms

Freundlich's isotherm follows the following equation:

$$Q = K_d C_e^{1/n} \quad (14)$$

Where K_d and n are characteristics of the materials used.

3.7 ANALYTICAL METHOD

3.7.1 Heavy Metal Analysis

Testing occurred primarily on the Hach DR 5000 spectrophotometer (Figure 3.4). Due to lack of availability, atomic absorption spectrophotometer could not be used all the time. However, it was essential to evaluate the difference in results determined from the HACH and AA machine simultaneously. Initially, a 10mg/L of each metal was prepared separately using distilled water. For each metal, 5 samples were used to test for different PTL dosages: 0, 2.5, 5, 7.5, and 10 g/L. The bottles, once prepared, were placed on the shaker and allowed to shake for 2 hours at 175 rpms. Once the samples have been shaken, they were filtered to reduce the effect of additional contact time on the results. The samples were then diluted twice: once to obtain a concentration of metal of 6mg/L and second to 2mg/L. To preserve the samples, their pHs were adjusted to a value of 2 or lower, where they can be stored for up to 6 months. The samples were tested on the AAS machine for the copper and chromium samples. And the concentration of the zinc samples were too high to be recorded on the AAS machine, their measurements were conducted on the ICP machine, where the machine follows a similar testing method as that of the AAS. These same samples were then tested for on the HACH DR 5000 Spectrophotometer. The same samples were tested on both machines and their results plotted against each other to obtain the figure in Figure **3.5**. The figure illustrates that results from both testing machines are relatively similar as they lie on and closely around the line 45 degree line and R^2 values were very close to 1. Even though HACH 5000 spectrophotometer is well-known in the industry, it is often avoided for research purposes. However, in this study, the performance was reasonable and reliable.

Figure 3.4: HACH DR 5000 Spectrophotometer

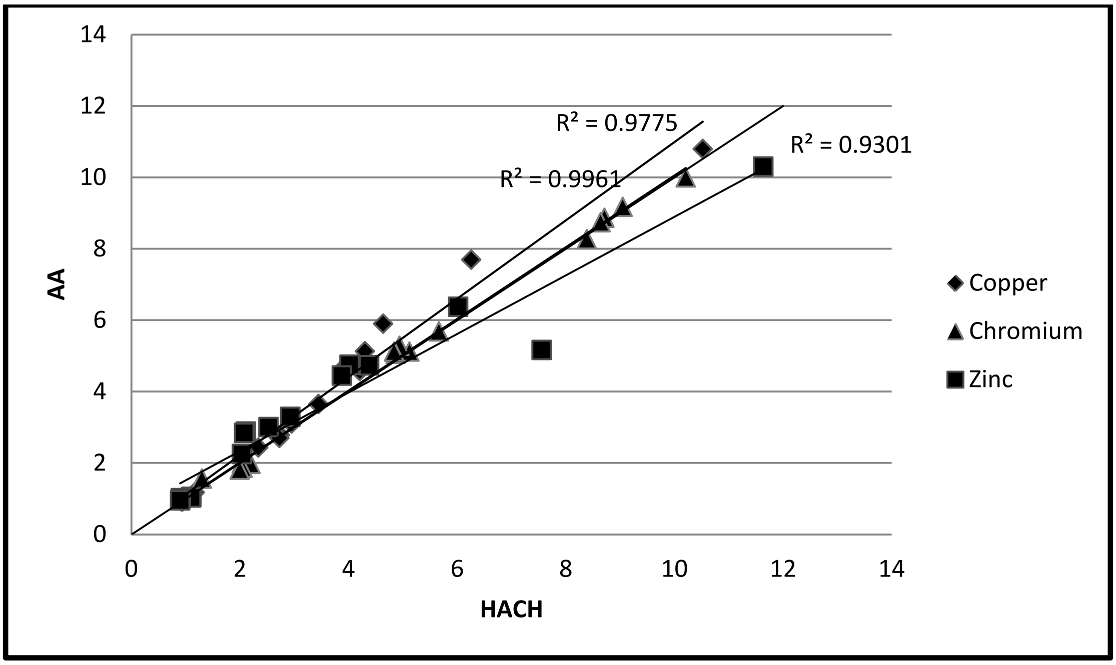


Figure 3.5: Relationship between AA and HACH

3.7.1.1 Copper

Copper was tested for using the USEPA Bicinchroninate Method, approved by the USEPA and Standard Method 3500 Cu C or E. This method entails using two 10mL sample cells, where both are filled with the sample, but one of the cells is reacted with one CuVer® 1 Copper Reagent powder pillow. The cell is shaken and allowed a two minute reaction time. Once this time is complete, the blank sample cell is inserted into the Hach DR5000 Spectrophotometer and is Zeroed. Then the prepared sample is inserted into the machine and the results are read. This procedure is performed for every sample. When the copper reagent is poured into the sample cell, the solution turns violet- purple colour depending on the concentration of the copper in the sample, hence, the more concentrated the copper, the more intense the colour of the solution.

3.7.1.2 Chromium

Chromium was tested for using the USEPA 1,5-Diphenylcarbohydrazide Method, accepted by USEPA and Standard Method 3500 Cr B and adapted from Standard Methods for the Examination of Water and Wastewater. This method entails using 2 10mL sample cells, where both are filled with the sample, but one of the cells is reacted with one Chromium Reagent powder pillow. The cell is shaken and allowed a five minute reaction time. Once this time is complete, the blank sample cell is inserted into the Hach DR5000 Spectrophotometer and is Zeroed. Then the prepared sample is inserted into the machine and the results are read. This procedure is performed for every sample. When the chromium reagent is poured into the sample cell, the solution turns pinkish-purple colour depending on the concentration of the chromium in the sample, hence, the more concentrated the chromium, the more intense the colour of the solution

3.7.1.3 Zinc

Zinc was tested for using the USEPA Zincon Method, approved by USEPA for wastewater analyses 3500 Zn B, and adapted from Standard Methods for the Examination of Water and Wastewater. This method entails using 2 10mL sample cells. The sample is filled to 20 mL in a 25mL cylinder and is reacted with one ZincoVer5 Reagent powder pillow. The cylinder is shaken until all the powder is dissolved completely. The prepared sample is then poured into the 10mL sample cell. The remaining 10mL in the cylinder is reacted with 0.5mL Cyclohexanone and shaken vigorously for 30 seconds. The samples are then left to react for three minutes. Once this time is complete, the blank sample cell (the first prepared sample cell) is inserted into the HACH DR5000 Spectrophotometer and is Zeroed. Then the prepared sample is inserted into the machine and the results are read. This procedure is performed for every sample. As the reagent is reacted with zinc in the 20mL sample, an orange solution forms. When the sample is reacted with the Cyclohexanone, the solution turns a deep blue if concentration of zinc is high, purple/brown for medium concentration, and orange/light brown for low concentrations. Hence, the more concentrated the zinc, the darker and more intense the colour of the solution.

3.7.2 Quality Control

For the batch tests, the sample bottles were washed thoroughly with distilled water to ensure that no residues remain that may have an effect on the results of future tests. For the column tests, the column, stoppers, tubes, and tub where thoroughly washed water and distilled water as well. All testing equipment was washed with distilled water. All the chemicals and materials were stored in a closed container to prevent outside entities from damaging or affecting the product.

CHAPTER 4 EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 BATCH TESTS

For the single batch tests, it was noticed the rate at which the PTL remove the metal decreases as the dosage increases. This is due to there being more palm tree leaves (PTL) dosage to collect the same concentration of metal, allowing each additional dose to take less metal. In other words, the more the total dosage of the PTL in the system, the less the rate in which a unit of PTL adsorbs the metal.

4.1.1 Copper

The results obtained for copper when placed in isolation in the water is shown in Figures 4.1 - 4.3 for 2, 6, and 10 mg/L initial concentration respectively. The percent removal of copper increased as the PTL dosage increased for all three initial concentrations. The percentage removal of copper decreased as the initial concentration increased, allowing for greatest removal efficiency to occur at 2mg/L initial concentration of copper, and the least efficiency at 10mg/L. For all three initial concentrations of copper, the overall highest percentage efficiency was obtained with a slightly acidic pH of 5, and lowest at a basic pH of 9. This is believed to be due to competition between the copper ions and protons to bind on the positively charged active sites surface at acidic pH values. As pH became less acidic, competition with protons decreased, and the ions could bind on to active sites. However, once pH became more basic (around pH 6), adsorption declines as metal hydroxides precipitate [37]. Figure 4.1 shows that varying the pH values have considerable difference in removal efficiency for 2mg/L C_o, allowing for a wider range of efficiency. For 6 and 10 mg/L C_o, however, this phenomenon is not observed, as varying the pH provides minor variations in removal efficiency.

It was determined that the slightly acidic pH and lower initial influent concentrations (C_o) were the most favourable condition for the adsorption of copper from the wastewater. The maximum percentage removal of the copper amounts to approximately 67.5% at 2mg/L C_o, 10g/L PTL dosage, and a pH value of 5. The lowest percentage removal of copper at amounts to approximately 31.5% at 10 mg/L C_o, 10g/L PTL dosage, and a pH of 9.

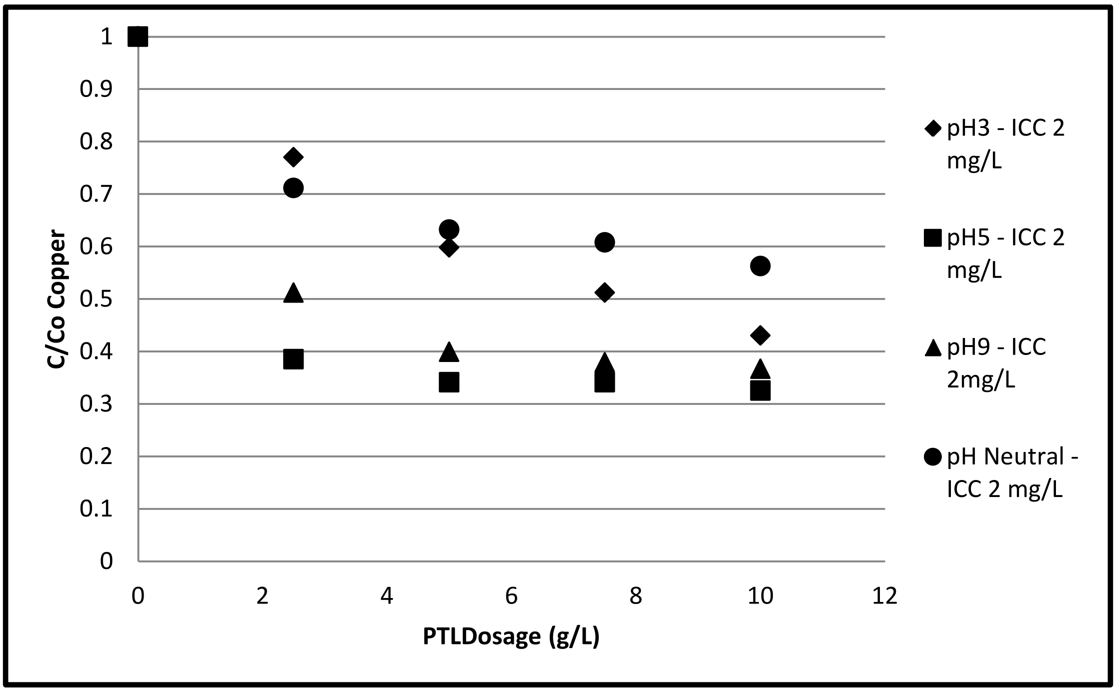


Figure 4.1: C/C_o vs. PTL Dosage of Copper with 2mg/L C_o

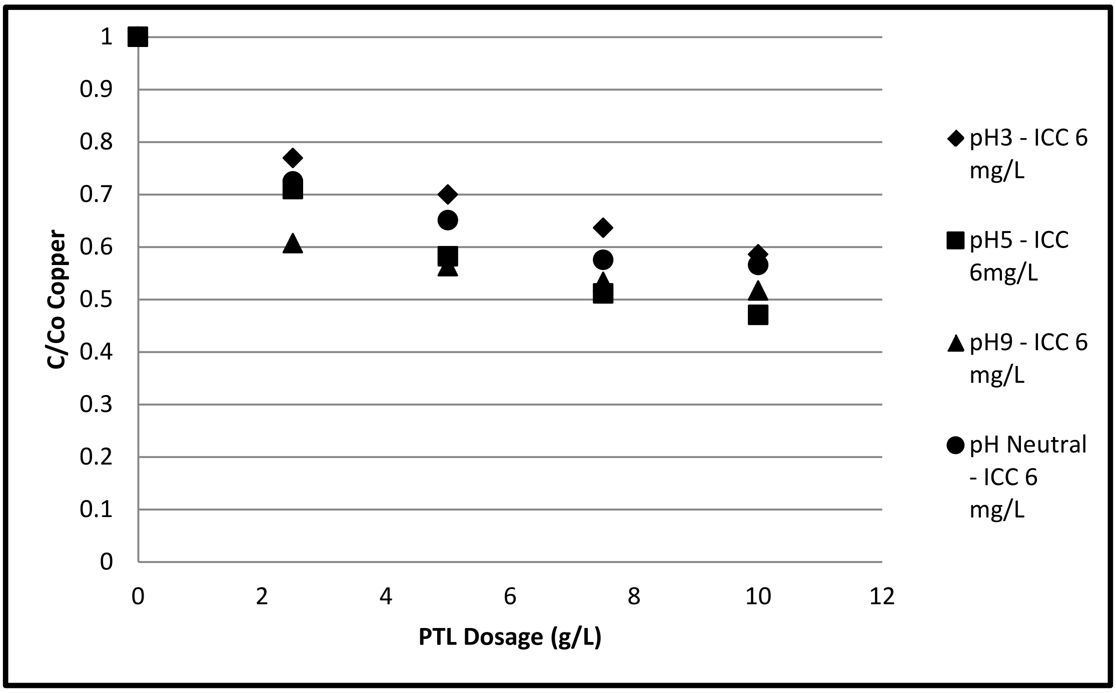


Figure 4.2: C/C_o vs. PTL Dosage of Copper with 6mg/L C_o

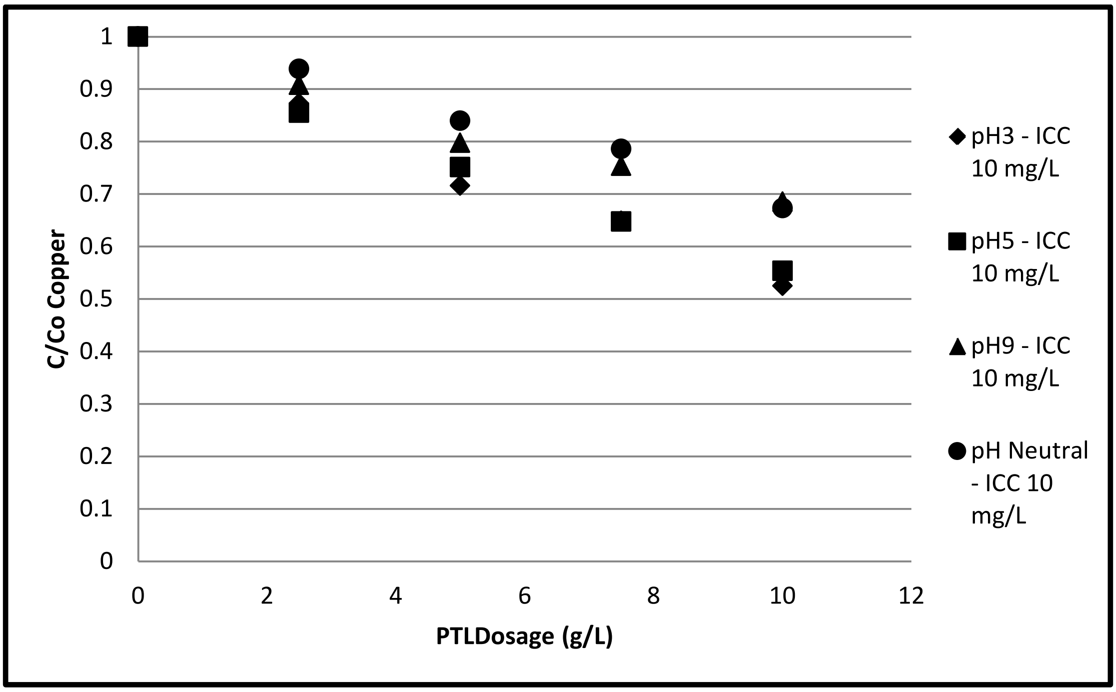


Figure 4.3: C/C$_o$ vs. PTL Dosage of Copper with 10mg/L C$_o$

4.1.2 Chromium

The results obtained for chromium when placed in isolation in the water is shown in Figures 4.4 - 4.6 for 2, 6, and 10 mg/L initial concentration respectively. The percent removal of chromium increased as the PTL dosage increased for all three initial concentrations.

The overall percentage removal of chromium was very high for all concentrations, with slightly lower results obtained with 10mg/L C_o at higher pH values. For all three initial concentrations of chromium, the overall highest percentage removal was obtained with an acidic pH of 3, and lowest at a basic pH of 9. This is believed to be due to the type and ionic state of the PTL's functional groups, hence, affecting the adsorption of chromium [34]. It was revealed that varying the pH values have considerable effect in removal efficiency for all initial concentration values of chromium.

It was determined that the acidic pH provided the most favourable condition for the adsorption of chromium from the wastewater. Lower initial concentrations provided higher removal efficiency at basic pH values; however, all initial concentration values provided very high removal efficiency for acidic pH values. The maximum percentage removal of the chromium amounts to 99.5% at 10mg/L C_o, 10g/L PTL dosage, and a pH value of 3. The lowest percentage removal of chromium at 10g/L PTL dosage corresponds to C_o of 6 for pH 9, with a value of 25.4%.

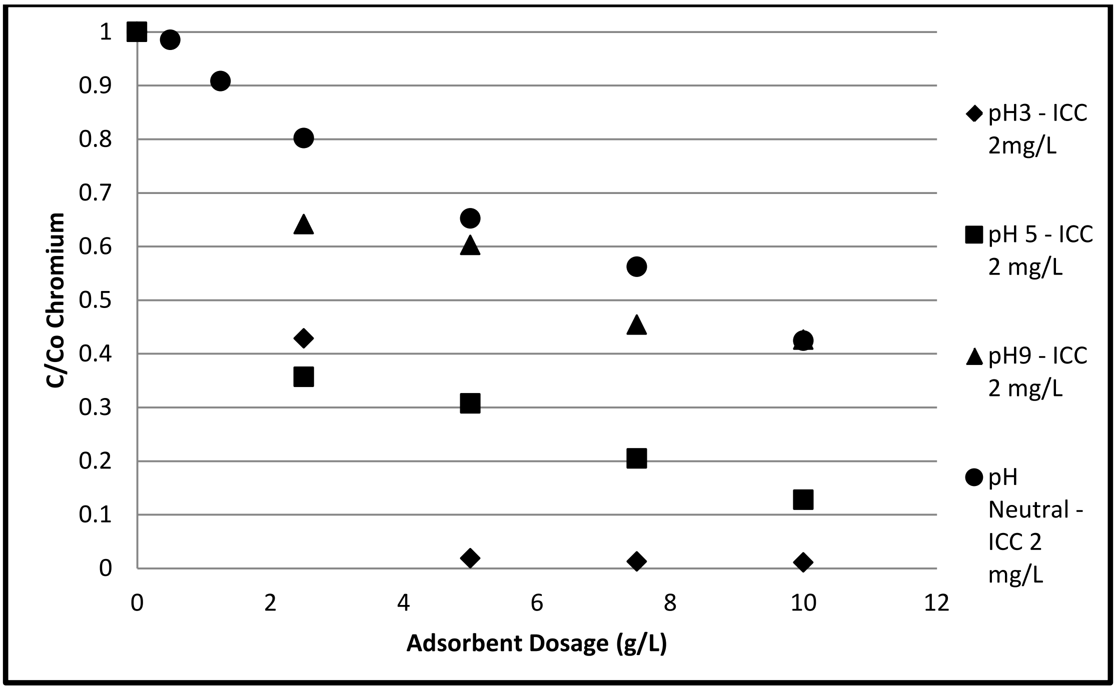


Figure 4.4: C/C_o vs. PTL Dosage of Chromium with 2mg/L C_o

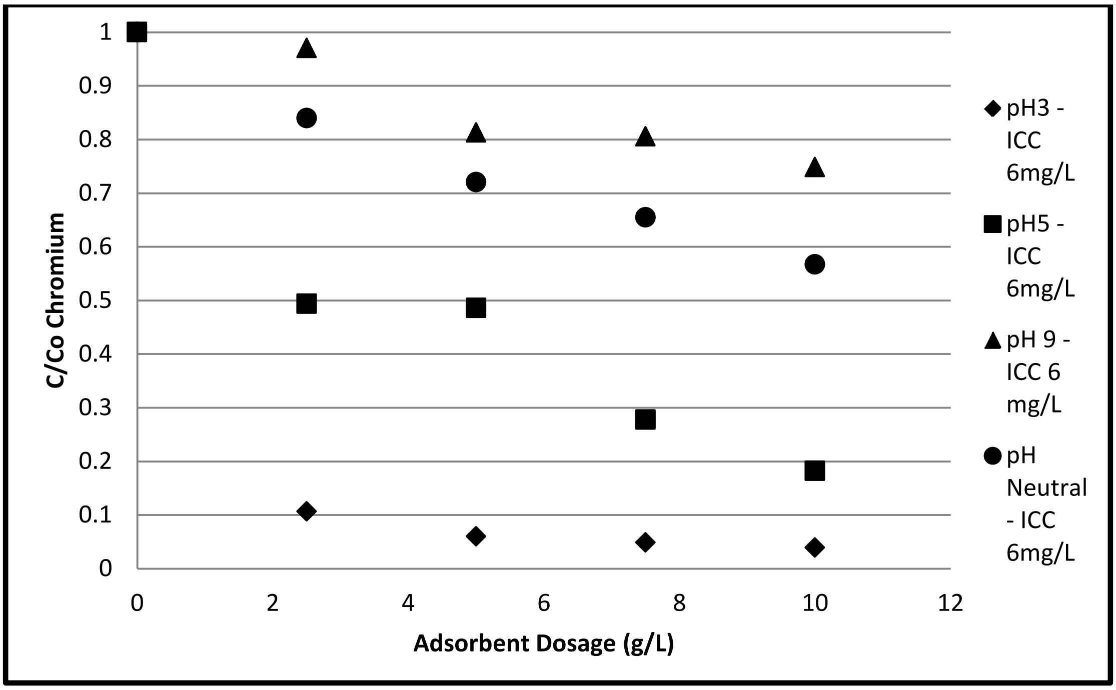


Figure 4.5: C/C_o vs. PTL Dosage of Chromium with 6mg/L C_o

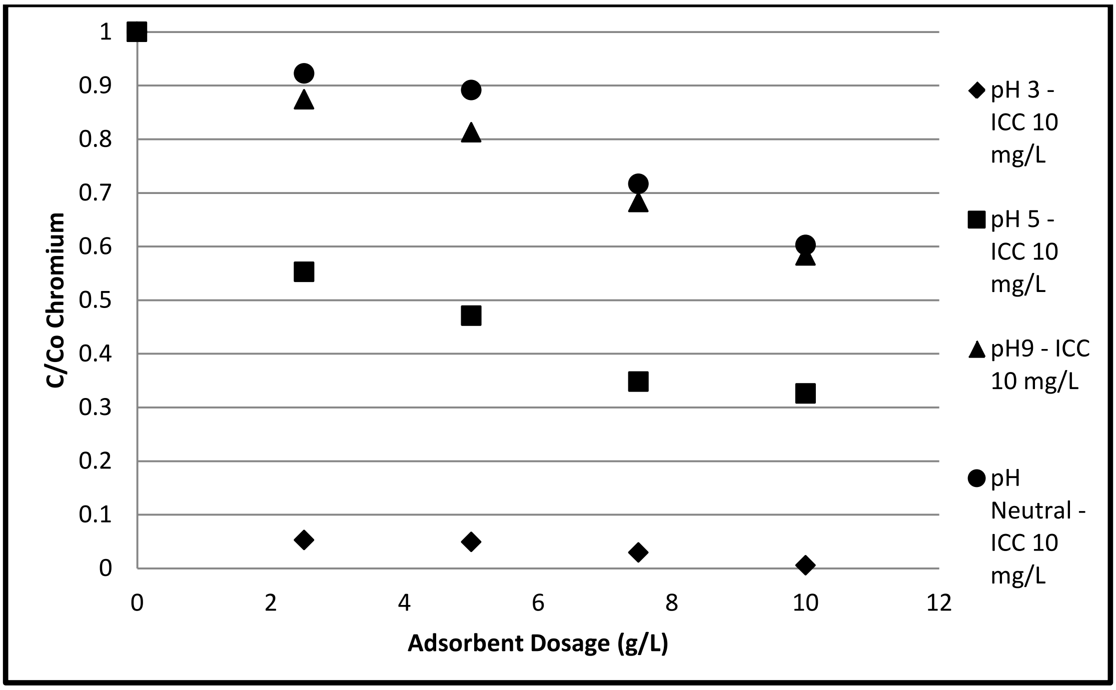


Figure 4.6: C/C$_o$ vs. PTL Dosage of Chromium with 10mg/L C$_o$

4.1.3 Zinc

The results obtained for zinc when placed in isolation in the water is shown in Figures 4.7 - 4.9 for 2, 6, and 10 mg/L initial concentration respectively. The percent removal of zinc increased as the PTL dosage increased for all three initial concentrations.

The overall percentage removal of zinc decreased as the initial concentration increased, allowing for greatest removal efficiency to occur at 2mg/L initial concentration of zinc, and the least overall efficiency at 10mg/L. For all three initial concentrations of zinc, the overall highest percentage efficiency of 86% was obtained with a basic pH of 9, and lowest of 28% at an acidic pH of 3. It is believed that acidic pH provided the least uptake of the metals due to cation competition effects with H_3O^- ion [45]. It was observed that varying the pH values have considerable difference in removal efficiency for all initial concentration values of zinc.

It was determined that the basic pH provided the most favourable condition for the adsorption of zinc from the wastewater. Lower initial concentrations provided higher removal efficiency at acidic pH values; however, all initial concentration values provided very high removal efficiency for basic pH values. The maximum percentage removal of the zinc amounts to approximately 86% at 2mg/L C_o, 10g/L PTL dosage, and a pH value of 9. The lowest percentage removal of zinc at 10g/L PTL dosage corresponds to C_o of 10 for pH 3, with a value of 28%.

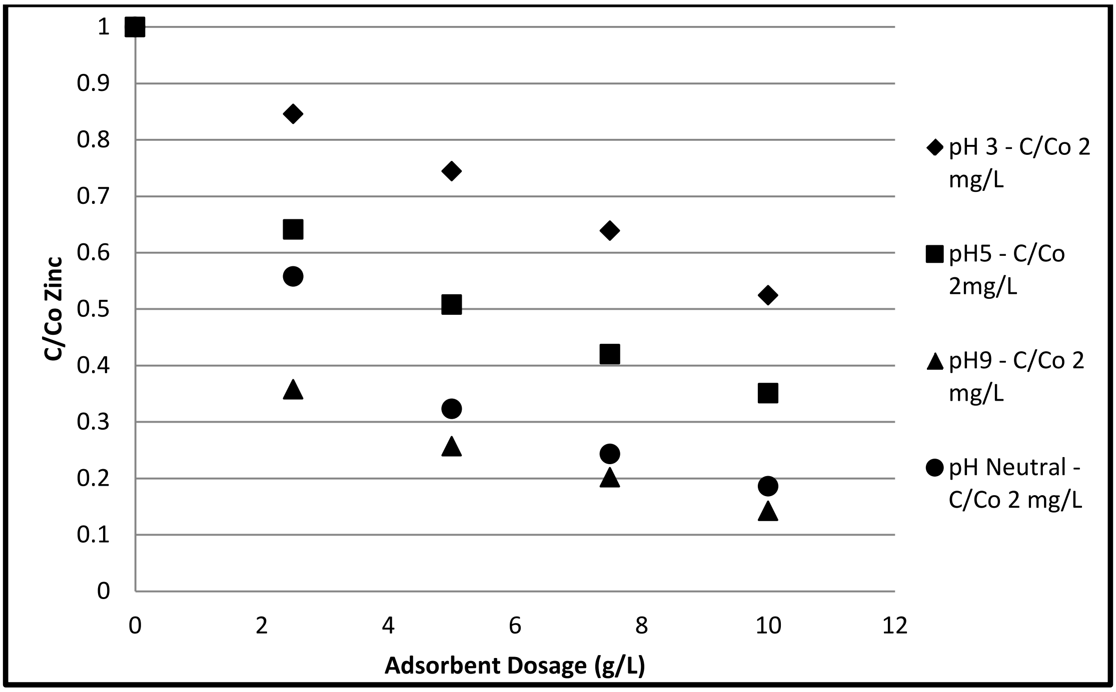


Figure 4.7: C/C$_o$ vs. PTL Dosage of Zinc with 2mg/L C$_o$

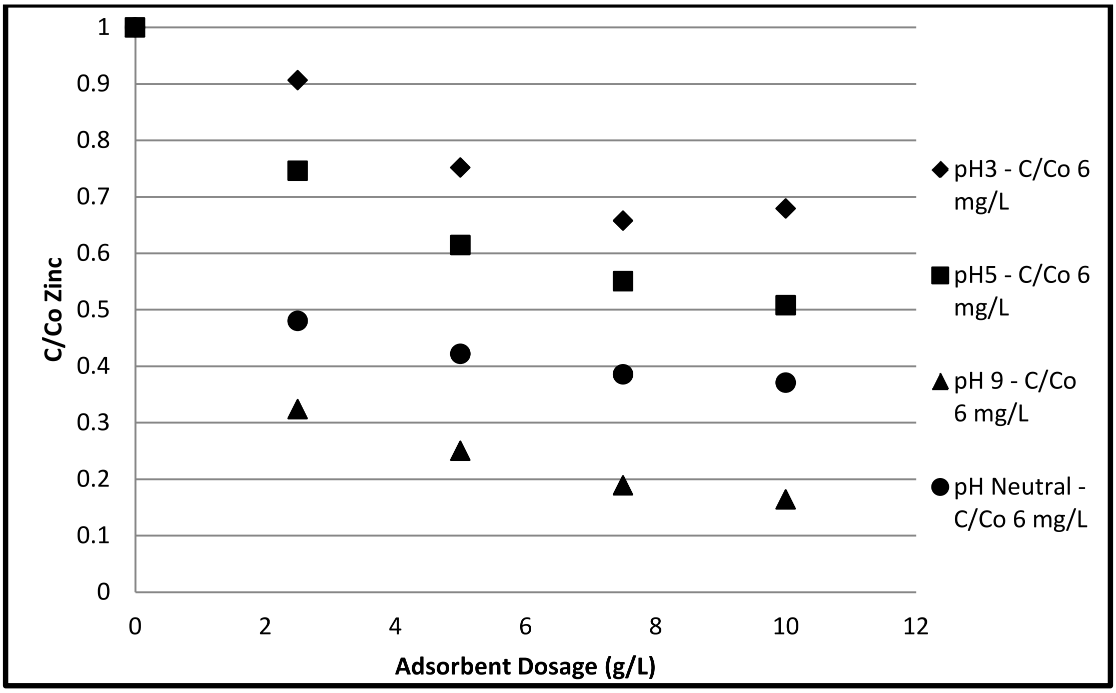


Figure 4.8: C/C$_o$ vs. PTL Dosage of Zinc with 6mg/L C$_o$

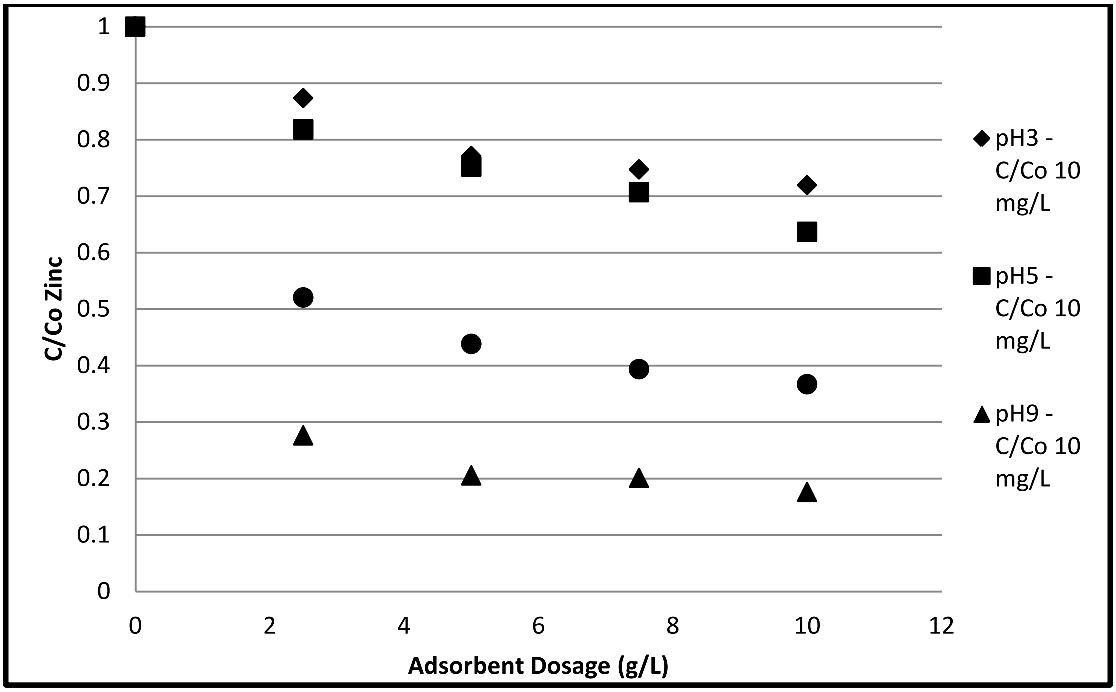


Figure 4.9: C/C$_o$ vs. PTL Dosage of Zinc with 10mg/L C$_o$

4.1.4 Competitive Adsorption

The metals may have different adsorption behaviour when in a mixture with other metals or substances; hence, an experiment was performed to evaluate this behaviour. The results obtained are shown in Figure 4.10 – 4.12 for copper, chromium, and zinc respectively. It is shown that the overall behaviour of the metals had not changed considerably. Chromium obtained the overall highest removal efficiency at approximately 98.5% in acidic pH, followed by zinc at 83.7% in basic pH, and copper at 82.7% in neutral pH.

Chromium was revealed to be the most competitive of the metals, as it achieved a removal efficiency of 87.9% in basic pH conditions, the lowest efficiency. In isolation, chromium obtained only 53.4%, 25.2% and 41.7% 2, 6, and 10 mg/L respectively at the same pH. For acidic conditions, chromium obtained a removal efficiency of 87.2%, 96.1%, and 99.5% for 2, 6 and 10 mg/L respectively when in isolation. Comparing results at the same initial concentration (2mg/L), chromium had vaguely higher removal efficiency in isolation at acidic pH, and almost 1.6 times higher when in combination than in isolation at basic conditions. This behaviour is believed to be due to competitiveness of the metals for active sites. It may also be due to the chromium ions binding to surfaces of sites other than PTL, hence, allowing for this larger percentage removal.

Zinc’s lowest removal efficiency in was 43.7% in the comparative tests, and 47.6%, 32.1%, and 28.1% for 2, 6, and 10 mg/L respectively in acidic pH. For basic conditions, zinc obtained a removal efficiency of 85.8%, 83.1%, and 82.4% for 2, 6 and 10 mg/L respectively when in isolation. Comparing results at the same initial concentration (2mg/L), zinc’s removal efficiency was slightly higher in isolation in acidic and basic pH than when in combination with chromium and zinc. It was due to the fact that zinc competed with chromium for the same surface sites.

Copper’s lowest removal efficiency was 50% in the comparative tests in acidic pH, and 43.8 %, 41.5%, and 31.5% for 2, 6, and 10 mg/L respectively in all pH values. The highest removal efficiency obtained for copper in isolation was at 67.58%, 52.9%, and 47.5% for 2, 6 and 10 mg/L respectively. Comparing results at the same initial concentration (2mg/L), copper’s removal efficiency was considerably higher when in combination with chromium and zinc, then when in isolation at any pH value. This is believed to be due to the same reasons as that of chromium.

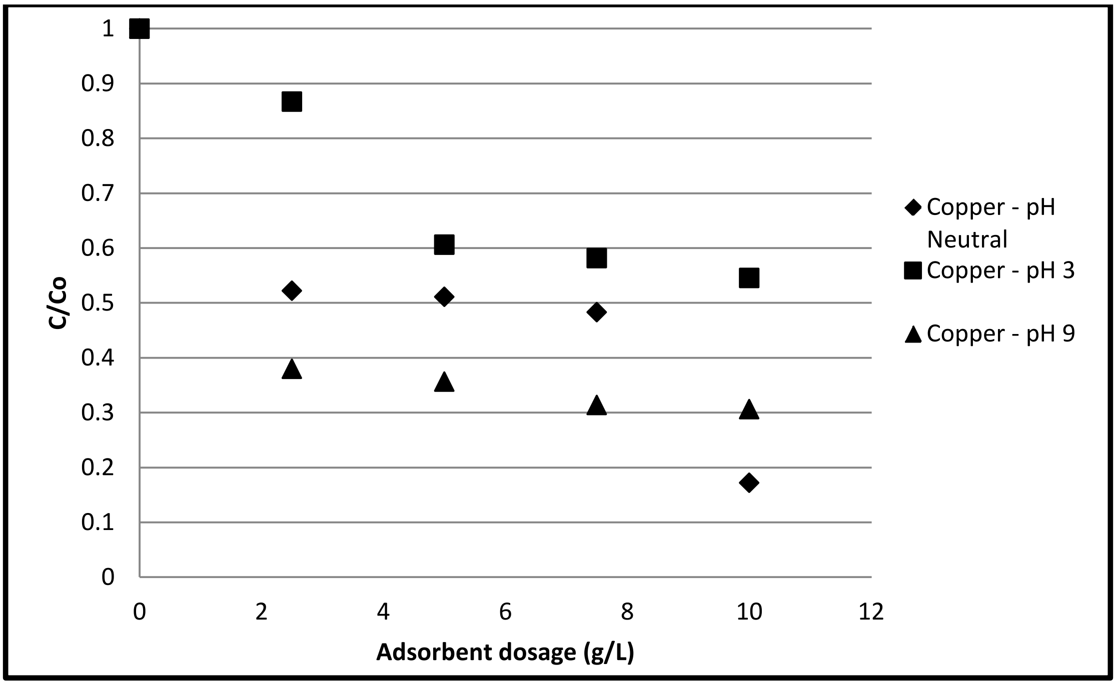


Figure 4.10: C/C_o vs. PTL Dosage of Copper in Comparative Batch Test

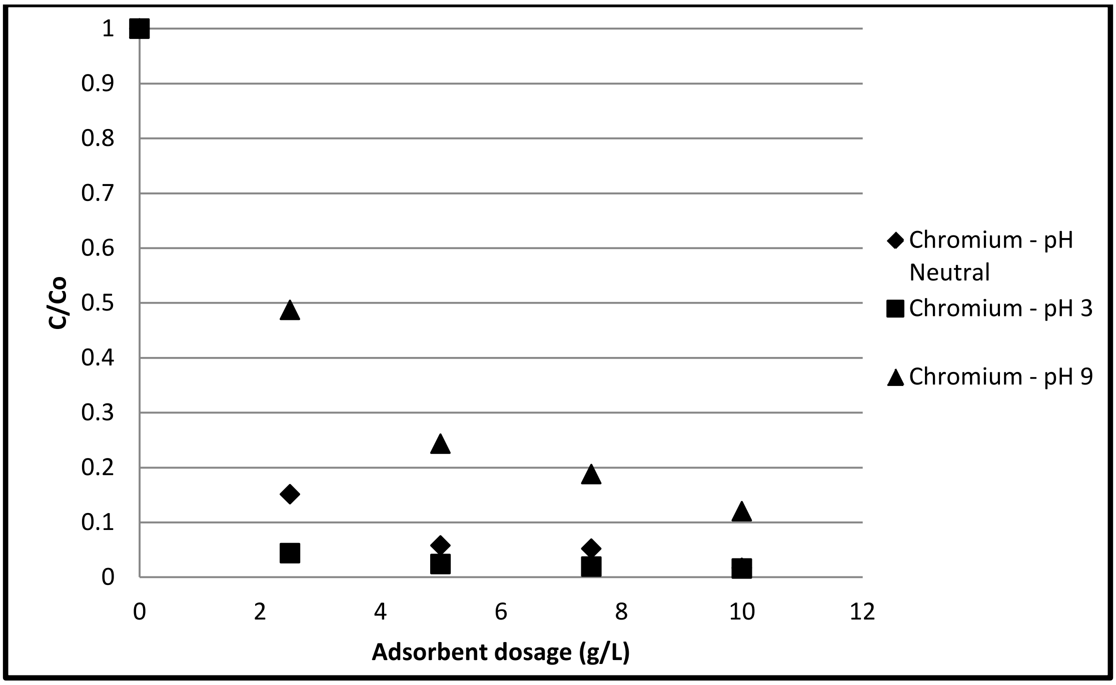


Figure 4.11: C/C_o vs. PTL Dosage of Chromium in Comparative Batch Test

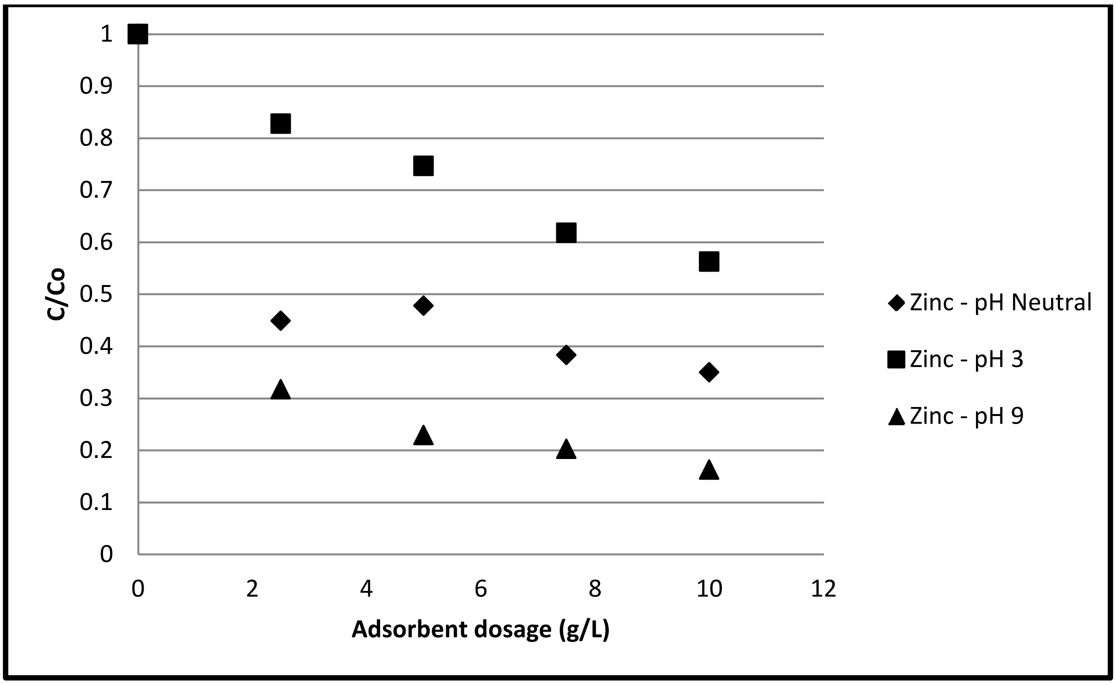


Figure 4.12: C/C_o vs. PTL Dosage of Zinc in Comparative Batch Test

4.2 ADSORPTION ISOTHERMS

The following section presents the isotherms obtained for each metal. The constants and regression coefficient are obtained from Figures 4.13 – 4.18. The closer the regression coefficient, R^2, is to 1, the more accurate the points on the figure lie on the linearized isotherm line. However, if the R^2 value is not close to 1, it does not mean that the experiments are unreliable; rather, it refers to the inability of the points to be linearized using the mentioned isotherm. Using another isotherm may perhaps obtain better R^2 values; however, Langmuir and Freundlich were used due to their widespread application in adsorption.

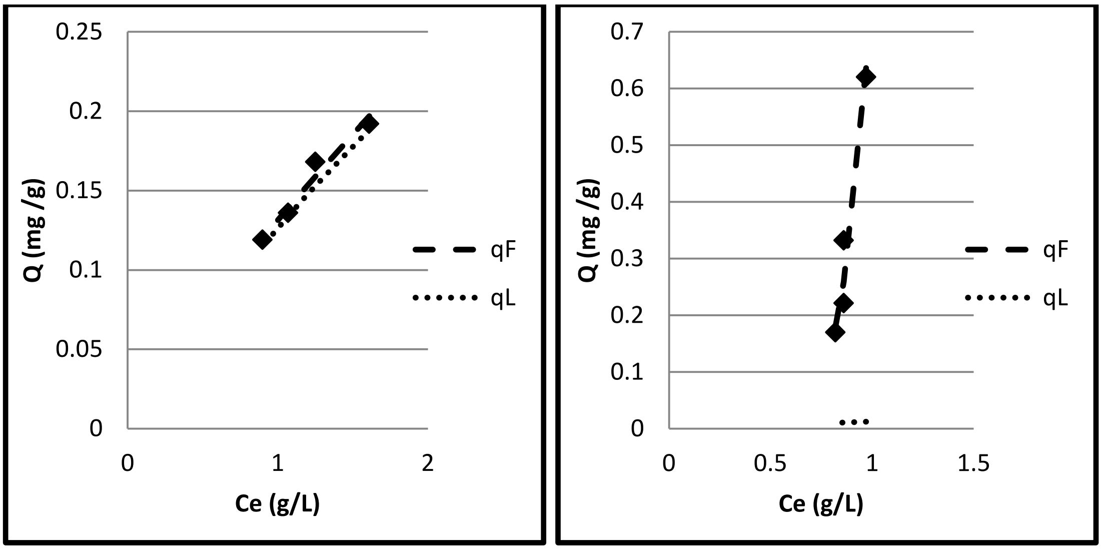
4.2.1 Copper

The results obtained from both Langmuir and Freundlich isotherms are shown in Table 4.1. As shown in the table, Freundlich and Langmuir isotherms both had R^2 values that are very close to 1 in most cases, as well as having lower values. The best results were obtained with Freundlich at C_o of 6 where all R^2 values surpass 0.93. Figures 4.13-4.15 represent the Langmuir and Freundlich isotherms for 2, 6, and 10 mg/L C_o. As can be seen, the linear line is of a positive slope for all graphs of all pH values. It can also be noted that the Freundlich isotherms were fairly accurate to fitting the linearization of the data points, unlike Langmuir isotherms which were fairly remote. This indicated that Freundlich isotherms were better suited to explain the partitioning on tree leaves. Langmuir values were fairly remote to the data points. Hence, for copper, it can be noted that Freundlich more accurately captures the linearization of the data points compared to Langmuir.

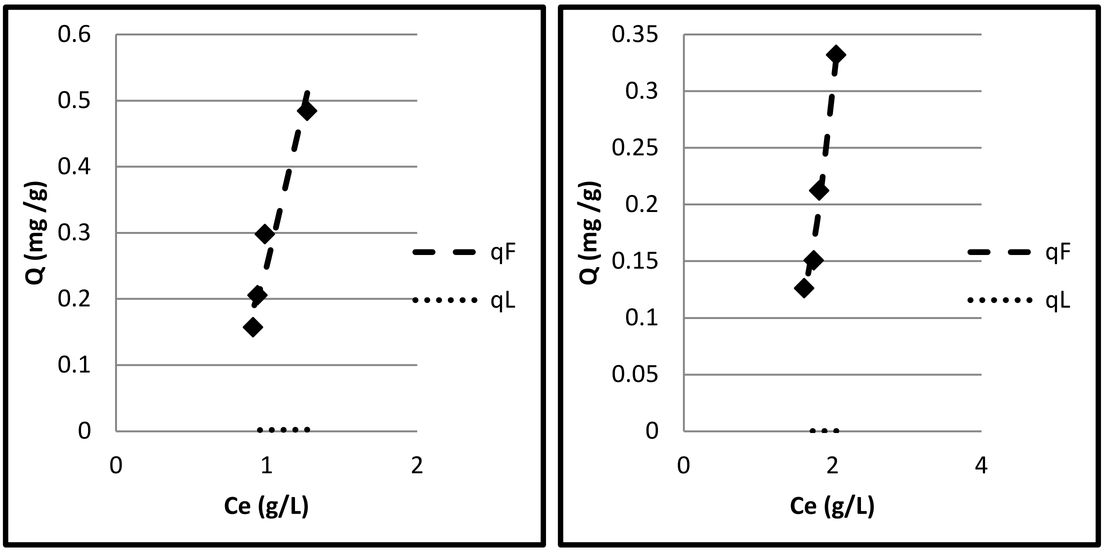
The figures for the determination of the Langmuir and Freundlich isotherm equations for 2, 6 and 10 mg/L initial concentration of copper can be found in Figure A.1.1 – A.1.6 in Appendix A.1

Table 4.1: Isotherm Models for Copper (II) using Palm Tree Leaves at different pH and initial concentration of Cu

Isotherm	**C_o (mg/L)**	**pH**	**Constants**		**Regression Coefficient**
	2		**q_0**	**b**	
Langmuir		3	0.9765625	0.148465649	0.5466
		5	-0.507176548	-0.02471982	0.7884
		9	-0.143317807	-0.012740493	0.6754
		neutral	-0.061961708	-0.001587947	0.9307
	2		**K_f**	**n**	
Freundlich		3	0.8508	0.131310665	0.9677
		5	7.4672	0.798730006	0.9041
		9	3.0456	0.247058614	0.8905
		neutral	4.273	0.015388631	0.9672
	6		**q_0**	**b**	
Langmuir		3	-0.172217821	-0.005279516	0.9534
		5	-0.499201278	-0.036776284	0.9169
		9	-0.087435516	-0.002107845	0.9538
		neutral	-0.149291611	-0.004908325	0.8462
	6		**Kf**	**n**	
Freundlich		3	2.8697	0.008014935	0.9547
		5	1.8739	0.051582217	0.9928
		9	6.4642	0.000371878	0.9981
		neutral	3.2859	0.008132049	0.9392
	10		**q_0**	**b**	
Langmuir		3	0.588997526	0.241957658	0.838
		5	1.250468926	0.149676094	0.7729
		9	0.918864284	0.066967734	0.2415
		neutral	0.15795792	-0.00727079	0.875
	10		**Kf**	**n**	
Freundlich		3	0.2107	0.325012452	0.2502
		5	0.5801	0.161845266	0.8981
		9	0.6528	0.091981397	0.4527
		Neutral	-0.7166	1.243368899	0.5895

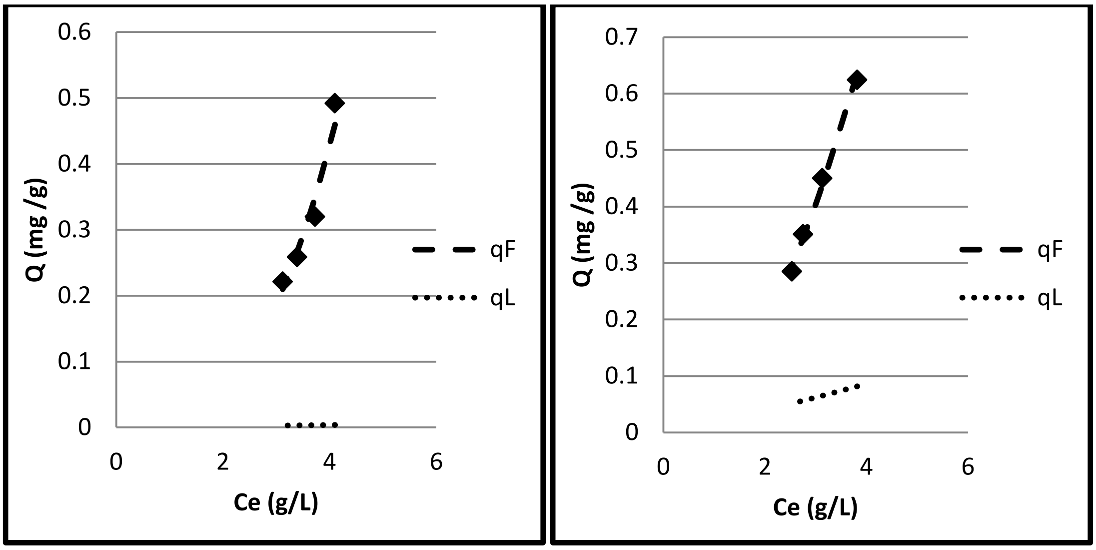


a) pH3 b) pH5



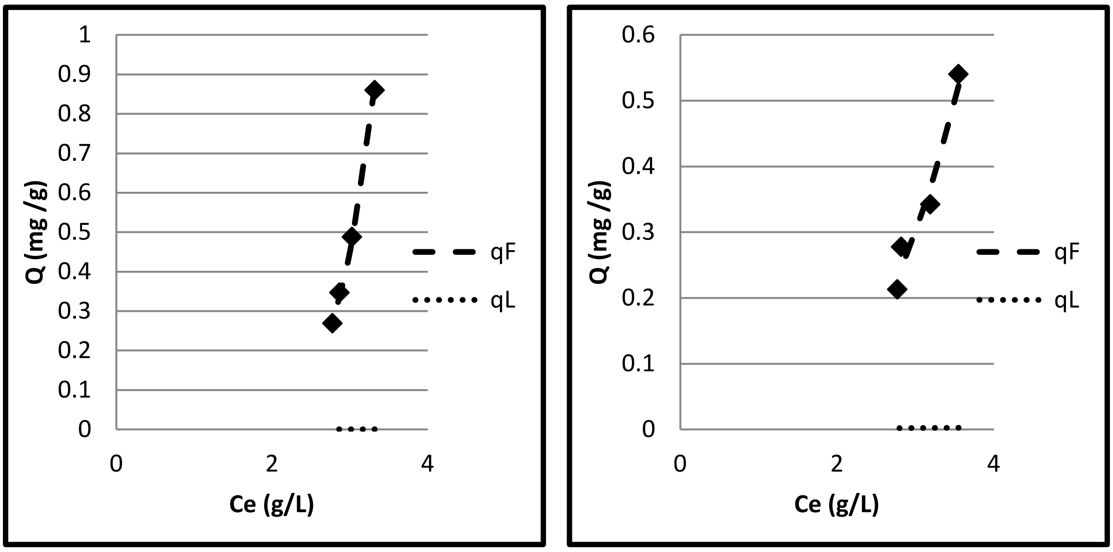
c) pH9 d) pH neutral

Figure 4.13: Adsorption Isotherms for Copper at 2 mg/L C_o and at different pHs



a) pH3

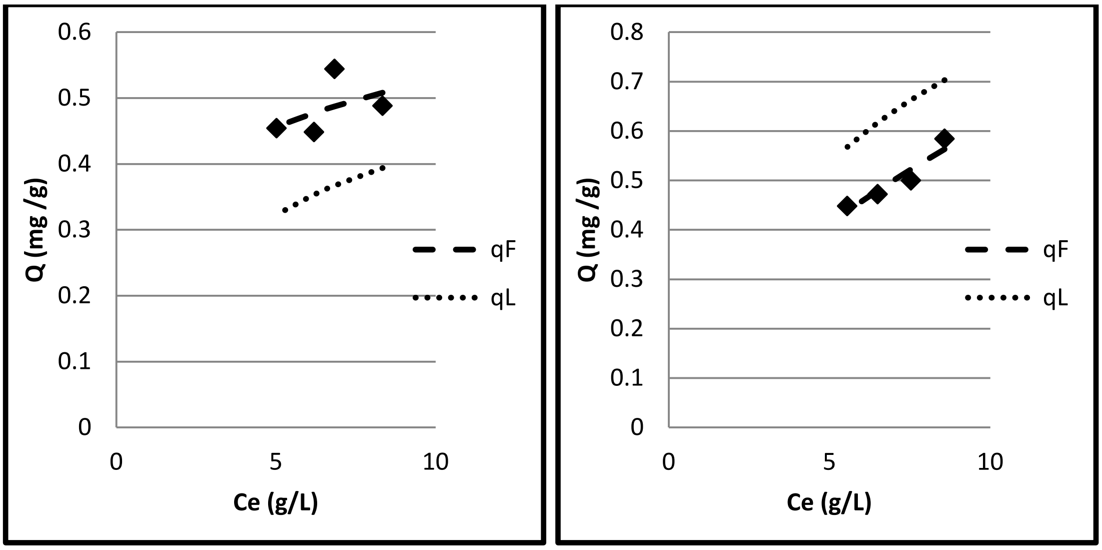
b) pH5



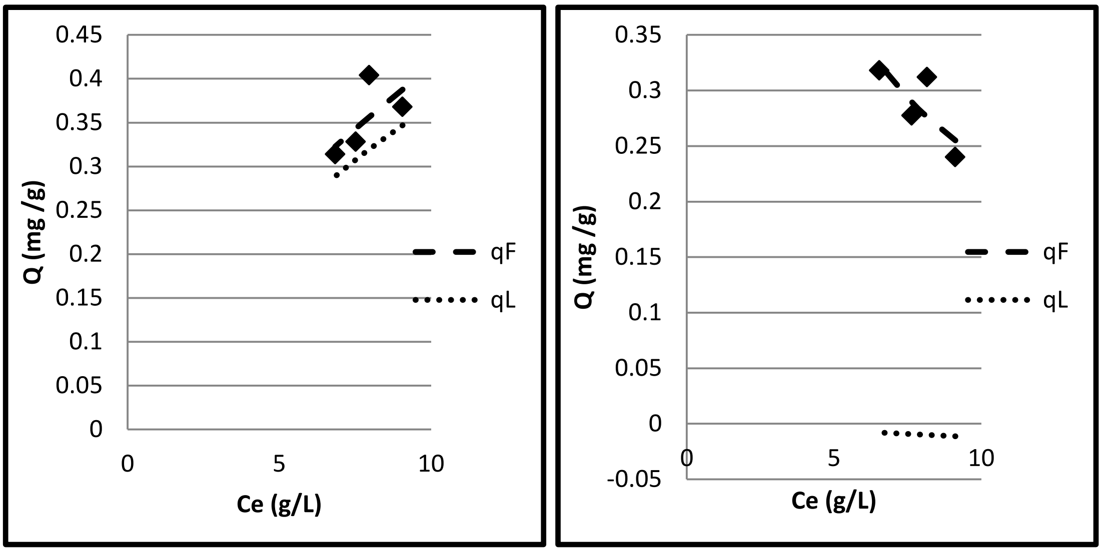
c) pH9

d) pH neutral

Figure 4.14: Adsorption Isotherms for Copper at 6 mg/L Co and at different pHs



a) pH3 b) pH5



c) pH9 d) pH neutral

Figure 4.15: Adsorption Isotherms for Copper at 10 mg/L Co and at different pHs

4.2.2 Chromium

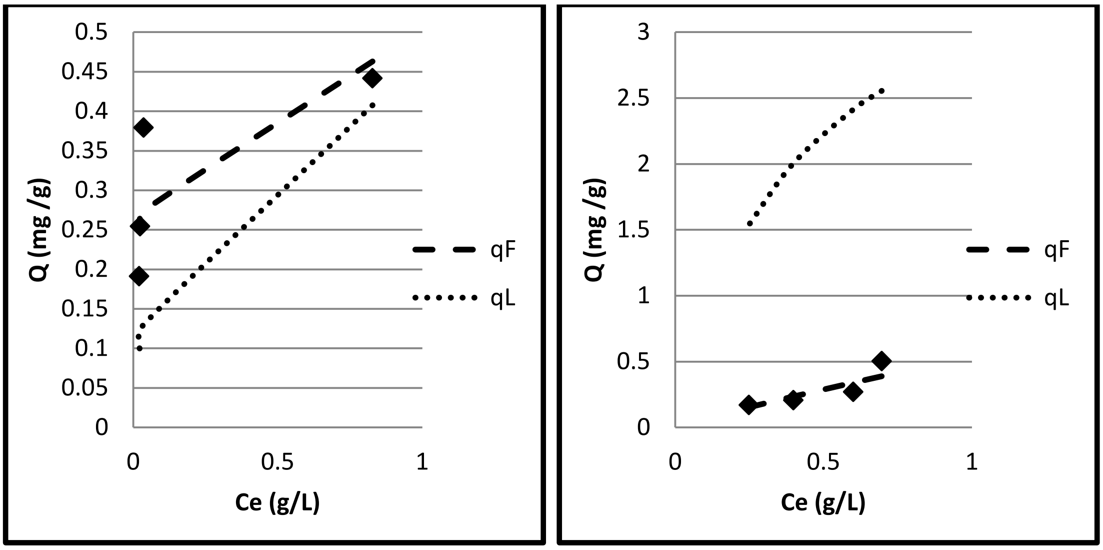
The results obtained from both Langmuir and Freundlich isotherms are shown in Table 4.2. As shown in the table, Freundlich isotherms are slightly better at linearizing the points although the R^2 values are not close to 1 and lie mostly around 0.5 – 0.9. However, both isotherms were unsuccessful at accurately capturing the points in a linear line. A different isotherm may obtain better values in terms of its ability to linearize the data points; however, none were used in this case.

Figures 4.16-4.18 represent that of the Langmuir and Freundlich isotherms for 2,6 and 10 mg/L C_o. As can be seen in the Langmuir isotherms, the linear line is of a positive slope except in the figure of the neutral pH. For Freundlich, the linear line has a positive slope for most pH-C_o combinations. It can also be noted from the figures that Freundlich represent much higher regression coefficients then that illustrated with Langmuir, as it was more able to capture the data points. Hence, for chromium, it can be noted that both isotherms do not accurately capture the linearization of the data points, however, Freundlich performs slightly better than Langmuir in its ability to linearize the data points.

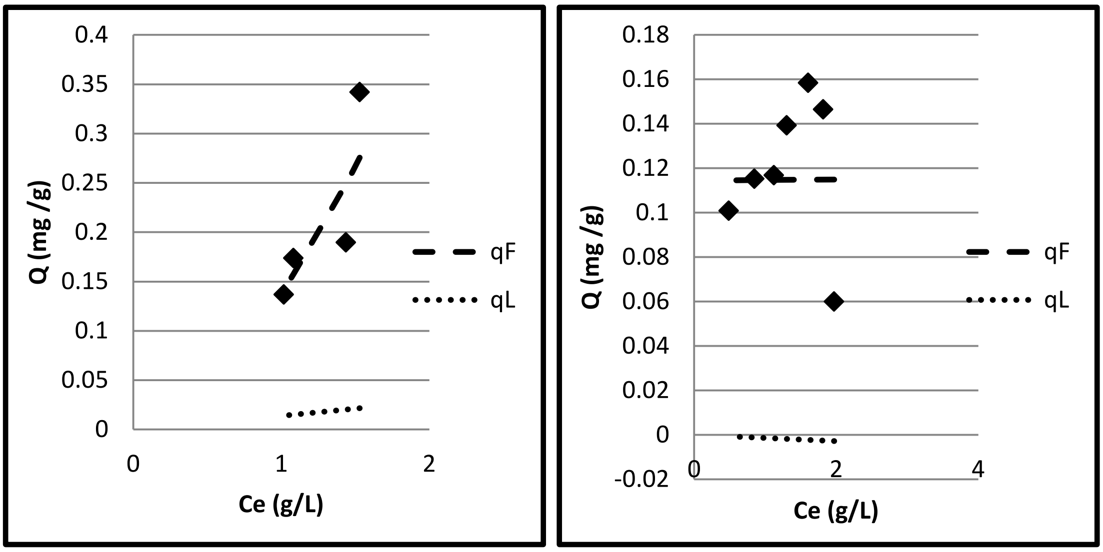
Langmuir and Freundlich isotherms for 6 and 10 mg/L initial concentration of chromium can be found in Figures A.1.7- A.1.12 Appendix A.1

Table 4.2: Isotherm Models for Chromium (VI) using Palm Tree Leaves at different pH and initial concentration of Cr

Isotherm	**C_o (mg/L)**	**pH**	**Constants**		**Regression Coefficient**
	2		**q_0**	**b**	
Langmuir		3	0.451345008	11.25548649	0.9995
		5	4.037141704	2.476166403	0.0158
		9	-0.363424916	-0.036647028	0.2377
		neutral	0.077748406	-0.01743707	0.5392
	2		**K_f**	**n**	
Freundlich		3	0.1672	0.477859253	0.5842
		5	0.9033	0.539013944	0.782
		9	1.6173	0.138547917	0.71
		neutral	0.0023	0.114736078	0.00001
	6		**q_0**	**b**	
Langmuir		3	-4.301075269	-9.75079408	0.7441
		5	1.933114247	1.187927393	0.2976
		9	0.021619284	-0.000120308	0.8466
		neutral	-5.285412262	-0.371192658	0.0613
	6		**K_f**	**n**	
Freundlich		3	1.3054	3.921931463	0.9901
		5	0.6025	0.496249406	0.5257
		9	-3.4589	29.08037483	0.6281
		neutral	1.0616	0.06821816	0.9398
	10		**q_0**	**b**	
Langmuir		3	4.118616145	0.324546952	0.4019
		5	-2.246686138	-14.17726354	0.5505
		9	0.522384161	2.104738024	0.523
		neutral	0.161399658	-4.281771523	0.7571
	10		**K_f**	**n**	
Freundlich		3	0.4317	1.684215708	0.6163
		5	1.5672	0.369427784	0.8958
		9	0.2134	0.562592339	0.1022
		neutral	-1.0733	0.589076042	0.6078

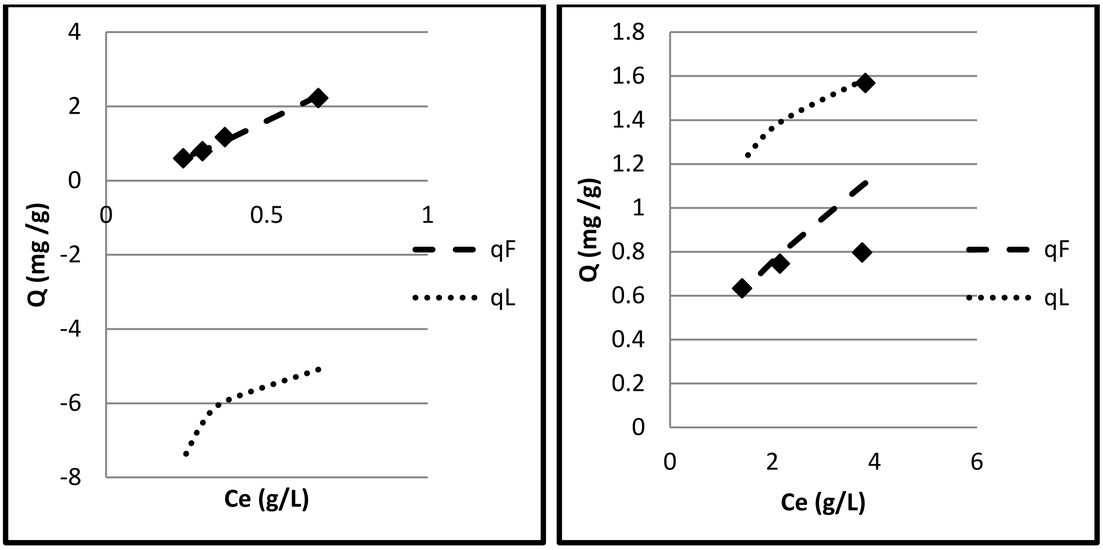


a) pH 3 b) pH 5

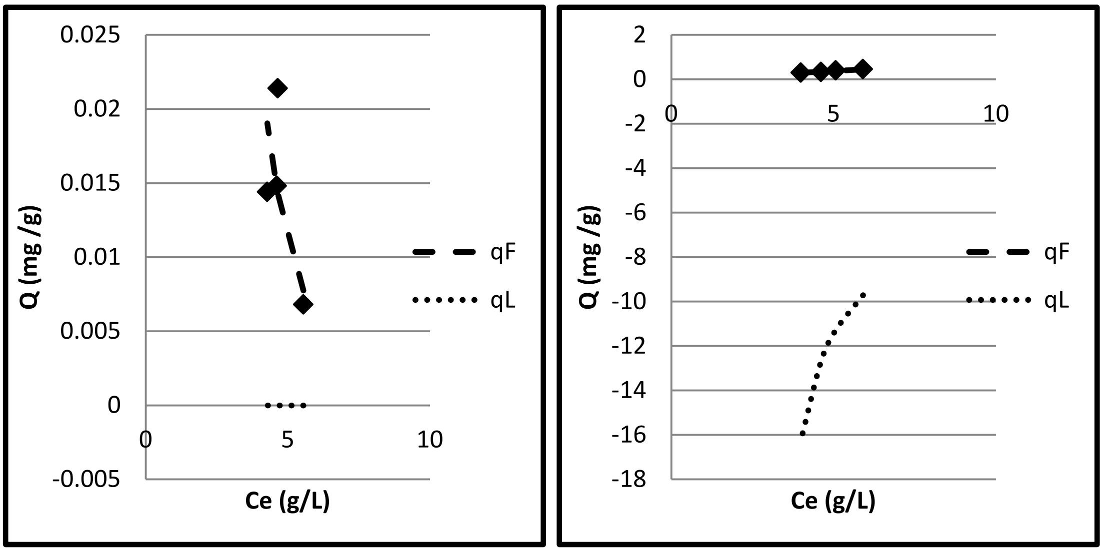


c) pH 9 d) pH Neutral

Figure 4.16: Adsorption Isotherms for Chromium at 2 mg/L C_o and at different pHs

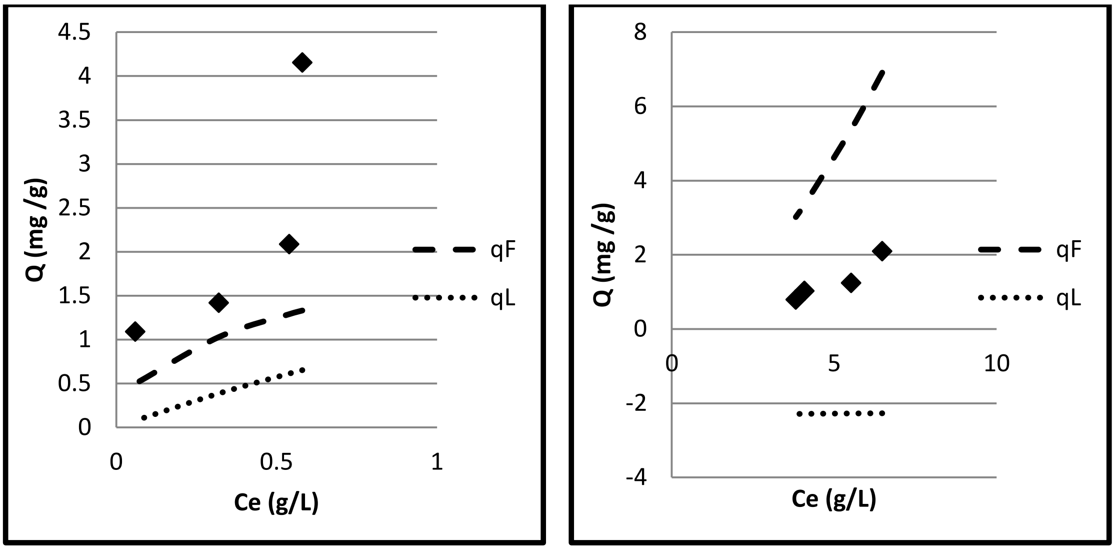


a) pH 3 b) pH 5

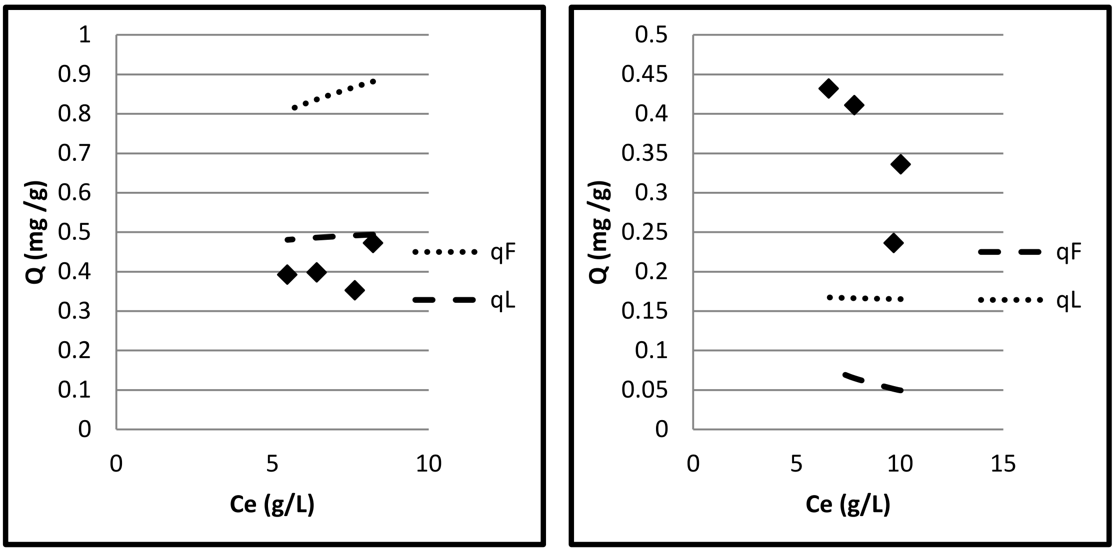


c) pH 9 d) pH Neutral

Figure 4.17: Adsorption Isotherms for Chromium at 6 mg/L C_o and at different pHs



a) pH 3 b) pH 5



c) pH 9 d) pH Neutral

Figure 4.18: Adsorption Isotherms for Chromium at 2 mg/L C_o and at different pHs

4.2.3 Zinc

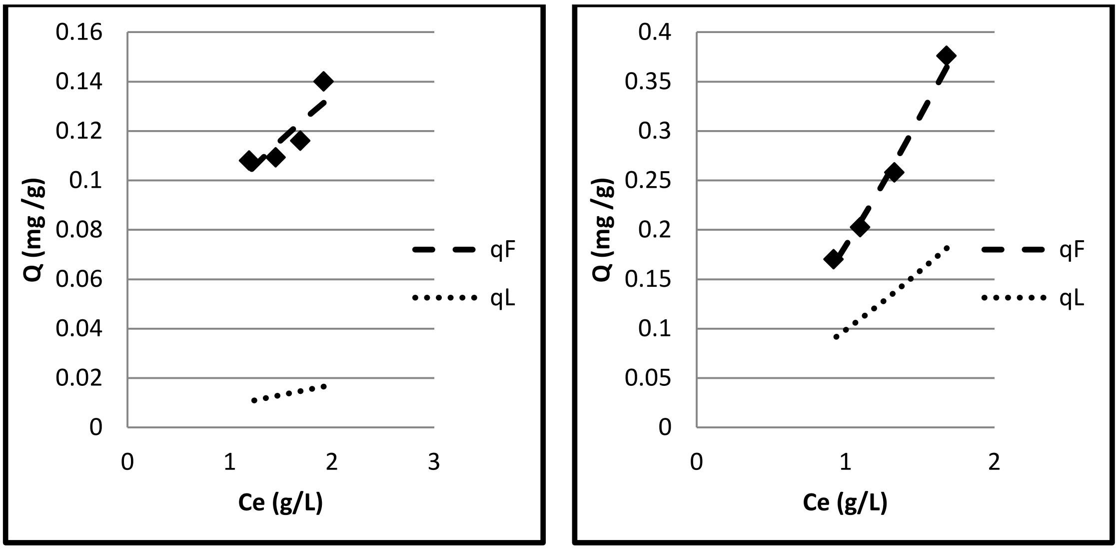
The results obtained from both Langmuir and Freundlich isotherms are shown in Table 4.3 . As shown in the table, both isotherms are well able to linearize the points as the R^2 values are close to 1 in most cases, with values above 0.9 in most cases. However, Freundlich represents a slightly higher advantage to Langmuir due to the higher R^2 values. The best R^2 values were obtained for Freundlich at 2 C_o where R^2 values range from 0.73 to 0.988

Figures 4.19-4.21 represent that of the Langmuir and Freundlich isotherms for 2, 6, and 10 mg/L C_o. As can be seen in the Langmuir isotherms, the line does not accurately capture the data points, and is remote from the values of the points. For Freundlich, on the other hand, the linear line has a positive slope for all pH values and was more accurately with smaller initial concentrations of zinc. It can also be noted that the Freundlich figures represent much higher regression coefficients then that observed with Langmuir as the line was able to successfully linearize the data points. However, as the concentration of zinc increased, neither isotherm successfully fitted the data points. Hence, for zinc, it can be noted that Freundlich more appropriately captures the linearization of the data points in smaller concentrations compared to Langmuir.

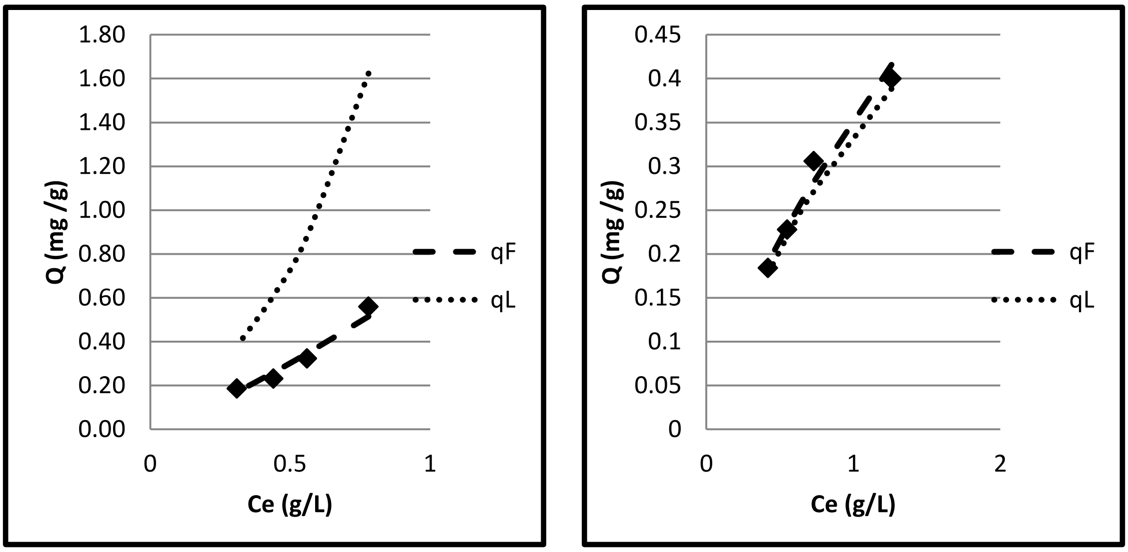
Langmuir and Freundlich isotherms for 6 and 10 mg/L initial concentration of zinc can be found in Figures A.1.13 – A.1.18 in Appendix A.1

Table 4.3: Isotherm Models for Zinc using Palm Tree Leaves at different pH and initial concentration of Zn

Isotherm	**C_o (mg/L)**	**pH**	**Constants**		**Regression Coefficient**
	2		**q_0**	**b**	
Langmuir		3	0.253845763	0.036338434	0.6658
		5	-0.76810815	-0.113748301	0.902
		9	-1.403508772	-0.687623719	0.4613
		neutral	0.961538462	0.537773189	0.927
	2		**K_f**	**n**	
Freundlich		3	0.4987	0.094929239	0.7343
		5	1.3228	0.183569278	0.9883
		9	1.1976	0.69294697	0.9527
		neutral	0.7122	0.352695566	0.9727
	6		**q_0**	**b**	
Langmuir		3	0.235637872	-0.535345681	0.4479
		5	-0.55769338	-8.809882327	0.8629
		9	-1.121076233	-2.970515695	0.9321
		neutral	-0.180014761	-3.024968047	0.945
	6		**K_f**	**n**	
Freundlich		3	-0.0993	0.604955728	0.0053
		5	1.863	4.252044814	0.9265
		9	1.6567	0.791915963	0.9798
		neutral	4.4972	0.159406139	0.9946
	10		**q_0**	**b**	
Langmuir		3	-0.005383	-8.523442967	0.3506
		5	-0.270168045	-11.23628897	0.7845
		9	-0.86400553	-3.391480905	0.7242
		neutral	-0.543351282	-6.846226154	0.9643
	10		**K_f**	**n**	
Freundlich		3	15.696	4.26779E-07	0.5258
		5	2.7628	0.068906828	0.878
		9	2.7692	0.489583622	0.937
		neutral	3.1457	0.13126987	0.9994

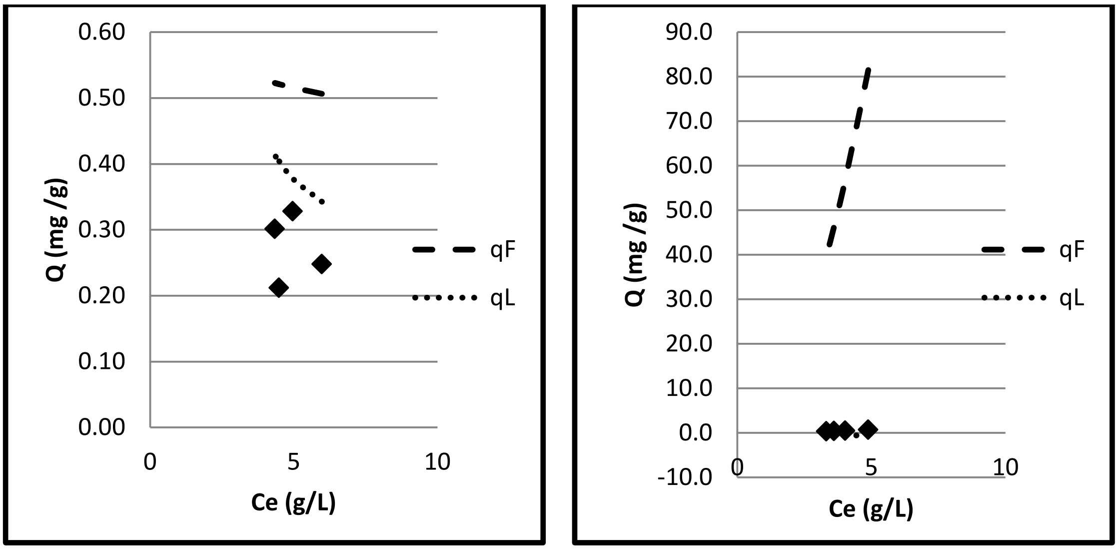


a) pH 3 b) pH 5



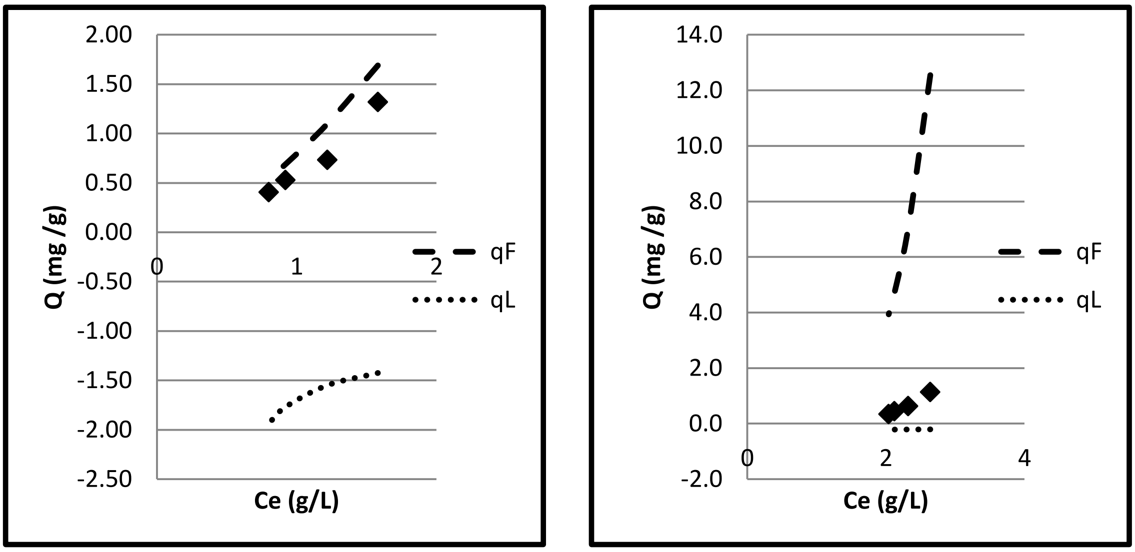
c) pH 9 d) pH Neutral

Figure 4.19: Adsorption Isotherm for Zinc at 2 mg/L C_o at different pHs



a) pH 3

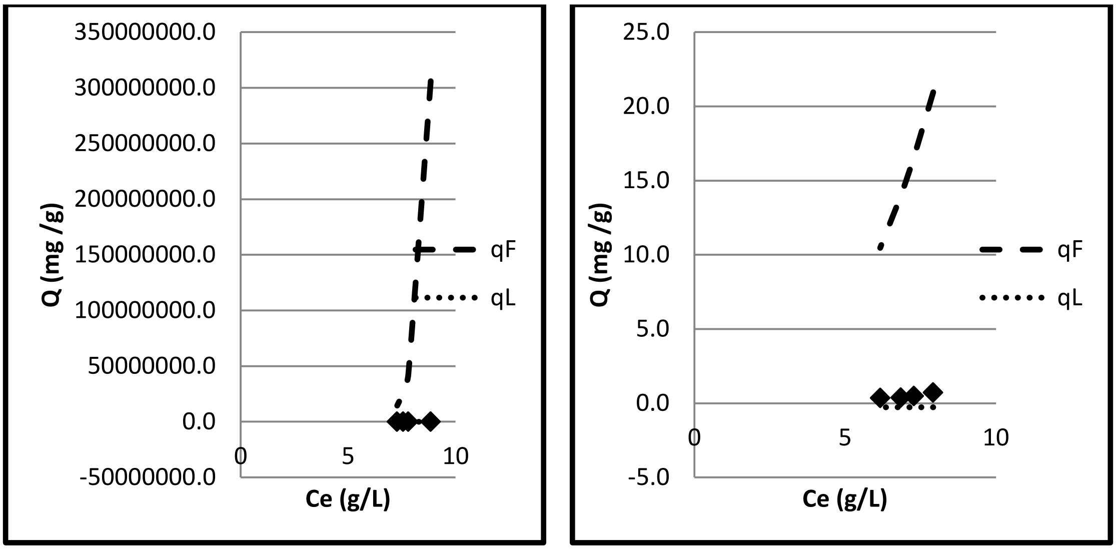
c) pH 5



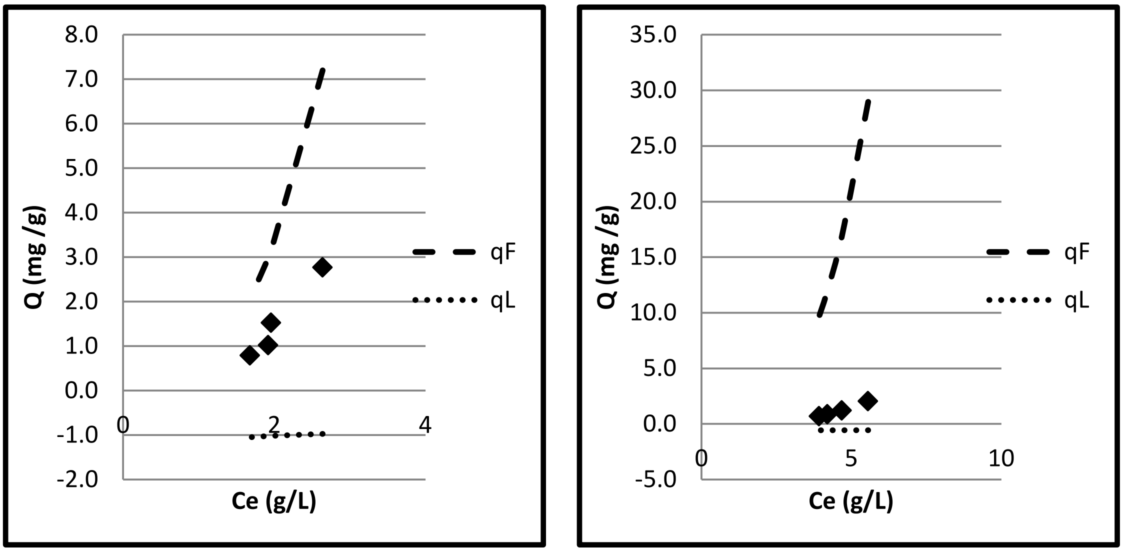
c) pH 9

d) pH Neutral

Figure 4.20: Adsorption Isotherm for Zinc at 6 mg/L Co at different pHs



a) pH 3 b) pH 5



c) pH 9 d) pH Neutral

Figure 4.21: Adsorption Isotherm for Zinc at 10 mg/L Co at different pHs

4.3 COLUMN TESTS

4.3.1 Neutral pH Column Test

Figure 4.22 shows the results obtained during the column tests. It can be observed that it requires approximately 2800 pore volumes to obtain exhaustion in chromium and zinc, which amounts to approximately 140 hours. The number of pore volumes is an indication to the total volume of pores that the water passed through to obtain exhaustion. It is a function of the volume of the wastewater that has passed in the column and the porosity of the PTL in the column. As this pH leaned more on the end where zinc is favoured to be adsorbed, it was expected that chromium concentration would rise in concentration fairly quickly, reaching exhaustion just shy from 24 hours. Zinc took the longest time with 140 hours until treatment was no longer effective.

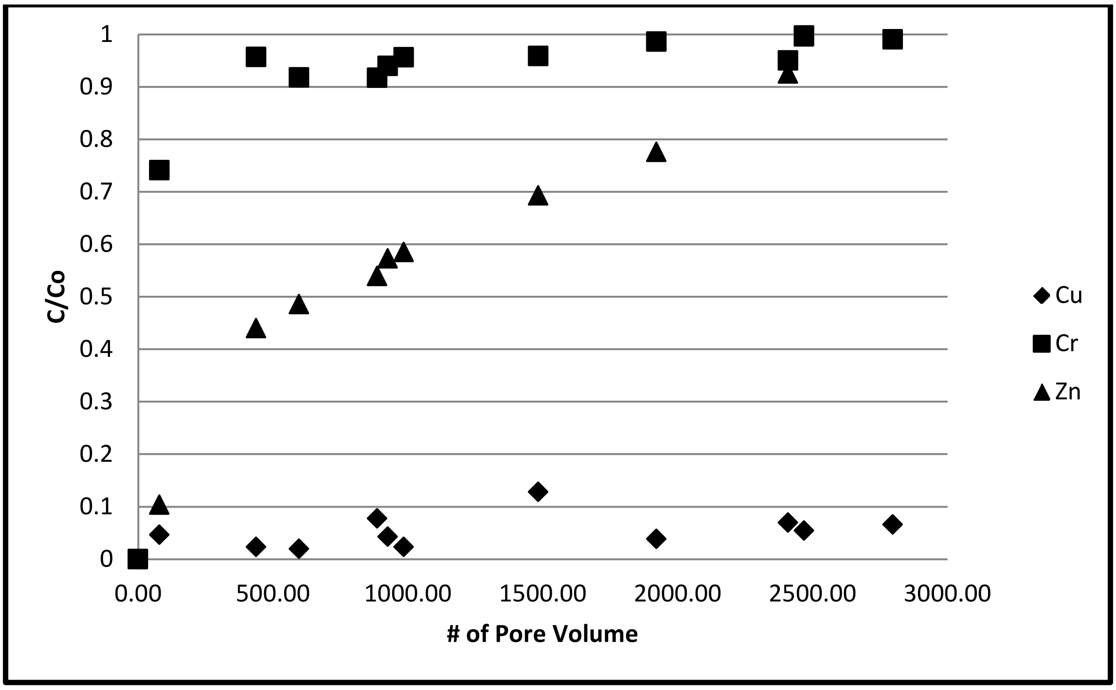


Figure 4.22: Column Test Results - pH Neutral

The total mass of the metals that were fed to the column is shown in Table 4.4. Chromium required the lowest mass as it reached the end of its treatment sooner than the others. Although only a small portion of copper was observed to have precipitated during the running of the experiment, it was still fed to the column.

Table 4.4: Total amount of metal ions sent to the column (mg)

Copper	239.24
Chromium	155.60
Zinc	223.48

4.3.2 Acidic pH Column Test

The results obtained were plotted in Figure 4.23. It illustrated the concentration of the metals in the effluent against the number of pore volumes of water produced. Initially, concentrations in the effluent were high and are thought to be due to the water seeping through the pores out of the column. The colour of the effluent was slightly yellow due to the organics of the PTL discolouring on the water but became clear within a few hours of running the experiment. Hence, as shown in the figure, initial concentration values of the metals were high in the effluent and then decreases. As this test was performed with a slightly acidic pH, it is expected that the most effective treatment be with the chromium metal, as was previously shown in the batch tests. It is also expected that the least treatment occur with the zinc metal, as zinc prefers a more basic environment. Also, the slightly acidic influent showed no signs of precipitation of the metals, unlike what was previously observed with the neutral environment, and what will be shown in the basic environment.

Figure 4.23 shows that the total number of pore volumes that occurred during the column test was approximately 2400, which amounts to approximately 287 hours. However, this value does not correspond to the exhaustion of the metal, but to the time that the column test was stopped after obtaining a high enough concentration value in the effluent. Zinc was the fastest to reach exhaustion after 52 hours, followed by copper at approximately 260 hours. Chromium only reached 60% at 287 hours before the experiment was stopped.

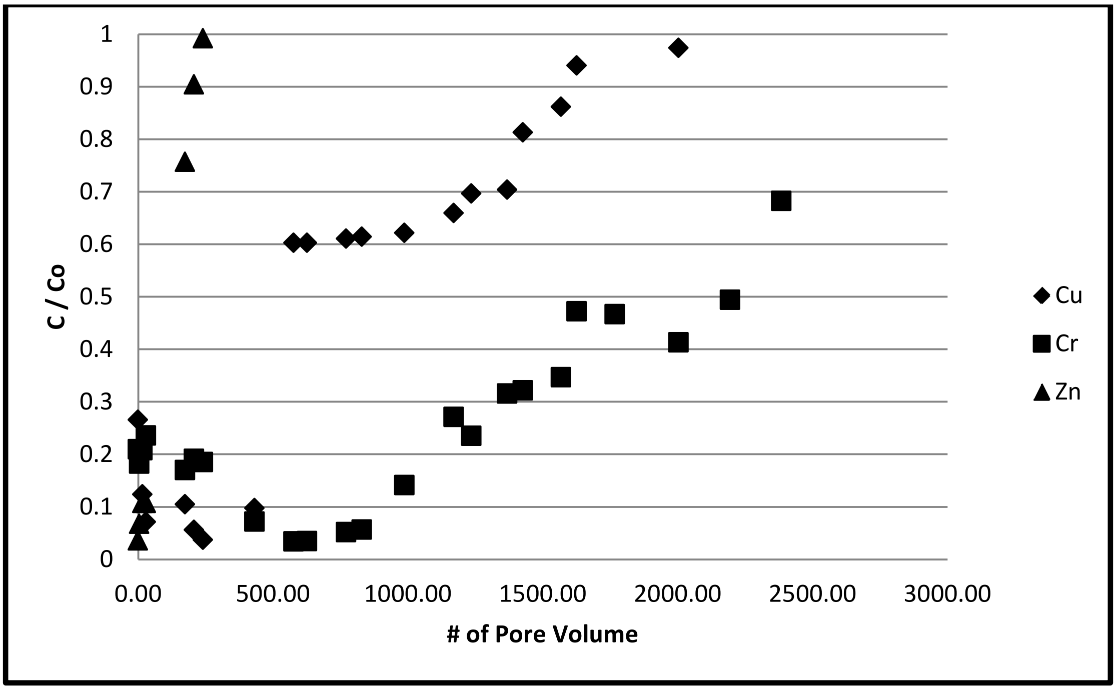


Figure 4.23: Column Test Results - pH5

Table 4.5 illustrates the mass of each metal that was sent to the column before its exhaustion. As shown, it takes zinc the least mass before exhaustion is reached. Chromium and copper show close values, however, referring back to Figure 4.23, it can be seen that copper has a higher ratio than chromium. Therefore, had the test been prolonged to allow both metal to reach a ratio of 1, chromium would have had the largest mass of metal sent to the column.

Table 4.5: Total amount of metal ions sent to the column (mg)

Copper	211.86
Chromium	207.27
Zinc	39.16

4.3.3 Basic pH Column Test

As was later evident, Zinc and Copper metals precipitated throughout the running of this experiment illustrated in Figure 4.24. It was later known that both these metals require a slightly basic pH to precipitate. Chromium continued to be treated, however, as was previously shown in the batch tests, basic pHs are not favourable for its treatment. Hence, concentrations quickly increased. Due to the precipitation of the metals, and the exhaustion of chromium, the experiment was stopped after the latter. Total time that the column test was running was 89 hours, which amounts to approximately 4 days.

At this pH, adsorption and precipitation occurred simultaneously. This is known as sorption discussed further in previous sections. Therefore, removal of the metals was not solely caused by their adsorption by the PTL, but also due to them precipitating in the influent tank.

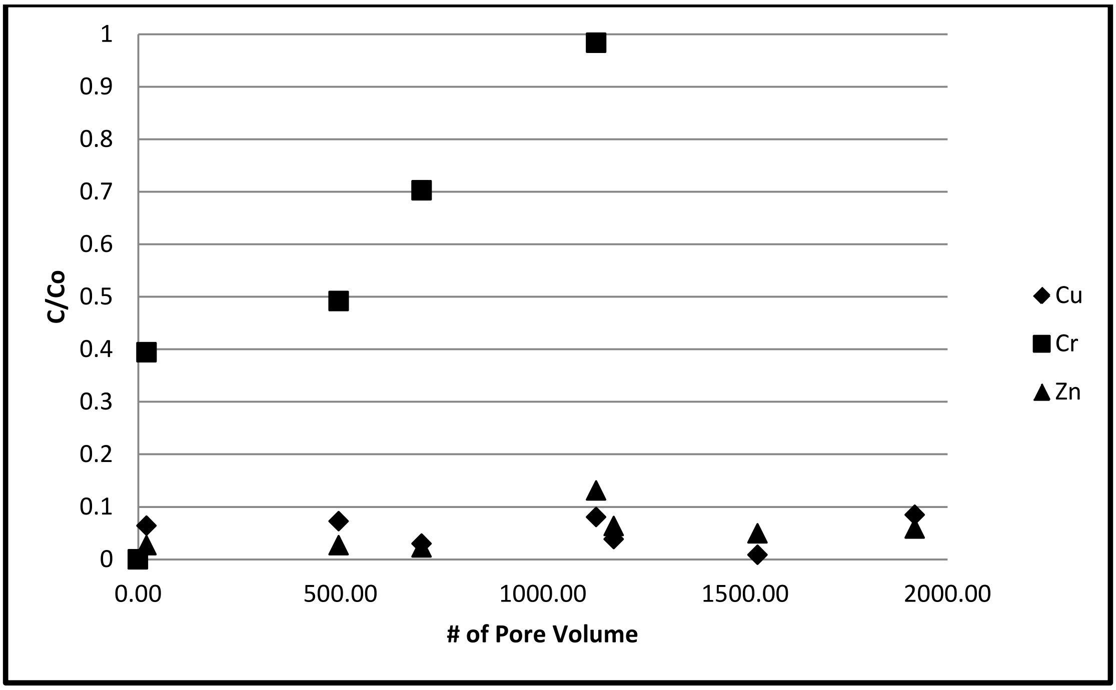


Figure 4.24: Column Tests Results - pH 9

The total amount of metal that was allowed to enter the column is shown in Table 4.6**: Total amount of metal ions sent to the column (mg)**. However, as the metals precipitated in large quantities, the values in the table represent what should have been the mass fed to the column assuming the experiment was not stopped prematurely.

Table 4.6: Total amount of metal ions sent to the column (mg)

Copper	163.14
Chromium	133.36
Zinc	153.42

4.4 DESORPTION

The results obtained, (Table 4.7), show that the acidic pH was more successful at recovering the metals compared to the basic pH. Hence, batch tests with incrementing PTL dosage were tested with acidic pH to determine the desorption capacity.

Table 4.7: Recovered Concentrations at different pH (in mg)

	pH 2.94	**pH 12.9**
Copper	4.78	0.1
Chromium	0.023	0.112
Zinc	0.63	0.08

Figure 4.25 illustrates the desorption capacity of the metals. It shows that copper was the most successful in recovering the metals from the PTL, followed closely by zinc. Chromium shows low recovery capacity compared to the other metals, however, it is still significant when treatment is performed in large volumes. From the figure, it can be seen that copper, chromium and zinc were successfully recovered during the desorption batch test. This, therefore, indicates that both the metals and the PTL may be reused.

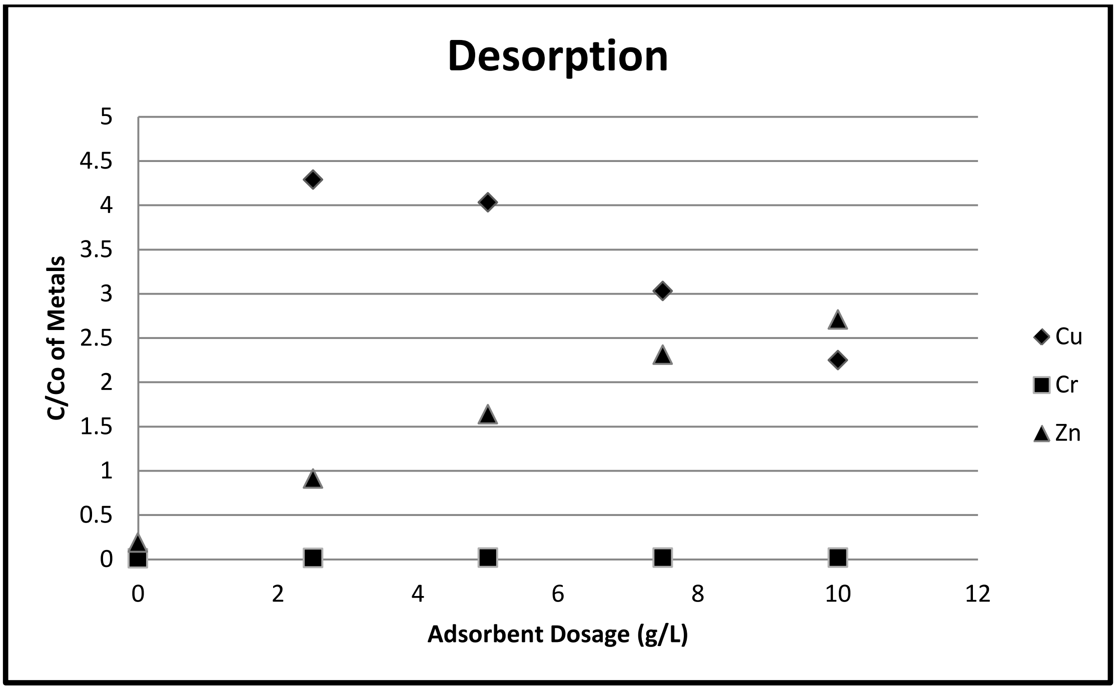


Figure 4.25: Recovery Capacity of Metals

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

Adsorption is a process that has been developing immensely as environmental issues rise. Adsorption has been used to remove many pollutants from wastewater, whether seawater or industrial wastewater, purifying drinking water, or as a polishing phase at the end of sewage treatment. These pollutants include heavy metals, which is the focus of this work. Heavy metals are toxic and hazardous to humans, marine life and the water body in which it is contained. The metals studied in this work include copper, chromium, and zinc, due to their abundance in water, in addition to their toxicity. Adsorbents used were palm tree leaves collected from Sharjah, United Arab Emirates due to their availability. Batch tests, column tests, and desorption tests were conducted. Batch tests revealed that PTL behave as good adsorbents in removing the metals at different conditions. These conditions varied in pH, C_o and PTL dosage. Copper resulted in a maximum of 67.5% adsorption at pH 5, 99.5% chromium at pH 3, and 86% zinc at pH 9. Batch tests were first performed with the metals separate in the solution. Another set of batch tests were conducted with a mixture of the metals to examine the competitive nature of the metals, and to also slightly mimic wastewater found in nature. Results showed that a maximum percent removal of 98.5% for chromium, 83.7% for zinc, and 82.7% for copper was obtained

Langmuir and Freundlich adsorption isotherms were used to linearize the data obtained from the batch tests. It was shown that in most cases these isotherms were capable of linearizing the data, however, proved unsuccessful in other cases. Freundlich was more successful for copper and zinc; however, neither accurately captured that of chromium. It is suggested that other isotherms be used.

Column tests verified that the PTL is successful in removing the metals from the wastewater, and were performed with the influent containing the mixture of all metals at different pH levels but same concentration values. For the column tests, breakthrough figures were employed to determine the time in which the metals breakthrough and exhaust after running the column tests. Approximately 3000 pore volumes were required to exhaust PTL adsorption capacity of chromium and zinc in the neutral pH. For basic pH, zinc required only 431 pore volumes for its exhaustion, chromium around 2500, and copper around 2000. Desorption tests evaluated the ability for the PTL to detach the metals in order to allow for the metals and material to be recovered and reused.

Desorption tests proved to be successful as the metals were able to be recovered. The wastewater used throughout all experiments was artificially prepared in the lab using distilled water. To produce the synthetic wastewater, solids containing the metal ion were dissolved in distilled water. In all tests, results have proven to be successful and the use of PTL has achieved the adsorption and desorption of copper, chromium, and zinc metals.

For future research, it is recommended that effects such as temperature, contact time, and agitation speed be investigated, as they were kept constant in this work. Also, studying the effect of performing these tests on actual wastewater is very beneficial. As copper, chromium, and zinc are not the only metals found in wastewater, studying the adsorption efficiency of PTL and other metals is also recommended. Studying the chemical process and behavior of metals that occurs with varying experimental conditions (such as pH, initial concentration, temperature, etc), or varying combinations of metals, will prove beneficial. Evaluating the efficiency of other materials that are also readily available in the Gulf Region is recommended. Developing a model to allow future researchers to predict the adsorption efficiency of PTL on heavy metals will be largely beneficial. It is also recommended to study the effect, feasibility, and practicality of having two treatment processes in series in real life: one with acidic pH and the other with basic pH as these gave the best treatment. Depending on the best pH for the metals existing in the wastewater, the treatment tanks can be placed in series and studied to determine the removal efficiency of the metals.

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APPENDIX A

A.1 BATCH TESTS

Copper

Experiments

Table A.1. 1: Batch Test Results - Copper - C_o 2mg/L - pH 3

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	2				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	2.09	1.61	1.25	1.07	0.9
Percentage removal		22.9665	40.1913	48.8038	56.9377
Q (mg Cu/g)	None	0.192	0.168	0.136	0.119
C/C_o	1	0.7703	0.5980	0.5119	0.43062
log(Cu)	None	0.2068	0.0969	0.0293	-0.0457
log(Q)	None	-0.7166	-0.7746	-0.8664	-0.9244
Cu/Q		8.3854	7.4404	7.8676	7.5630

Table A.1.2: Batch Test Results - Copper - C_o 2mg/L - pH 5

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	2				
pH	5				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	2.52	0.97	0.86	0.86	0.82
Percentage removal		61.5079	65.8730	65.8730	67.4603
Q (mg Cu/g)	None	0.6200	0.3320	0.2213	0.1700
C/C_o	1	0.3849	0.3413	0.3413	0.3254
log(Cu)	None	-0.0132	-0.0655	-0.0655	-0.0862
log(Q)	None	-0.2076	-0.4789	-0.6550	-0.7696
Cu/Q		1.5645	2.5904	3.8855	4.8235

Table A.1. 3: Batch Test Results - Copper - C_o 2mg/L - pH 9

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	2				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	2.48	1.27	0.99	0.94	0.91
Percentage removal		48.7903	60.0806	62.0968	63.3065
Q (mg Cu/g)	None	0.4840	0.2980	0.2053	0.1570
C/C_o	1	0.5121	0.3992	0.3790	0.3669
log(Cu)	None	0.1038	-0.0044	-0.0269	-0.0410
log(Q)	None	-0.3152	-0.5258	-0.6875	-0.8041
Cu/Q		2.6240	3.3221	4.5779	5.7962

Table A.1. 4: Batch Test Results - Copper - C_o 2mg/L - pH Neutral

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	2				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	2.88	2.05	1.82	1.75	1.62
Percentage removal		28.819	36.8055	39.2361	43.75
Q (mg Cu/g)	None	0.332	0.212	0.1506	0.126
C/C_o	1	0.7118	0.6319	0.6076	0.5625
log(Cu)	None	0.3117	0.2601	0.2430	0.2095
log(Q)	None	-0.4788	-0.6736	-0.8219	-0.8996
Cu/Q		6.1746	8.5849	11.6150	12.8571

Table A.1.5: Batch Test Results - Copper - C_o 6mg/L - pH 3

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	6				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	5.33	4.1	3.73	3.39	3.12
Percentage removal		23.0769	30.0187	36.3977	41.4634
Q (mg Cu/g)	None	0.492	0.32	0.2586	0.221
C/C_o	1	0.7692	0.6998	0.6360	0.5853
log(Cu)	None	0.6127	0.5717	0.5301	0.4941
log(Q)	None	-0.3080	-0.4948	-0.5872	-0.6556
Cu/Q		8.3333	11.6562	13.1056	14.1176

Table A.1. 6:Batch Test Results - Copper - C_o 6mg/L - pH 5

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	6				
pH	5				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	5.38	3.82	3.13	2.75	2.53
Percentage removal		28.9962	41.8215	48.8847	52.9739
Q (mg Cu/g)	None	0.624	0.45	0.3506	0.285
C/C_o	1	0.7100	0.5817	0.5111	0.4702
log(Cu)	None	0.5820	0.4955	0.4393	0.4031
log(Q)	None	-0.2048	-0.3467	-0.4551	-0.5451
Cu/Q		6.1217	6.9555	7.8422	8.8771

Table A.1.7: Batch Test Results - Copper - C_o 6mg/L - pH 9

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	6				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	5.47	3.32	3.03	2.87	2.78
Percentage removal		39.3053	44.6069	47.5319	49.1773
Q (mg Cu/g)	None	0.86	0.488	0.3466	0.269
C/C_o	1	0.6069	0.5631	0.5334	0.5167
log(Cu)	None	0.5211	0.4814	0.4578	0.4440
log(Q)	None	-0.0655	-0.3115	-0.4600	-0.5702
Cu/Q		3.8604	6.2090	8.2788	10.3345

Table A.1.8: Batch Test Results - Copper - C_o 6mg/L - pH Neutral

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	6				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	4.9	3.55	3.19	2.82	2.77
Percentage removal		27.5510	34.8979	42.4489	43.4693
Q (mg Cu/g)	None	0.54	0.342	0.2773	0.213
C/C_o	1	0.7244	0.6510	0.5755	0.5653
log(Cu)	None	0.5502	0.5037	0.4502	0.4424
log(Q)	None	-0.2676	-0.4659	-0.5569	-0.6716
Cu/Q		6.5740	9.3274	10.1682	13.0046

Table A.1. 9: Batch Test Results - Copper – C_o 10 mg/L - pH 3

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	10				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	9.56	8.34	6.84	6.2	5.02
Percentage removal		12.7615	28.4518	35.1464	47.4895
Q (mg Cu/g)	None	0.244	0.272	0.224	0.227
C/C_o	1	0.8723	0.7154	0.6485	0.5251
Log(Cu)	None	0.9211	0.8350	0.7923	0.7007
log(Q)	None	-0.6126	-0.5654	-0.6497	-0.6439
Cu/Q		34.1803	25.1470	27.6785	22.1145

Table A.1.10: Batch Test Results - Copper – C_o 10 mg/L - pH 5

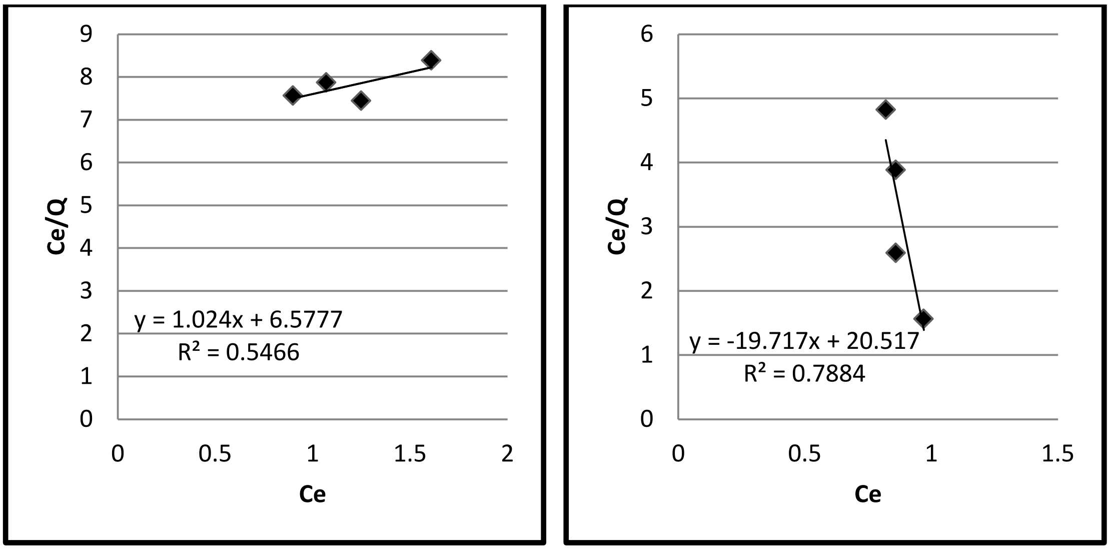
Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	10				
pH	5				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	10.04	8.58	7.54	6.5	5.56
Percentage removal		14.5418	24.900	35.2589	44.6215
Q (mg Cu/g)	None	0.292	0.25	0.236	0.224
C/C_o	1	0.8545	0.7509	0.6474	0.5537
log(Cu)	None	0.9334	0.8773	0.8129	0.7450
log(Q)	None	-0.5346	-0.6020	-0.6270	-0.6497
Cu/Q		29.3835	30.16	27.5423	24.8214

Table A.1.11: Batch Test Results - Copper - C_o 10 mg/L - pH 9

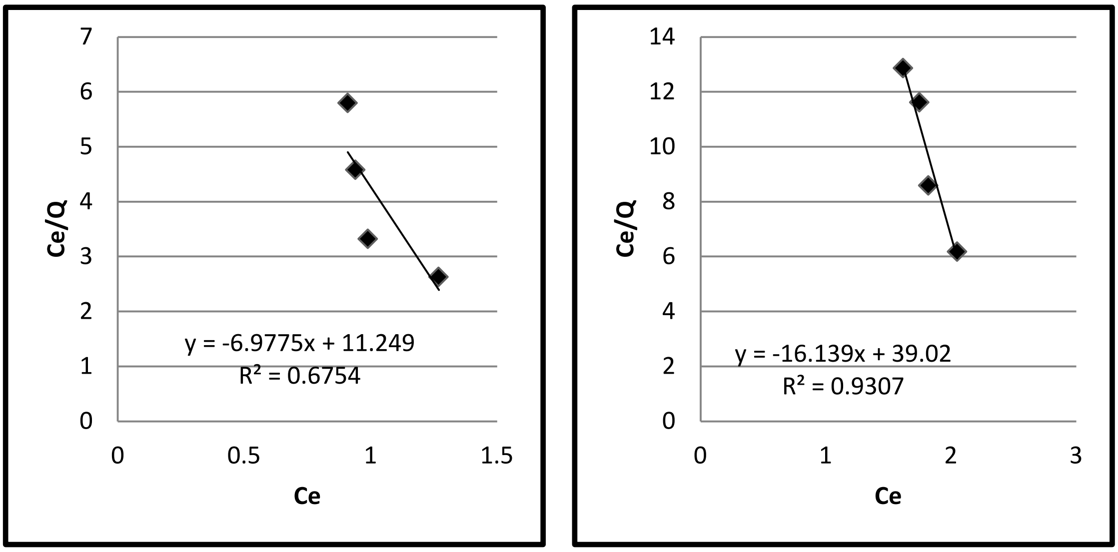
Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	10				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	9.98	9.06	7.96	7.52	6.84
Percentage removal		9.2184	20.2404	24.6492	31.4629
Q (mg Cu/g)	None	0.184	0.202	0.164	0.157
C/C_o	1	0.9078	0.7975	0.7535	0.6853
log(Cu)	None	0.9571	0.9009	0.8762	0.8350
log(Q)	None	-0.7351	-0.6946	-0.7851	-0.8041
Cu/Q		49.2391	39.4059	45.8536	43.5668

Table A.1.12: Batch Test Results - Copper - C_o 10 mg/L - pH Neutral

Metal	**Copper (Cu)**				
Concentration of Metal (mg/L)	10				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cu (g/L)	9.72	9.12	8.16	7.64	6.54
Percentage removal		6.1728	16.0493	21.3991	32.7160
Q (mg Cu/g)	None	0.12	0.156	0.1386	0.159
C/C_o	1	0.9382	0.8395	0.7860	0.6728
log(Cu)	None	0.9599	0.9116	0.8830	0.8155
log(Q)	None	-0.9208	-0.8068	-0.8580	-0.7986
Cu/Q		76	52.3076	55.0961	41.1320



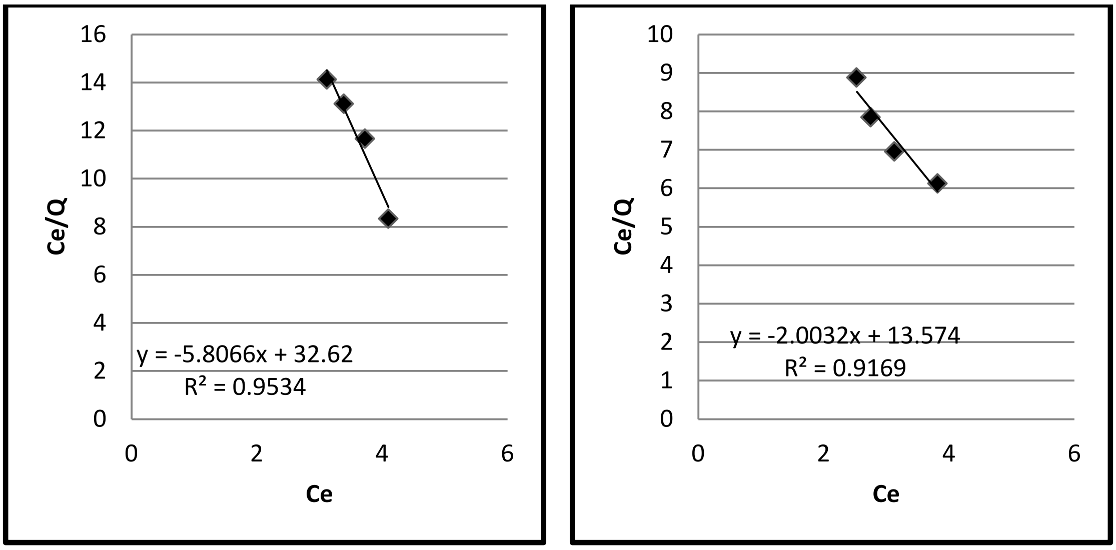
a) pH3 b) pH5



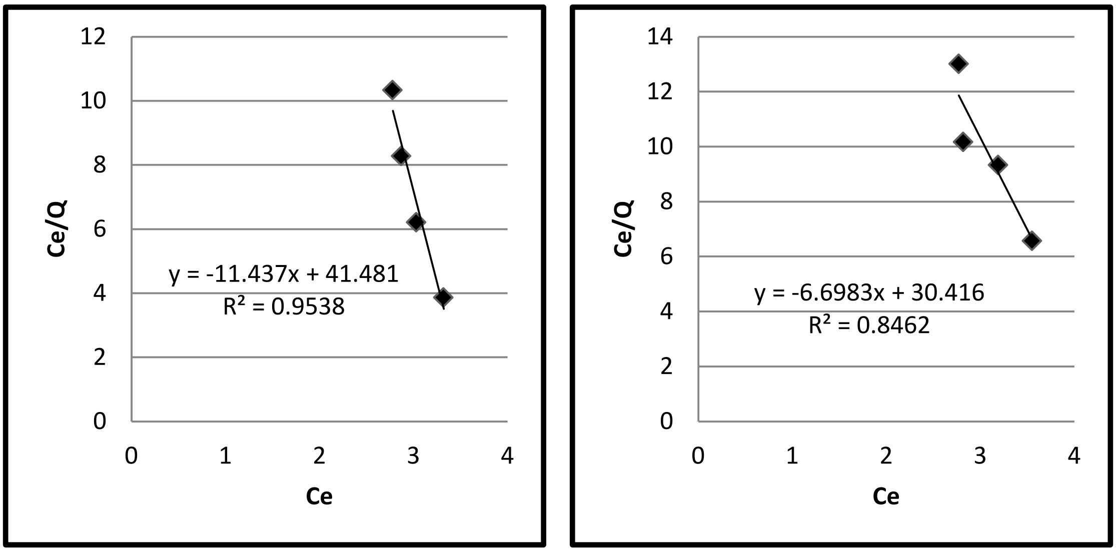
c) pH9 d) pH neutral

Figure A.1.1: Langmuir Isotherms for Copper at 2 mg/L Co and at different pHs

Adsorption Isotherms

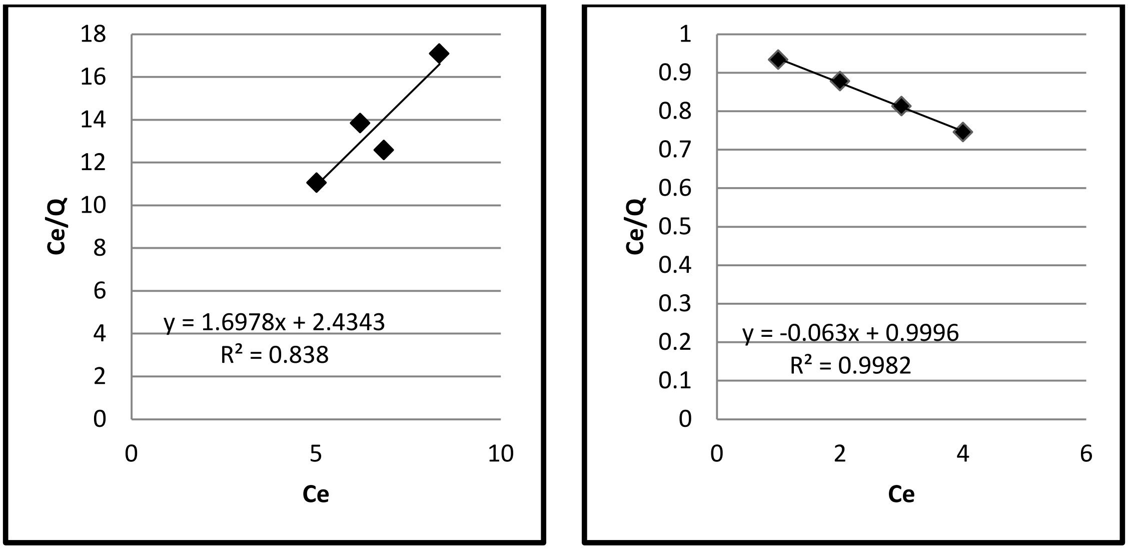


a) pH 3 b) pH 5

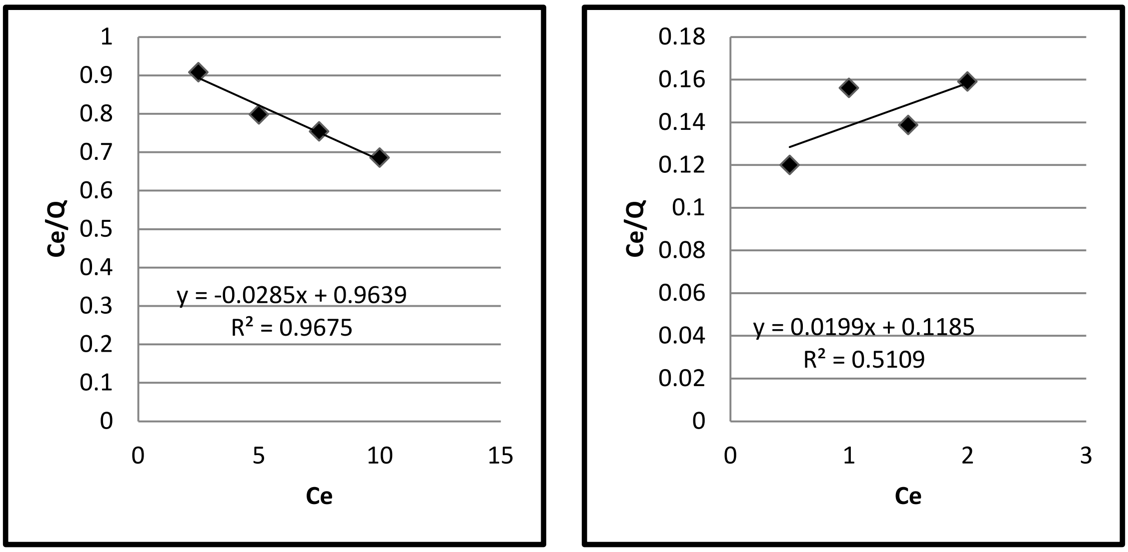


c) pH 9 d) pH Neutral

Figure A.1.2: Langmuir Isotherms for Copper at 6 mg/L C_o and at different pHs

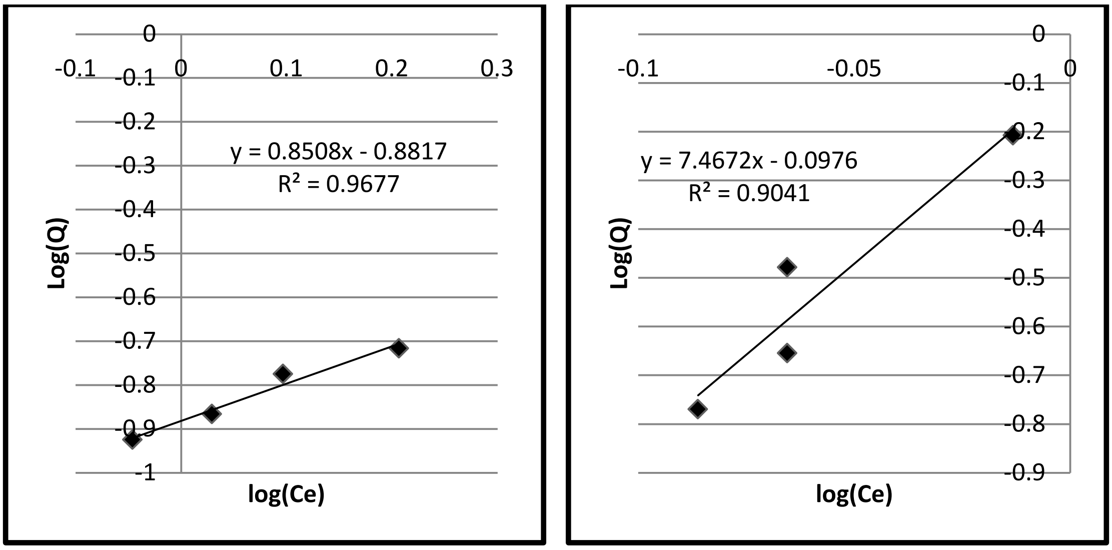


a) pH 3 b) pH 5



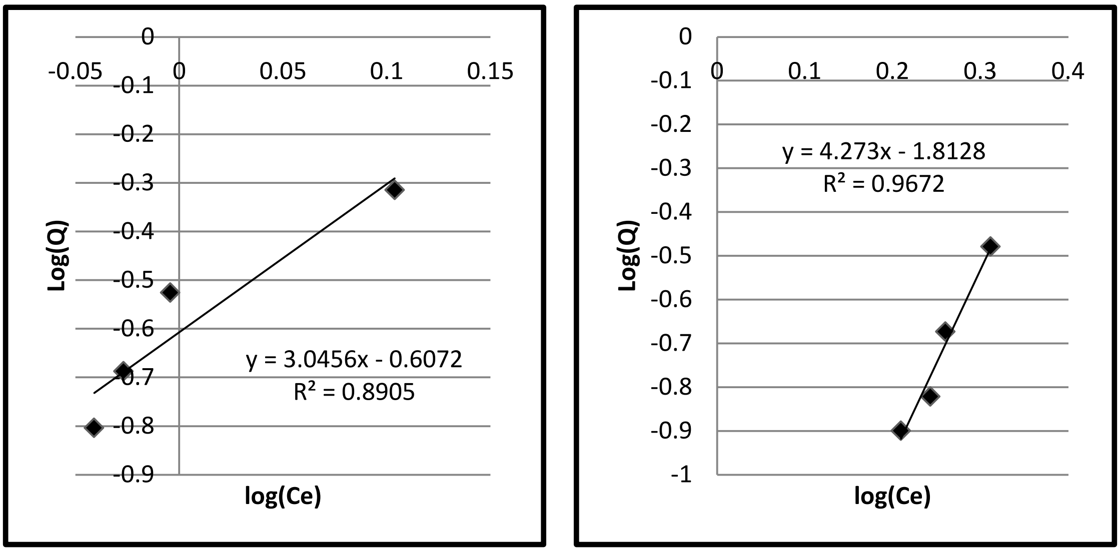
c) pH 9 d) pH Neutral

Figure A.1.3: Langmuir Isotherms for Copper at 10 mg/L C_o and at different pHs



a) pH 3

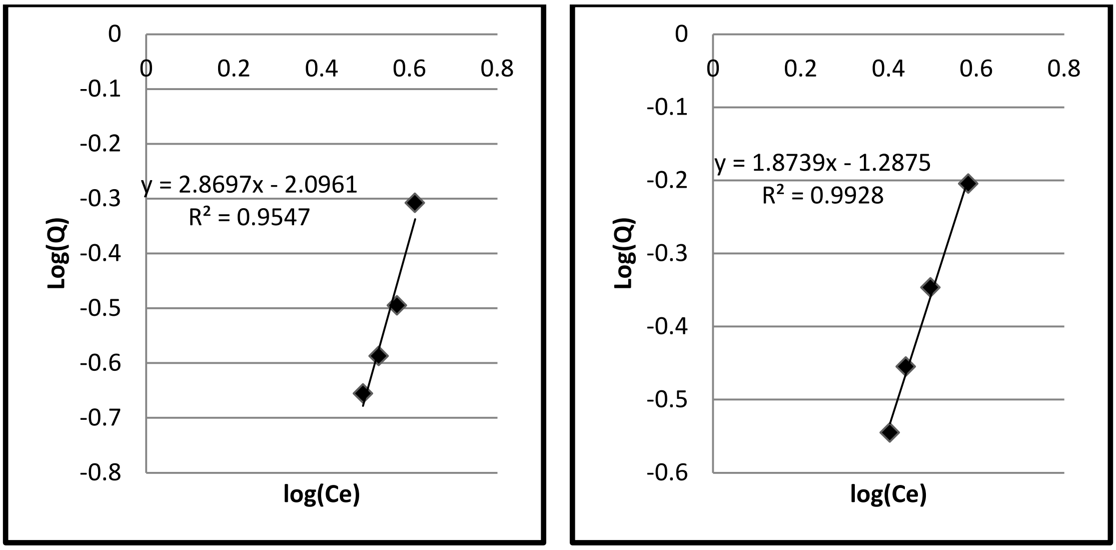
b) pH 5



c) pH 9

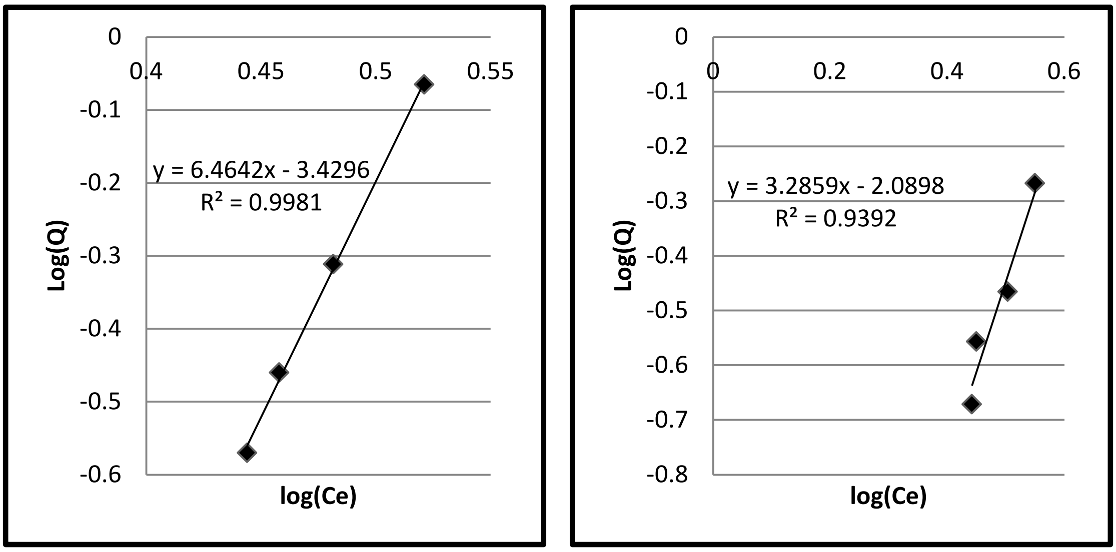
d) pH Neutral

Figure A.1.4: Freundlich Isotherms for Copper at 2 mg/L C_o and at different pHs



a) pH 3

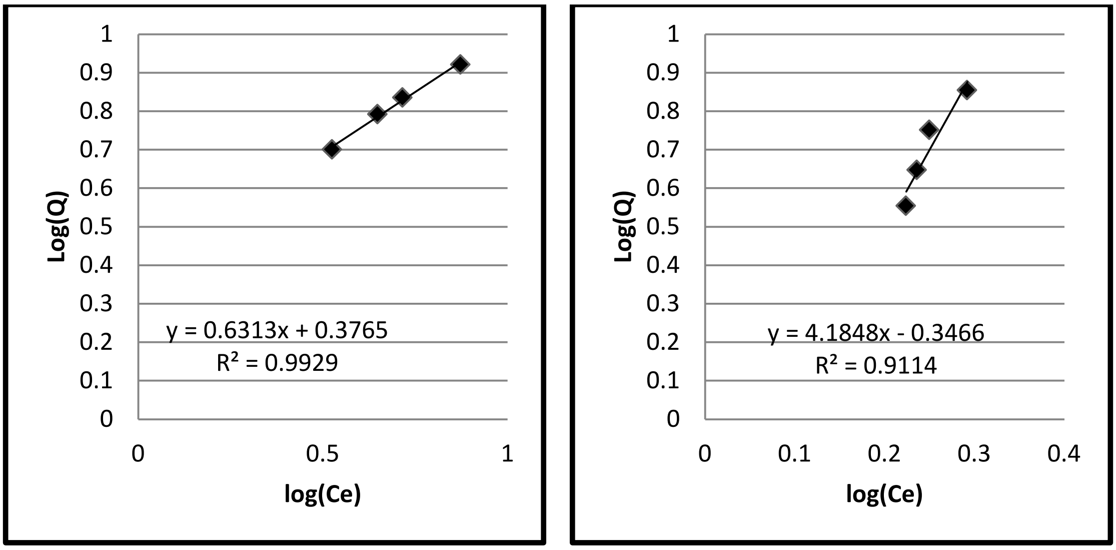
b) pH 5



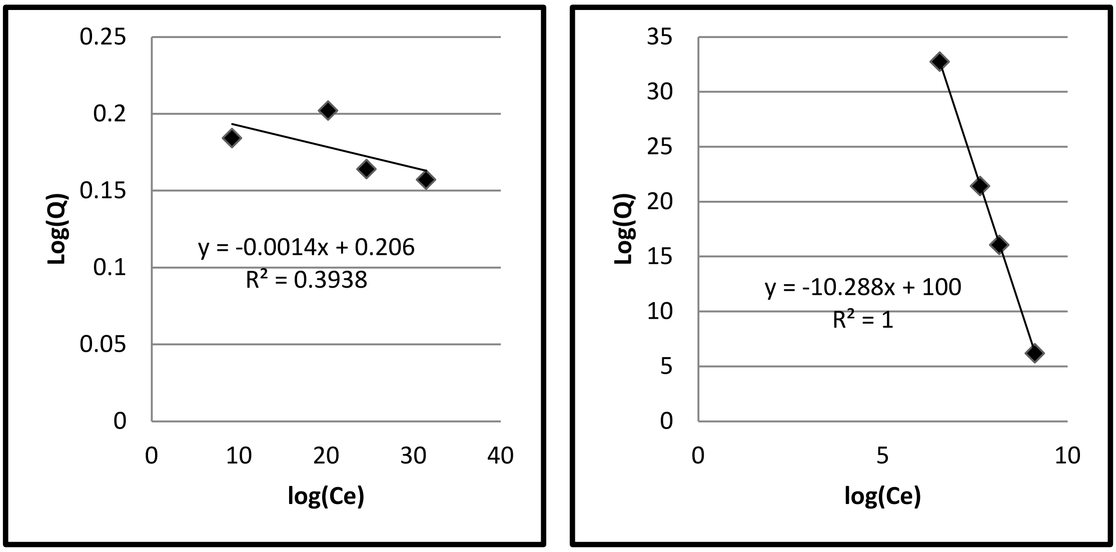
c) pH 9

d) pH Neutral

Figure A.1.5: Freundlich Isotherms for Copper at 6 mg/L C_o and at different pHs



a) pH 3 b) pH 5



c) pH 9 d) pH Neutral

Figure A.1.6: Freundlich Isotherms for Copper at 10 mg/L C_o and at different pHs

Chromium

Table A.1.13: Batch Test Results - Chromium - C_o 2 mg/L - pH3

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	2				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (g/L)	1.932	0.828	0.036	0.024	0.021
Percentage removal		57.1428	98.1366	98.7577	98.9130
Q (mg Cr/g)	None	0.4416	0.3792	0.2544	0.1911
C/C_o	1	0.4285	0.0186	0.0124	0.0108
log(Cr)	None	-0.0819	-1.4436	-1.6197	-1.6777
log(Q)	None	-0.3549	-0.4211	-0.5944	-0.7187
Cr/Q		1.875	0.0949	0.0943	0.1098

Table A.1.14: Batch Test Results - Chromium - C_o 2 mg/L - pH5

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	2				
pH	5				
Concentration of Adsorbent (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (mg/L)	1.95	0.696	0.6	0.399	0.249
Percentage removal		64.3076	69.2307	79.5384	87.2307
Q (mg Cr/g)	None	0.5016	0.27	0.2068	0.1701
C/C_o	1	0.3569	0.3076	0.2046	0.1276
log(Cr)	None	-0.1573	-0.2218	-0.3990	-0.6038
log(Q)	None	-0.2996	-0.5686	-0.6844	-0.7692
Cr/Q		1.3875	2.2222	1.9294	1.4638

Table A.1.15: Batch Test Results - Chromium – C_o 2 mg/L - pH9

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	2				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	□0
Concentration Cr (mg/L)	2.385	1.53	1.437	1.083	1.017
Percentage removal		35.8490	39.7484	54.5911	57.3584
Q (mg Cr/g)	None	0.342	0.1896	0.1736	0.1368
C/C_o	1	0.6415	0.6025	0.4540	0.4264
log(Cr)	None	0.1846	0.1574	0.0346	0.0073
log(Q)	None	-0.4659	-0.7221	-0.7604	-0.8639
Cr/Q		4.4736	7.5791	6.2384	7.4342

Table A.1.16: Batch Test Results - Chromium - C_o 2 mg/L - pH Neutral

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	2				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of Adsorbent (g/L)	0	2.5	5	7.5	10
Concentration Cr (mg/L)	2.001	1.605	1.305	1.125	0.849
Percentage removal		19.7901	34.7826	43.7781	57.5712
Q (mg Cr/g)	None	0.1584	0.1392	0.1168	0.1152
C/C_o	1	0.8020	0.6521	0.56221	0.4242
log(Cr)	None	0.2054	0.1156	0.0511	-0.0711
log(Q)	None	-0.8002	-0.8563	-0.9325	-0.9385
Cr/Q		10.1325	9.375	9.6318	7.3697

Table A.1.17: Batch Test Results - Chromium - C_o 6 mg/L - pH 3

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	6				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (g/L)	6.2	0.66	0.37	0.3	0.24
Percentage removal		89.3548	94.0322	95.1612	96.1290
Q (mg Cr/g)	None	2.216	1.166	0.7866	0.596
C/C_o	1	0.1064	0.0596	0.04838	0.0387
log(Cr)	None	-0.1804	-0.4317	-0.5228	-0.6197
log(Q)	None	0.3455	0.0666	-0.1042	-0.2247
Cr/Q		0.2978	0.3173	0.3813	0.4026

Table A.1.18: Batch Test Results - Chromium - C_o 6 mg/L - pH 5

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	6				
pH	5				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (mg/L)	7.74	3.82	3.76	2.15	1.41
Percentage removal		50.6459	51.4211	72.2222	81.7829
Q (mg Cr/g)	None	1.568	0.796	0.7453	0.633
C/C_o	1	0.4935	0.4857	0.2777	0.1821
log(Cr)	None	0.5820	0.5751	0.3324	0.1492
log(Q)	None	0.1953	-0.0990	-0.1276	-0.1985
Cr/Q		2.4362	4.7236	2.8846	2.2274

Table A.1.19: Batch Test Results - Chromium - C_o 6 mg/L - pH 9

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	6				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (mg/L)	5.72	5.55	4.65	4.61	4.28
Percentage removal		2.9720	18.7062	19.4056	25.1748
Q (mg Cr/g)	None	0.0068	0.0214	0.0148	0.0144
C/C_o	1	0.9702	0.8129	0.8059	0.7482
log(Cr)	None	0.7442	0.6674	0.6637	0.6314
log(Q)	None	-2.1674	-1.6695	-1.8297	-1.8416
Cr/Q		816.1764	217.2897	311.4864	297.2222

Table A.1.20: Batch Test Results - Chromium - C_o 6 mg/L - pH Neutral

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	6				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (mg/L)	7.04	5.91	5.07	4.61	3.99
Percentage removal		16.0511	27.9829	34.5170	43.3238
Q (mg Cr/g)	None	0.0452	0.0394	0.0324	0.0305
C/C_o	1	0.8394	0.7201	0.6548	0.5667
log(Cr)	None	0.7715	0.7050	0.6637	0.6009
log(Q)	None	-1.3448	-1.4045	-1.4894	-1.5157
Cr/Q		130.7522	128.6802	142.2839	130.8196

Table A.1.21: Batch Test Results - Chromium – C_o 10 mg/L - pH 3

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	10				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (g/L)	10.96	0.58	0.54	0.32	0.06
Percentage removal		94.7080	95.0729	97.0803	99.4525
Q (mg Cr/g)	None	4.152	2.084	1.4186	1.09
C/C_o	1	0.0529	0.0492	0.0292	0.0054
log(Cr)	None	-0.2365	-0.2676	-0.4948	-1.2218
log(Q)	None	0.6182	0.3188	0.1518	0.0374
Cr/Q		0.1396	0.2591	0.2255	0.0550

Table A.1.22: Batch Test Results - Chromium - C_o 10 mg/L - pH 5

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	10				
pH	5				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (mg/L)	11.72	6.48	5.52	4.08	3.82
Percentage removal		44.7098	52.9010	65.1877	67.4061
Q (mg Cr/g)	None	2.096	1.24	1.0186	0.79
C/C_o	1	0.5529	0.4709	0.3481	0.3259
log(Cr)	None	0.8115	0.7419	0.6106	0.5820
log(Q)	None	0.3213	0.0934	0.0080	-0.1023
Cr/Q		3.0916	4.4516	4.0052	4.8354

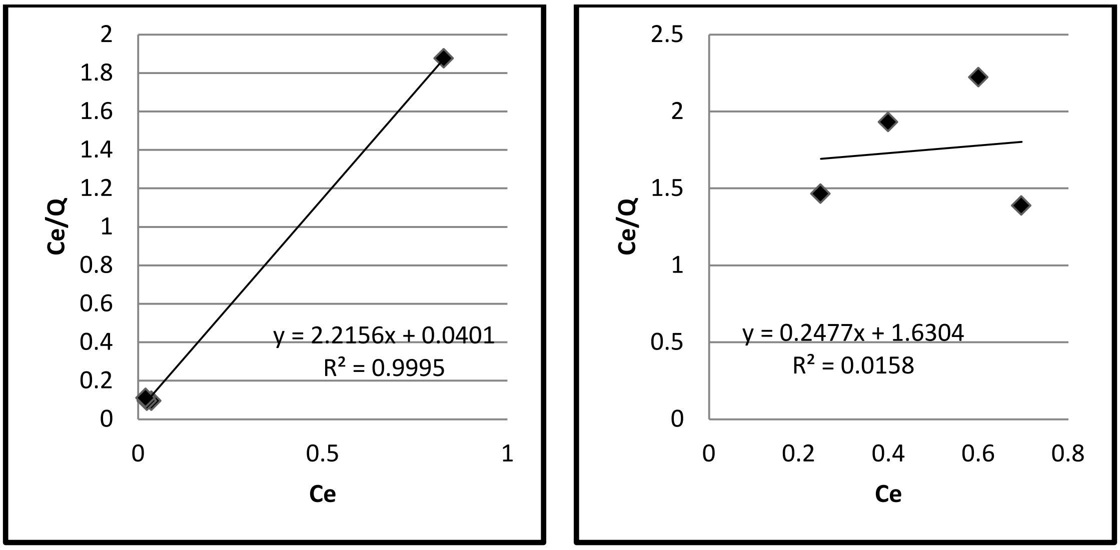
Table A.1.23: Batch Test Results - Chromium - C_o 10 mg/L - pH 9

Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	10				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Cr (mg/L)	9.4	8.22	7.64	6.42	5.48
Percentage removal		12.5531	18.7234	31.7021	41.7021
Q (mg Cr/g)	None	0.0236	0.0176	0.0198	0.0196
C/C_o	1	0.8744	0.8127	0.6829	0.5829
log(Cr)	None	0.9148	0.8831	0.8075	0.7387
log(Q)	None	-1.6270	-1.7544	-1.7018	-1.7077
Cr/Q		348.3050	434.0909	323.1543	279.5918

Table A.1.24: Batch Test Results - Chromium - C_o 10 mg/L - pH Neutral

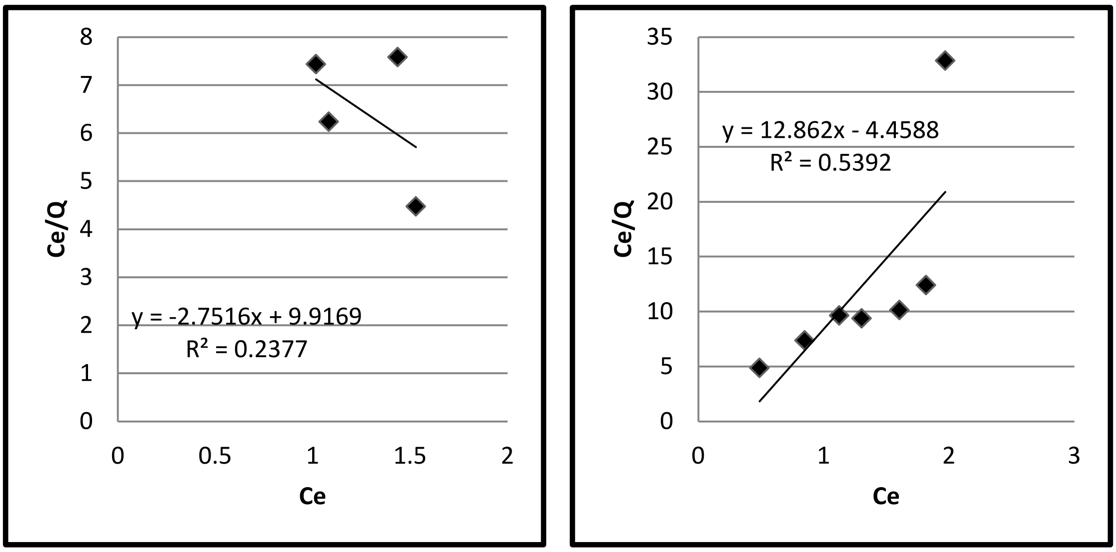
Metal	**Chromium (Cr)**				
Concentration of Metal (mg/L)	10				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Conc from Hach (mg/L)	10.88	10.04	9.7	7.8	6.56
Percentage removal		7.7205	10.8455	28.3088	39.7058
Q (mg Cr/g)	None	0.0168	0.0118	0.0205	0.0216
C/C_o	1	0.9227	0.8915	0.7169	0.6029
log(Cr)	None	1.0017	0.9867	0.8920	0.8169
log(Q)	None	-1.7746	-1.9281	-1.6875	-1.6655
Cr/Q		597.6190	822.0338	379.8701	303.7037

Adsorption Isotherms



a) pH 3

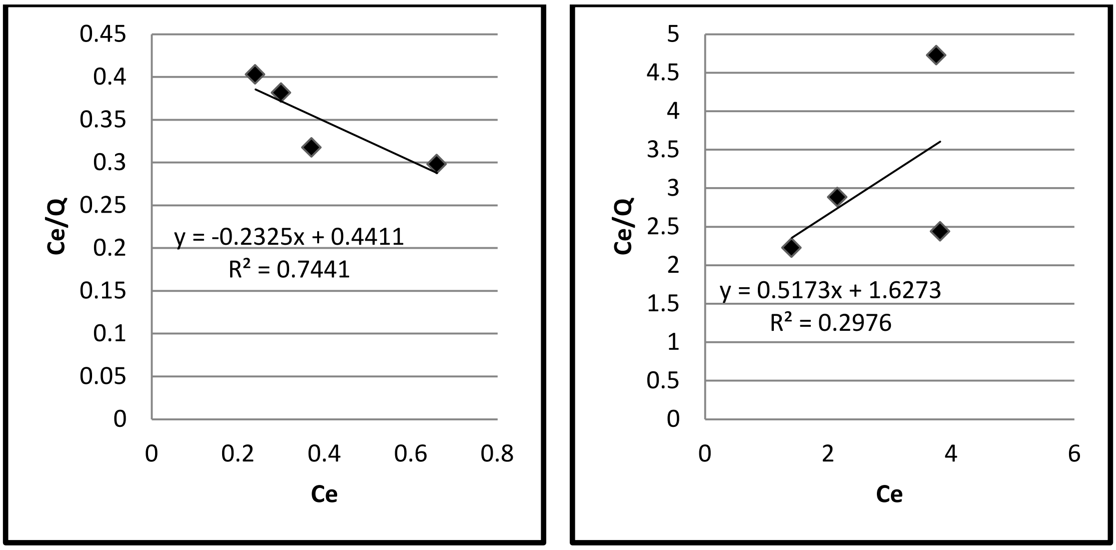
b) pH 5



c) pH 9

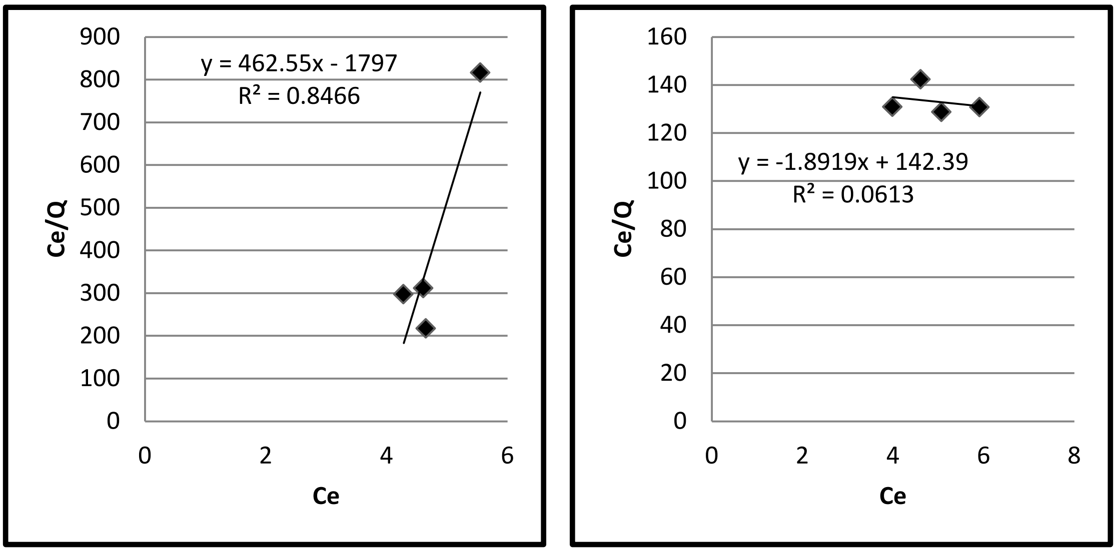
d) pH Neutral

Figure A.1.7: Langmuir Isotherms for Chromium at 2 mg/L C_o and at different pHs



a) pH 3

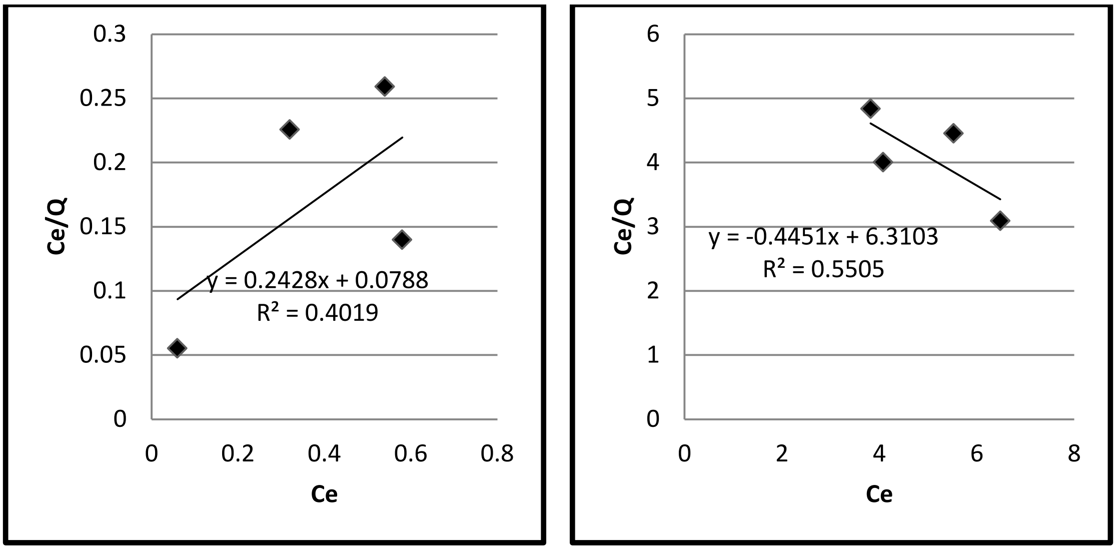
b) pH 5



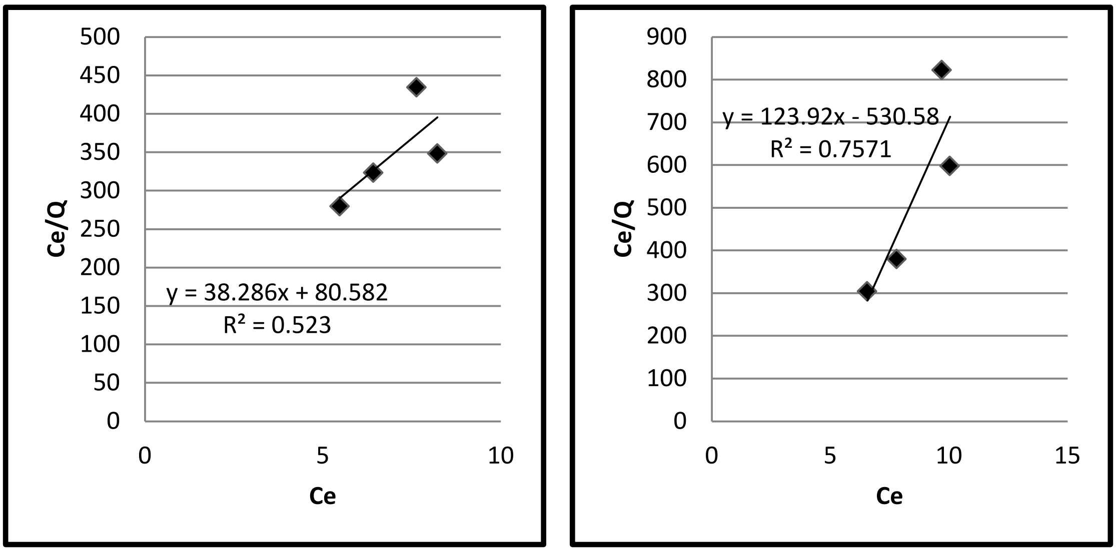
c) pH 9

d) pH Neutral

Figure A.1.8: Langmuir Isotherms for Chromium at 6 mg/L C_o and at different pHs

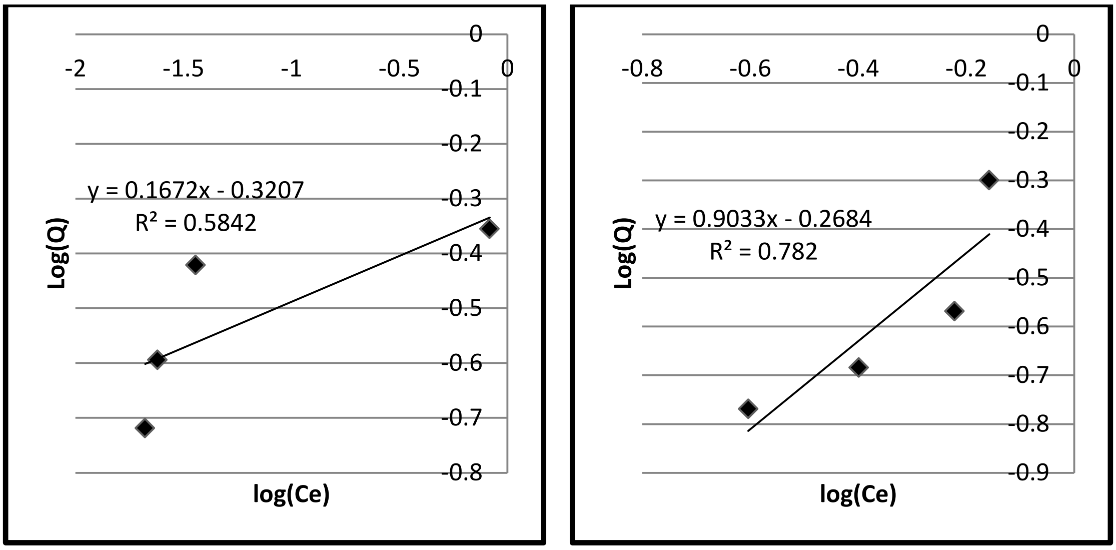


a) pH 3 b) pH 5

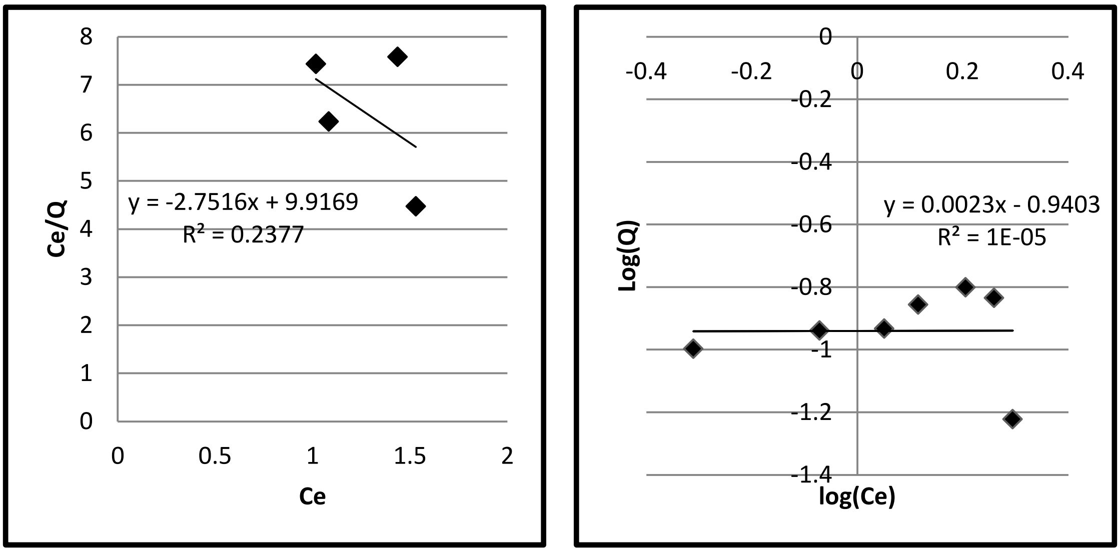


c) pH 9 d) pH Neutral

Figure A.1. 9: Langmuir Isotherms for Chromium at 10 mg/L C_o and at different pHs

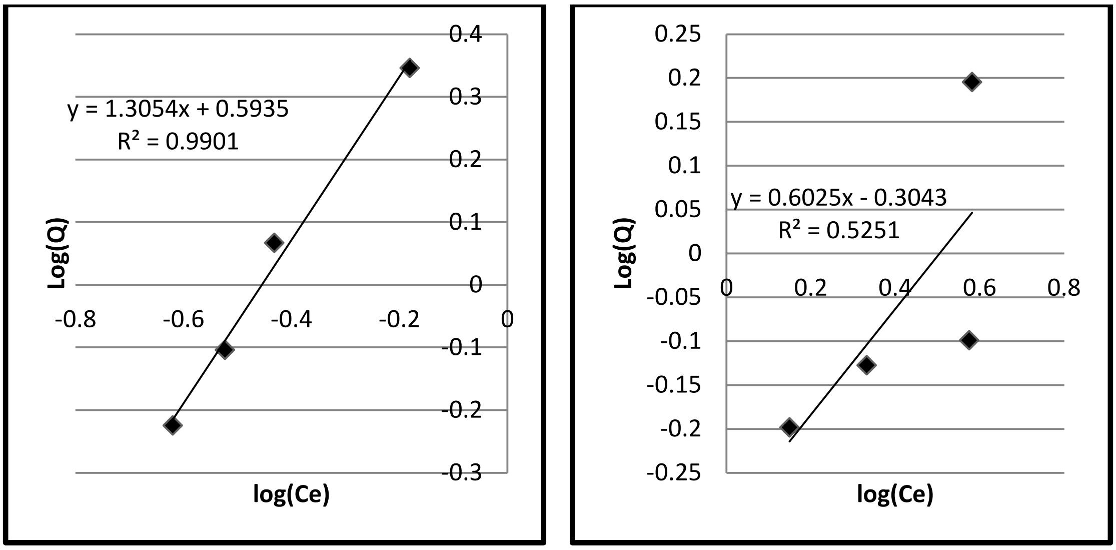


a) pH 3 b) pH 5



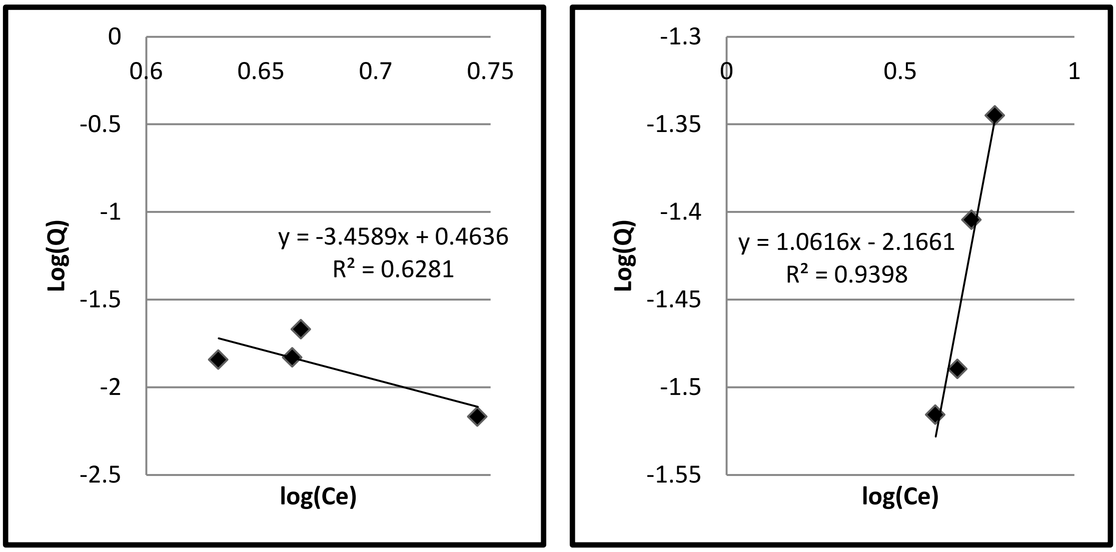
c) pH 9 d) pH Neutral

Figure A.1.10: Freundlich Isotherms for Chromium at 2mg/L C_o at different pHs



a) pH 3

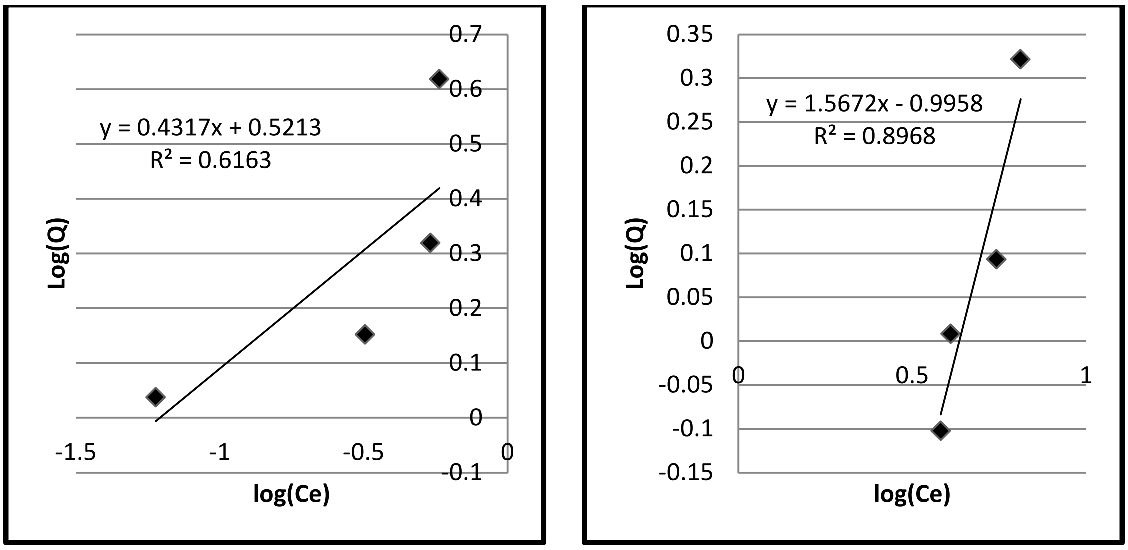
b) pH 5



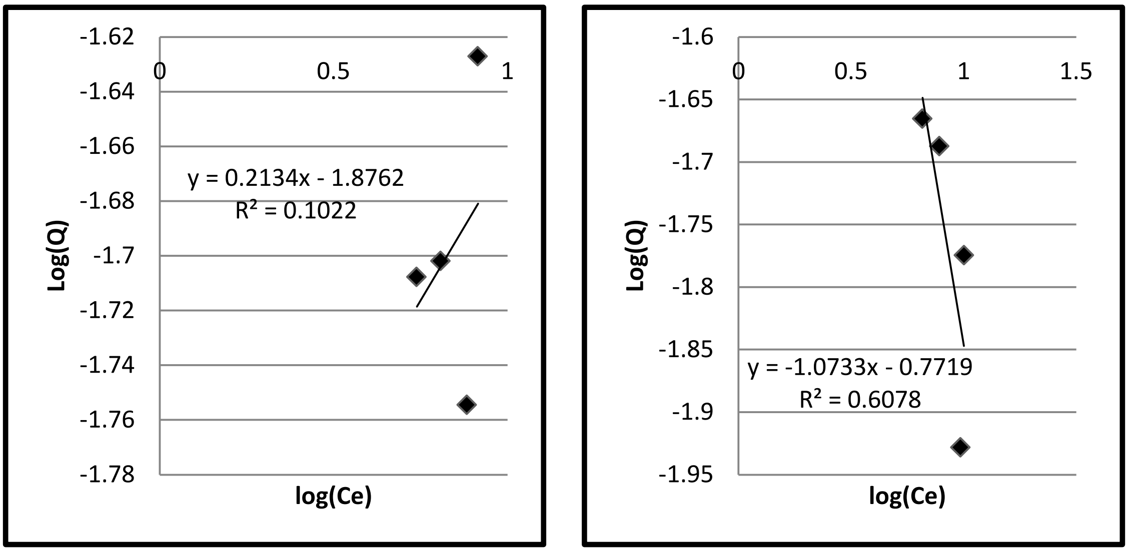
c) pH 9

d) pH Neutral

Figure A.1.11: Freundlich Isotherms for Chromium at 6 mg/L C_o at different pHs



a) pH 3 b) pH 5



c) pH 9 d) pH Neutral

Figure A.1.12: Freundlich Isotherms for Chromium at 10 mg/L C_o at different pHs

Zinc

Table A.1.25: Batch Test Results - Zinc - C_o 2 mg/L - pH 3

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	2				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (g/L)	2.27	1.92	1.69	1.45	1.19
Percentage removal		15.4185	25.5506	36.1233	47.5771
Q (mg Zn/g)	None	0.14	0.116	0.1093	0.108
C/C_o	1	0.8458	0.7445	0.6387	0.5242
log(Zn)	None	0.2833	0.2278	0.1613	0.0755
log(Q)	None	-0.8538	-0.9355	-0.9612	-0.9665
Zn/Q		13.7142	14.5689	13.26219	11.0185

Table A.1.26: Batch Test Results - Zinc - C_o 2 mg/L - pH 5

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	2				
pH	5				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (g/L)	2.62	1.68	1.33	1.1	0.92
Percentage removal		35.8778	49.2366	58.0152	64.8854
Q (mg Zn/g)	None	0.376	0.258	0.2026	0.17
C/C_o	1	0.6412	0.5076	0.4198	0.3511
log(Zn)	None	0.2253	0.1238	0.0414	-0.0362
log(Q)	None	-0.4248	-0.5883	-0.6932	-0.7695
Zn/Q		4.4680	5.1550	5.4276	5.4117

Table A.1.27: Batch Test Results - Zinc - C_o 2 mg/L - pH 9

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	2				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (g/L)	2.18	0.78	0.56	0.44	0.31
Percentage removal		64.2202	74.3119	79.8165	85.7798
Q (mg Zn/g)	None	0.5600	0.3240	0.2320	0.1870
C/C_o	1	0.3578	0.2569	0.2018	0.1422
log(Zn)	None	-0.1079	-0.2518	-0.3565	-0.5086
log(Q)	None	-0.2518	-0.4895	-0.6345	-0.7282
Zn/Q		1.3929	1.7284	1.8966	1.6578

Table A.1. 28: Batch Test Results - Zinc - C_o 2 mg/L - pH Neutral

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	2				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (g/L)	2.26	1.26	0.73	0.55	0.42
Percentage removal		44.2477	67.6991	75.6637	81.4159
Q (mg Zn/g)	None	0.4	0.306	0.228	0.184
C/C_o	1	0.5575	0.3230	0.2433	0.1858
log(Zn)	None	0.1003	-0.1366	-0.2596	-0.3767
log(Q)	None	-0.3979	-0.5142	-0.6420	-0.7351
Zn/Q		3.15	2.3856	2.4122	2.2826

Table A.1.29: Batch Test Results - Zinc - C_o 6 mg/L - pH 3

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	6				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (mg/L)	6.6	5.98	4.96	4.34	4.48
Percentage removal		9.3939	24.8485	34.2424	32.1212
Q (mg Zn/g)	None	0.1240	0.1640	0.1507	0.1060
C/C_o	1	0.9061	0.7515	0.6576	0.6788
log(Zn)	None	0.7767	0.6955	0.6375	0.6513
log(Q)	None	-0.9066	-0.7852	-0.8220	-0.9747
Zn/Q		48.2258	30.2439	28.8053	42.2642

Table A.1.30: Batch Test Results - Zinc - C_o 6 mg/L - pH 5

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	6				
pH	5				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (mg/L)	6.54	4.88	4.02	3.6	3.32
Percentage removal		25.3823	38.5321	44.9541	49.2355
Q (mg Zn/g)	None	0.6640	0.5040	0.3920	0.3220
C/C_o	1	0.7462	0.6147	0.5505	0.5076
log(Zn)	None	1.4045	1.5858	1.6528	1.6923
log(Q)	None	-0.1778	-0.2976	-0.4067	-0.4921
Zn/Q		7.3494	7.9762	9.1837	10.3106

Table A.1.31: Batch Test Results - Zinc - C_o 6 mg/L - pH 9

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	6				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (g/L)	4.88	1.58	1.22	0.92	0.8
Percentage removal		67.6230	75.0000	81.1475	83.6066
Q (mg Zn/g)	None	1.3200	0.7320	0.5280	0.4080
C/C_o	1	0.3238	0.2500	0.1885	0.1639
log(Zn)	None	0.1987	0.0864	-0.0362	-0.0969
log(Q)	None	0.1206	-0.1355	-0.2774	-0.3893
Zn/Q		1.1970	1.6667	1.7424	1.9608

Table A.1. 32: Batch Test Results - Zinc - C_o 6 mg/L - pH Neutral

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	6				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (g/L)	5.5	2.64	2.32	2.12	2.04
Percentage removal		52.0000	57.8182	61.4545	62.9091
Q (mg Zn/g)	None	1.1440	0.6360	0.4507	0.3460
C/C_o	1	0.4800	0.4218	0.3855	0.3709
log(Zn)	None	0.4216	0.3655	0.3263	0.3096
log(Q)	None	0.0584	-0.1965	-0.3461	-0.4609
Zn/Q		2.3077	3.6478	4.7041	5.8960

Table A.1. 33: Batch Test Results - Zinc - C_o 10 mg/L - pH 3

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	10				
pH	3				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (mg/L)	10.12	8.84	7.8	7.56	7.28
Percentage removal		12.6482	22.9249	25.2964	28.0632
Q (mg Zn/g)	None	0.1280	0.1160	0.0853	0.0710
C/C_o	1	0.8735	0.7708	0.7470	0.7194
log(Zn)	None	0.9465	0.8921	0.8785	0.8621
log(Q)	None	-0.8928	-0.9355	-1.0689	-1.1487
Zn/Q		69.0625	67.2414	88.5938	102.5352

Table A.1.34: Batch Test Results - Zinc - C_o 10 mg/L - pH 5

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	10				
pH	5				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (mg/L)	9.68	7.92	7.28	6.84	6.16
Percentage removal		18.1818	24.7934	29.3388	36.3636
Q (mg Zn/g)	None	0.7040	0.4800	0.3787	0.3520
C/C_o	1	0.8182	0.7521	0.7066	0.6364
log(Zn)	None	0.8987	0.8621	0.8351	0.7896
log(Q)	None	-0.1524	-0.3188	-0.4217	-0.4535
Zn/Q		11.2500	15.1667	18.0634	17.5000

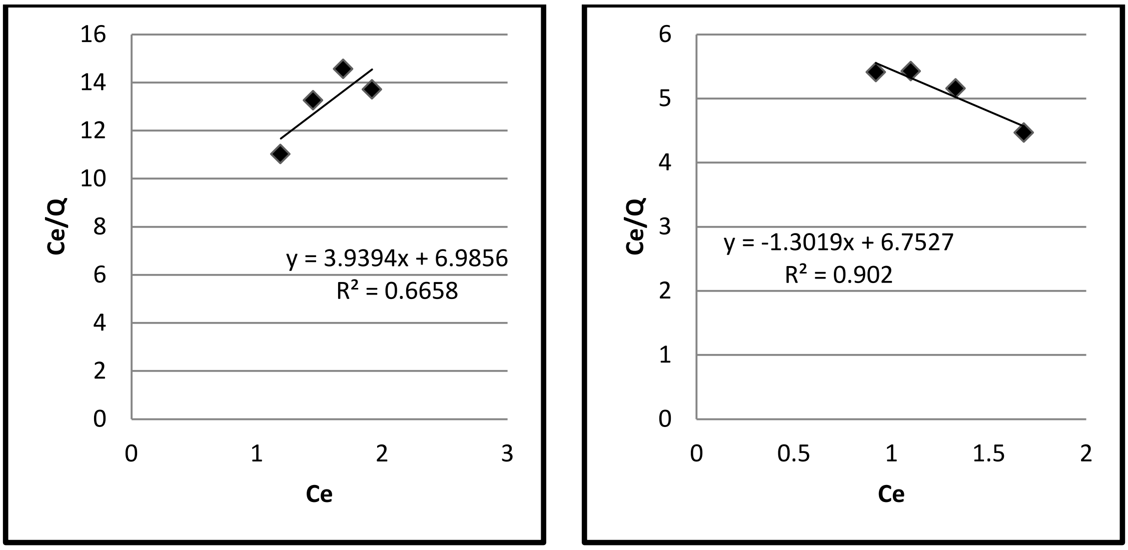
Table A.1.035: Batch Test Results - Zinc - C_o 10 mg/L - pH 9

Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	10				
pH	9				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (g/L)	9.56	2.64	1.96	1.92	1.68
Percentage removal		72.3849	79.4979	79.9163	82.4268
Q (mg Zn/g)	None	2.7680	1.5200	1.0187	0.7880
C/C_o	1	0.2762	0.2050	0.2008	0.1757
log(Zn)	None	0.4216	0.2923	0.2833	0.2253
log(Q)	None	0.4422	0.1818	0.0080	-0.1035
Zn/Q		0.9538	1.2895	1.8848	2.1320

Table A.1.36: Batch Test Results - Zinc - C_o 10 mg/L - pH Neutral

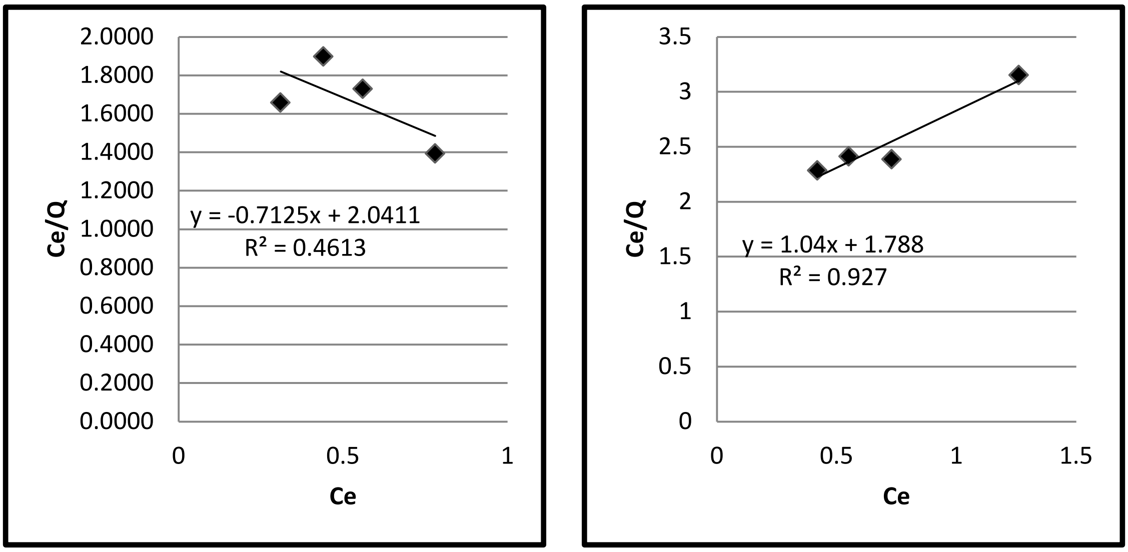
Metal	**Zinc (Zn)**				
Concentration of Metal (mg/L)	10				
pH	Neutral				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10
Concentration Zn (g/L)	10.68	5.56	4.68	4.2	3.92
Percentage removal		47.9401	56.1798	60.6742	63.2959
Q (mg Zn/g)	None	2.0480	1.2000	0.8640	0.6760
C/C_o	1	0.5206	0.4382	0.3933	0.3670
log(Zn)	None	0.7451	0.6702	0.6232	0.5933
log(Q)	None	0.3113	0.0792	-0.0635	-0.1701
Zn/Q		2.7148	3.9000	4.8611	5.7988

Adsorption Isotherms



a) pH 3

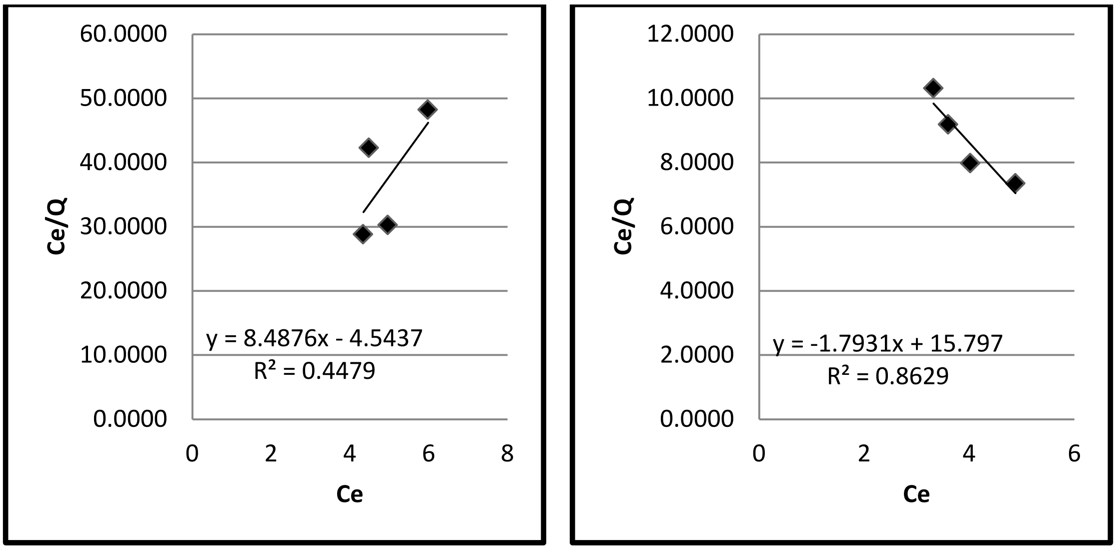
b) pH 5



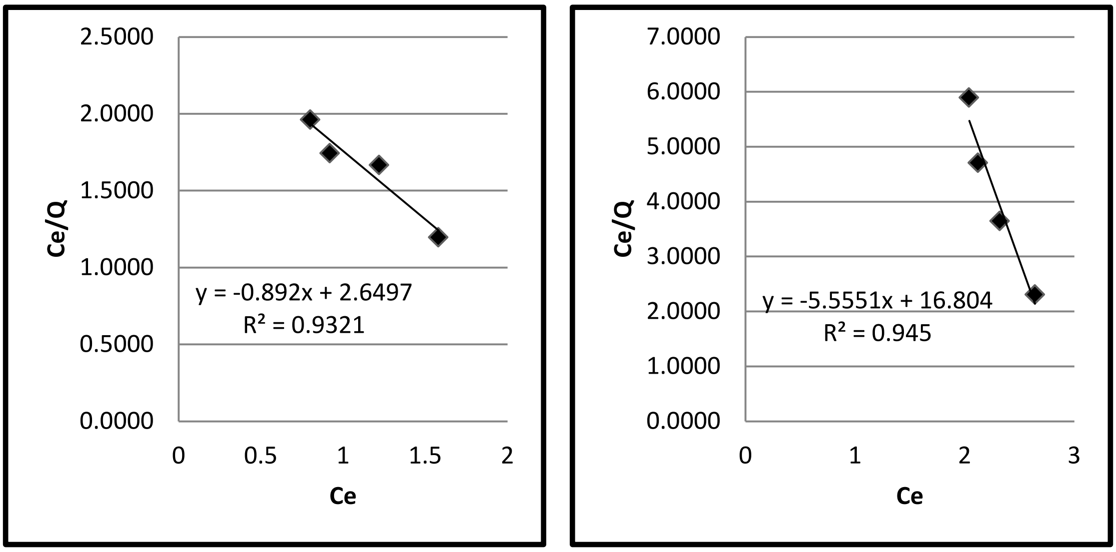
c) pH 9

d) pH Neutral

Figure A.113: Langmuir Isotherm for Zinc at 2 mg/L C_o at different pHs

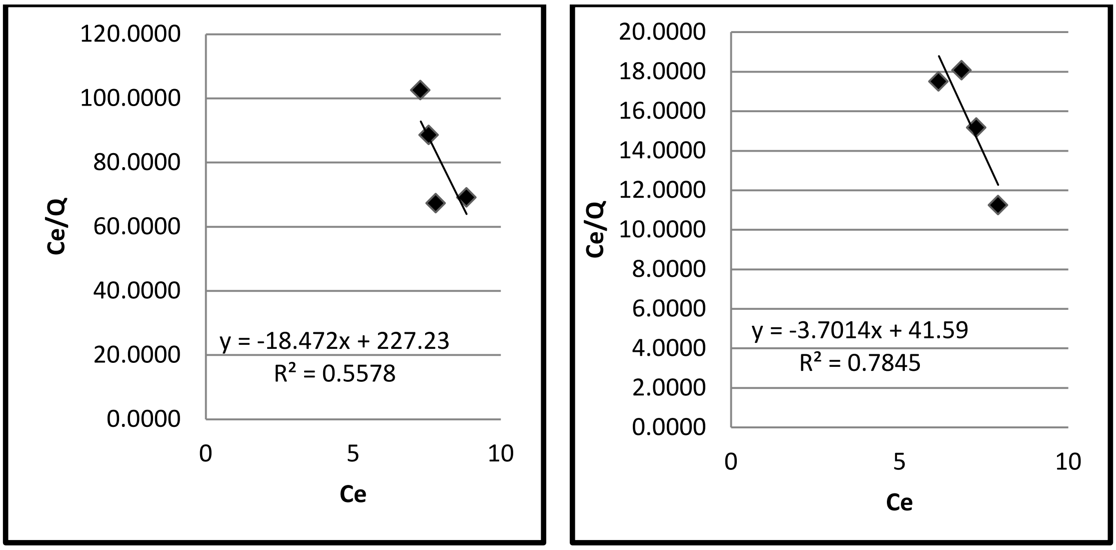


a) pH 3 b) pH 5

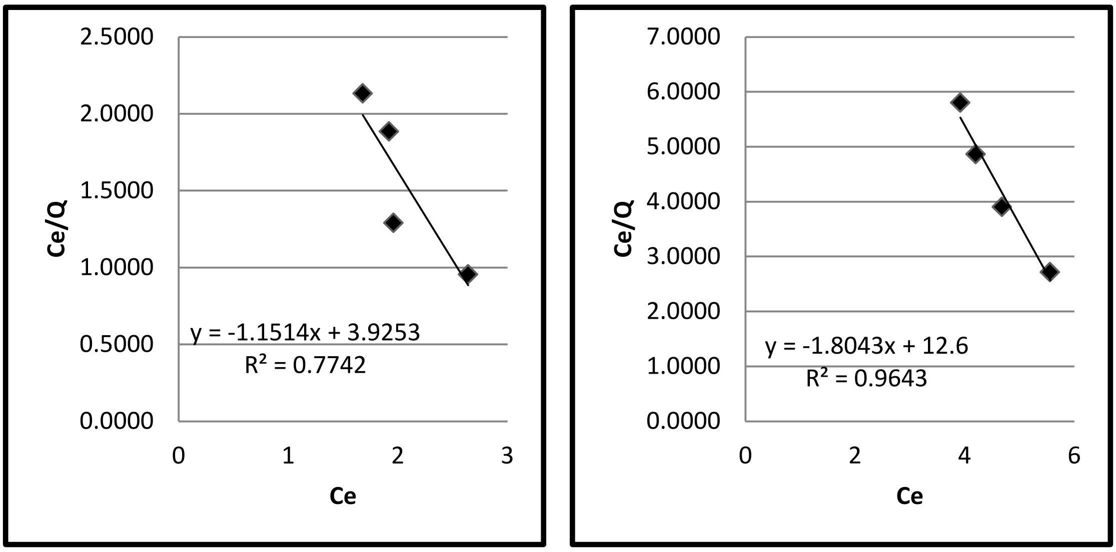


c) pH 9 d) pH Neutral

Figure A.1.14: Langmuir Isotherm for Zinc at 6 mg/L C_o at different pHs

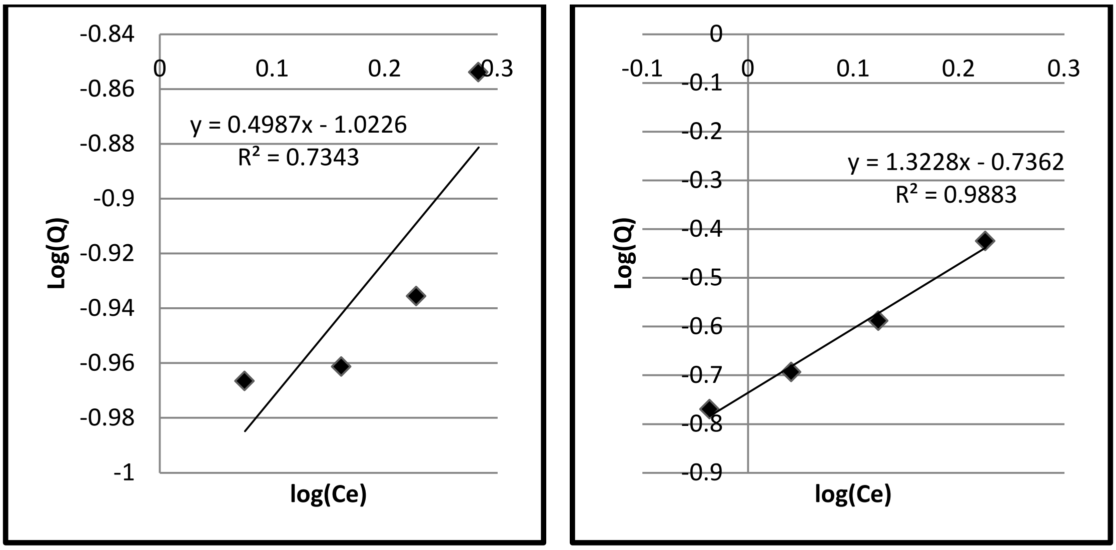


a) pH 3 b) pH 5



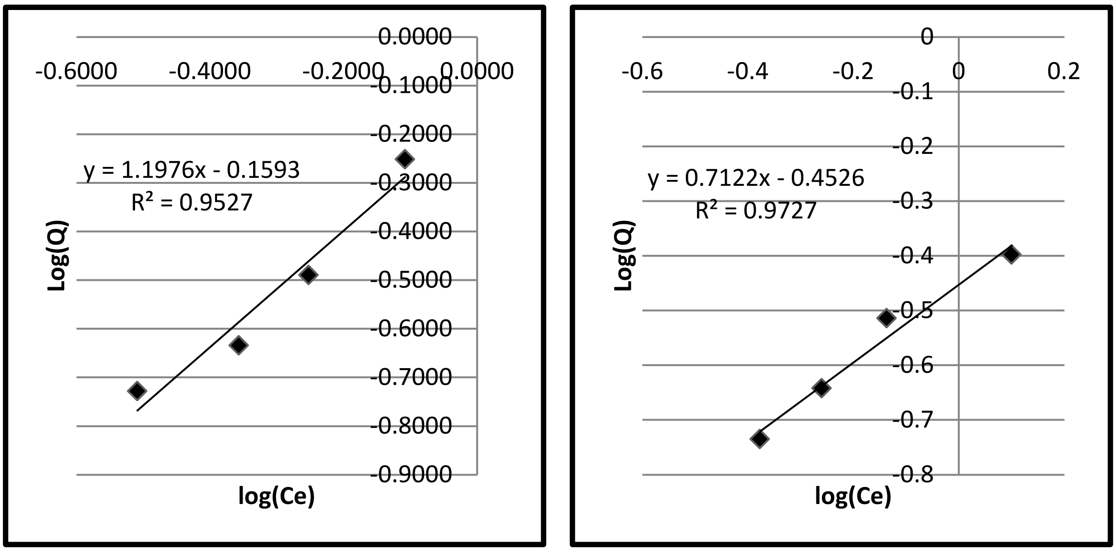
c) pH 9 d) pH Neutral

Figure A.1.15: Langmuir Isotherm for Zinc at 10 mg/L C_o at different pHs



a) pH 3

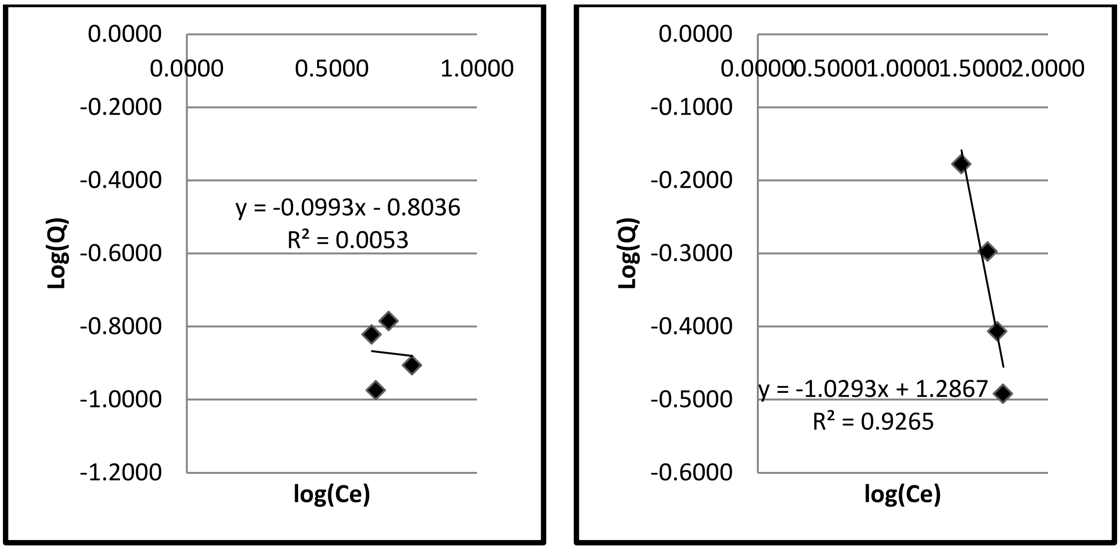
b) pH 5



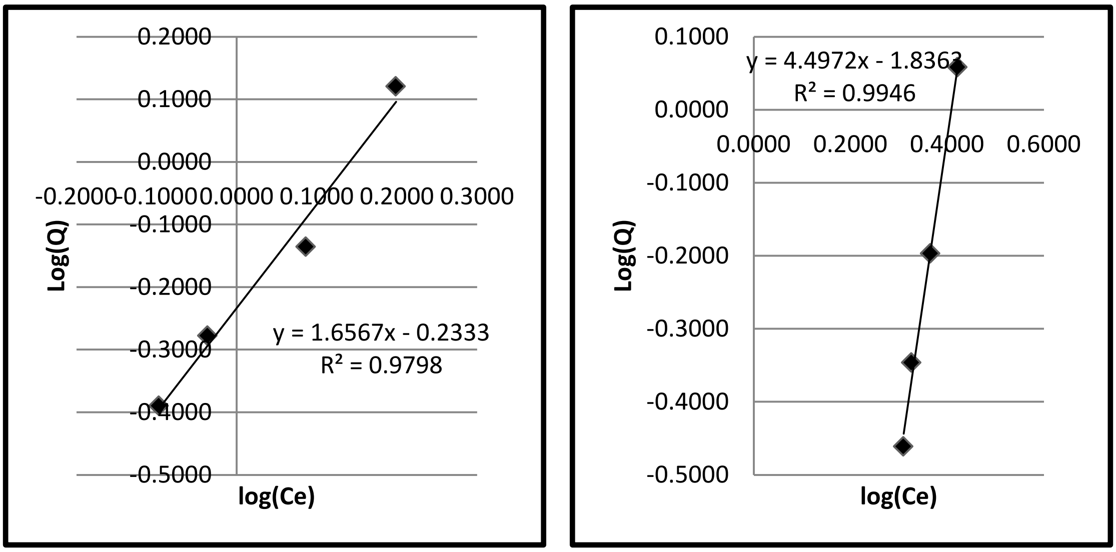
c) pH 9

d) pH Neutral

Figure A.1.16: Freundlich Isotherm for Zinc at 2 mg/L C_o at different pHs

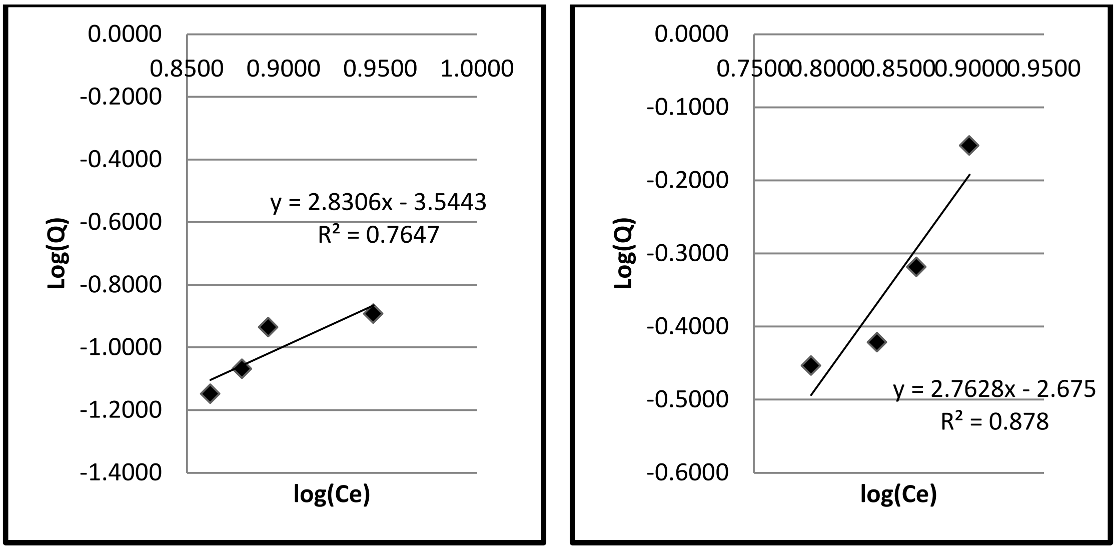


a) pH 3 b) pH 5

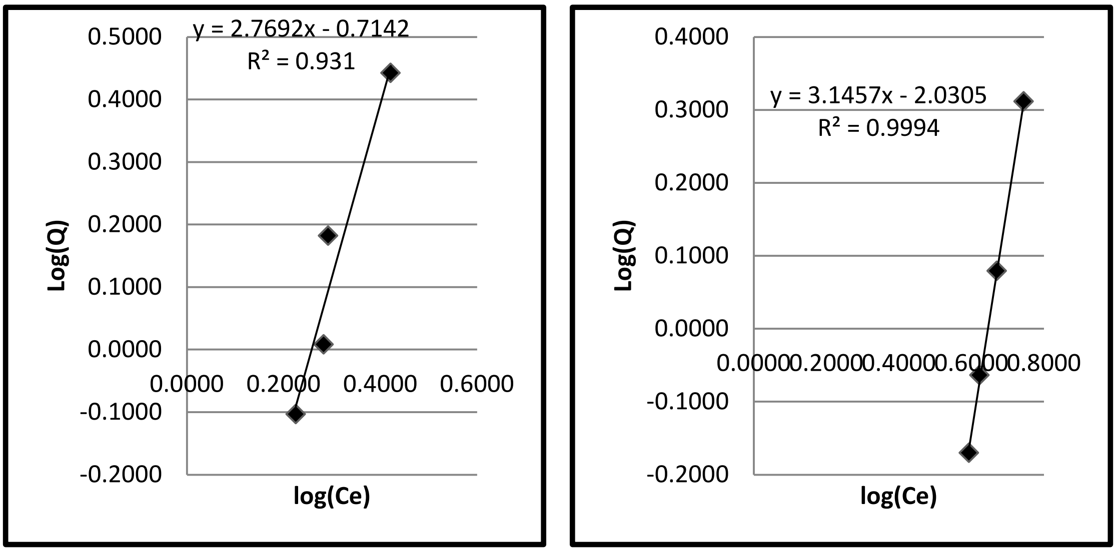


c) pH 9 d) pH Neutral

Figure A.1.17: Freundlich Isotherm for Zinc at 6 mg/L C_o at different pHs



a) pH 3 b) pH 5



c) pH 9 d) pH Neutral

Figure A.1.18: Freundlich Isotherm for Zinc at 10 mg/L C_o at different pHs

Competitive

Table A.1.37: Batch Test Results - Competitive - C_o 2 mg/L - pH Neutral

Metal	**Copper (Cu)**					**Chromium (Cr)**					**Zinc (Zn)**				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2	0	0.5	1	1.5	2	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10	0	2.5	5	7.5	10	0	2.5	5	7.5	10
Concentration Metal (mg/L)	1.8	0.94	0.92	0.87	0.31	1.53	0.232	0.089	0.08	0.026	2.65	1.19	0.86	0.69	0.63
Percentage removal		47.78	48.89	51.67	82.78		84.88	94.20	94.78	98.31		55.09	67.55	73.96	76.2264
Q (mg Metal/g)		0.344	0.176	0.124	0.149		0.521	0.342	0.229	0.177		0.584	0.358	0.261	0.202
C/C_o	1	0.52	0.51	0.48	0.17	1	0.15	0.06	0.05	0.02	1	0.45	0.48	0.38	0.35
log(Metal)		-0.027	-0.036	-0.061	-0.509		-0.634	-1.051	-1.097	-1.585		0.075	-0.065	-0.161	-0.201
log(Q)		-0.463	-0.754	-0.907	-0.829		-0.283	-0.467	-0.639	-0.751		-0.234	-0.446	-0.583	-0.695
Metal/Q		2.733	5.227	7.016	2.081		0.445	0.260	0.349	0.147		2.038	2.402	2.640	3.119

Table A.1.38: Batch Test Results - Competitive - C_o 2 mg/L - pH 3

Metal	**Copper (Cu)**					**Chromium (Cr)**					**Zinc (Zn)**				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2	0	0.5	1	1.5	2	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10	0	2.5	5	7.5	10	0	2.5	5	7.5	10
Concentration Metal (mg/L)	1.65	1.43	1	0.96	0.9	1.548	0.068	0.037	0.03	0.024	3.43	2.84	2.56	2.12	1.93
Percentage removal		20.56	44.44	46.667	50.00		95.61	97.61	98.06	98.45		17.20	25.36	38.19	43.73
Q (mg Metal/g)		0.088	0.130	0.092	0.075		0.592	0.302	0.202	0.152		0.236	0.174	0.174	0.150
C/C_o	1	0.87	0.61	0.58	0.54	1	0.04	0.024	0.02	0.01	1	0.83	0.75	0.62	0.56
log(Metal)		0.155	0.000	-0.017	-0.049		-1.167	-1.431	-1.522	-1.619		0.453	0.408	0.326	0.285
log(Q)		-1.055	-0.886	-1.036	-1.124		-0.227	-0.519	-0.693	-0.817		-0.627	-0.759	-0.757	-0.823
Metal/Q		16.250	7.692	10.434	12.00		0.114	0.122	0.148	0.157		12.033	14.712	12.137	12.866

Table A.1. 39: Batch Test Results - Competitive - C_o 2 mg/L - pH 9

Metal	**Copper (Cu)**					**Chromium (Cr)**					**Zinc (Zn)**				
Concentration of PTL (g/200mL)	0	0.5	1	1.5	2	0	0.5	1	1.5	2	0	0.5	1	1.5	2
Concentration of PTL (g/L)	0	2.5	5	7.5	10	0	2.5	5	7.5	10	0	2.5	5	7.5	10
Concentration Metal (mg/L)	2.58	0.98	0.92	0.81	0.79	1.76	0.857	0.428	0.331	0.212	2.27	0.72	0.52	0.46	0.37
Percentage removal		62.0155	64.3411	68.6047	69.3798		51.3068	75.6818	81.1932	87.9545		68.2819	77.0925	79.7357	83.7004
Q (mg Metal/g)		0.6400	0.3320	0.2360	0.1790		0.3612	0.2664	0.1905	0.1548		0.6200	0.3500	0.2413	0.1900
C/C_o	1	0.3798	0.3566	0.3140	0.3062	1	0.4869	0.2432	0.1881	0.1205	1	0.3172	0.2291	0.2026	0.1630
log(Metal)		-0.0088	-0.0362	-0.0915	-0.1024		-0.0670	-0.3686	-0.4802	-0.6737		-0.1427	-0.2840	-0.3372	-0.4318
log(Q)		-0.1938	-0.4789	-0.6271	-0.7471		-0.4423	-0.5745	-0.7200	-0.8102		-0.2076	-0.4559	-0.6174	-0.7212
Metal/Q		1.5313	2.7711	3.4322	4.4134		2.3726	1.6066	1.7372	1.3695		1.1613	1.4857	1.9061	1.9474

Table A.1.40: Analytical Method (Compare Hach and AA/ICP)

10mg/L	**Copper**		**Chromium**		**Zinc**	
Bottles	Hach	AA	Hach	AA	Hach	ICP
1	10.52	10.789	10.21	9.992	11.64	10.3003
2	4.64	5.897	9.05	9.173	7.56	5.16712
3	4.3	5.129	8.71	8.864	4.38	4.73359
4	4.21	4.571	8.64	8.741	4.02	4.74905
5	3.88	4.609	8.39	8.262	3.88	4.44723
6mg/L						
Bottles						
1	6.26	7.69	5.665	5.68	6.02	6.36958
2	3.45	3.649	5.125	5.114	2.93	3.29232
3	2.95	3.098	4.94	5.277	2.53	3.00217
4	2.74	2.783	4.87	5.052	2.11	2.88103
5	2.73	2.699	4.84	5.114	2.08	2.83999
2mg/L						
Bottles						
1	2.34	2.426	2.04	1.988	2.04	2.24709
2	1.17	1.173	2.2	1.973	1.11	1.04972
3	0.97	1.006	2.05	1.864	1.1	1.02673
4	0.94	0.912	2	1.811	0.91	1.01203
5	0.92	0.927	1.3	1.562	0.9	0.94741

A.2. COLUMN TESTS

Table A.2.41: Column Test Results - Competitive - C_o 2 mg/L - pH Neutral

Flow (mL/min)	**12**											
Volume (cm3)	79.52											
m after - m before (g)	36.169											
Hours	0.00	4.00	22.00	30.00	44.50	46.50	49.50	74.50	96.50	121.00	124.00	140.50
Minutes	0	240	1320	1800	2670	2790	2970	4470	5790	7260	7440	8430
Volume passed total (ml)	0.00	2880	15840	21600	32040	33480	35640	53640	69480	87120	89280	101160.00
# of columns	0.00	36.22	199.20	271.63	402.92	421.03	448.19	674.55	873.74	1095.57	1122.74	1272.13
# of pore volumes	0.00	79.63	437.94	597.20	885.84	925.65	985.37	1483.04	1920.98	2408.69	2468.41	2796.87
Metal												
Cu	2.58	0.12	0.06	0.05	0.2	0.11	0.06	0.33	0.1	0.18	0.14	0.17
Cr	1.678	1.243	1.605	1.54	1.539	1.577	1.604	1.609	1.655	1.594	1.674	1.662
Zn	2.41	0.25	1.06	1.17	1.3	1.38	1.41	1.67	1.87	2.23	2.4	2.46
C/C_o Cu	0	0.0465	0.0232	0.0193	0.0775	0.0426	0.0232	0.1279	0.0387	0.0697	0.0542	0.0658
C/C_o Cr	0	0.7407	0.9564	0.9177	0.9171	0.9398	0.9558	0.9588	0.9862	0.9499	0.9976	0.9904
C/C_o Zn	0	0.1037	0.4398	0.4854	0.5394	0.5724	0.5850	0.6929	0.7759	0.9253	0.9958	1.0207

Table A.2.42: Column Test Results - Competitive - C_o 2 mg/L - pH 5

Flow (mL/min)	**5**											
Volume (cm3)	79.52											
m after - m before(g)	36.169											
Hours		0.00	0.50	2.00	3.50	21.00	25.00	29.00	52.00	69.50	75.50	93.00
Minutes		0.00	30.00	120.00	210.00	1260.00	1500.00	1740.00	3120.00	4170.00	4530.00	5580.00
Volume passed total (ml)		0.00	150.00	600.00	1050.00	6300.00	7500.00	8700.00	15600.00	20850.00	22650.00	27900.00
# of columns		0.00	1.89	7.55	13.20	79.23	94.32	109.41	196.18	262.20	284.83	350.86
# of pore volumes		0.00	4.15	16.59	29.03	174.18	207.36	240.54	431.31	576.46	626.23	771.38
Metal												
Cu	2.67	0.71	0.55	0.33	0.19	0.28	0.15	0.1	0.26	1.61	1.61	1.63
Cr	1.783	0.374	0.325	0.371	0.421	0.303	0.341	0.331	0.128	0.061	0.062	0.093
Zn	2.51	0.09	0.17	0.27	0.27	1.9	2.27	2.49	2.78	3.22	2.94	2.86
C Cu / C_o		0.2659	0.2060	0.1236	0.0712	0.1049	0.0562	0.0375	0.0974	0.6030	0.6030	0.6105
C Cr / C_o		0.2098	0.1823	0.2081	0.2361	0.1699	0.1913	0.1856	0.0718	0.0342	0.0348	0.0522
C Zn / C_o		0.0359	0.0677	0.1076	0.1076	0.7570	0.9044	0.9920	1.1076	1.2829	1.1713	1.1394

Table A.2.43: Column Test Results - Competitive - C_o 2 mg/L - pH 5 (Continued)

Hours	**100.00**	**119.00**	**141.00**	**149.00**	**165.00**	**172.00**	**189.00**	**196.00**	**213.00**	**241.50**	**264.50**	**287.50**
Minutes	6000.00	7140.00	8460.00	8940.00	9900.00	10320.00	11340.00	11760.00	12780.00	14490.00	15870.00	17250.00
Volume passed total (ml)	30000	35700	42300	44700	49500	51600	56700	58800	63900	72450	79350	86250
# of columns	377.26	448.94	531.94	562.12	622.48	648.89	713.03	739.44	803.57	911.09	997.86	1084.63
# of pore volumes	829.44	987.03	1169.51	1235.86	1368.58	1426.64	1567.64	1625.70	1766.71	2003.10	2193.87	2384.64
Metal												
Cu	1.64	1.66	1.76	1.86	1.88	2.17	2.3	2.51		2.6	2.82	2.75
Cr	0.101	0.252	0.484	0.42	0.563	0.574	0.618	0.842	0.832	0.737	0.881	1.217
Zn	2.78	2.61	2.84	2.49	2.62	2.69	2.68	3.36	3.21	2.92	2.71	2.2
C Cu / C_o	0.6142	0.6217	0.6592	0.6966	0.7041	0.8127	0.8614	0.9401	0.9521	0.9738	1.0562	1.0300
C Cr / C_o	0.0566	0.1413	0.2715	0.2356	0.3158	0.3219	0.3466	0.4722	0.4666	0.4133	0.4941	0.6826
C Zn / C_o	1.1076	1.0398	1.1315	0.9920	1.0438	1.0717	1.0677	1.3386	1.2650	1.1633	1.0797	0.8765

Table A.2.44: Column Test Results - Competitive - C_o 2 mg/L - pH 9

Flow (mL/min)	**13**							
Volume (cm3)	79.52							
m after - m before (g)	36.169							
Hours	0.00	1.00	23.00	32.50	52.50	54.50	71.00	89.00
Minutes	0	60	1380	1950	3150	3270	4260	5340
Volume passed total (ml)	0	780	17940	25350	40950	42510	55380	69420
# of columns	0.00	9.81	225.60	318.79	514.96	534.58	696.43	872.99
# of pore volumes	0.00	21.57	496.00	700.88	1132.19	1175.32	1531.15	1919.32
Metal								
Cu	2.35	0.15	0.17	0.07	0.19	0.09	0.02	0.2
Cr	1.921	0.757	0.945	1.35	1.89	1.716	1.712	1.681
Zn	2.21	0.06	0.06	0.05	0.29	0.14	0.11	0.13
C/C_o Cu	0	0.0638	0.0723	0.0298	0.0809	0.0383	0.0085	0.0851
C/C_o Cr	0	0.3941	0.4919	0.7028	0.9839	0.8933	0.8912	0.8751
C/C_o Zn	0	0.0271	0.0271	0.0226	0.1312	0.0633	0.0498	0.0588

A.3 DESORPTION

Table A.3.45: Desorption Concentrations of Metals - Acidic pH

			Metal (mg/L)	
Concentration of PTL (g/200mL)	Concentration of PTL (g/L)	Cu	Cr	Zn
0	0	0	0.012	0.19
0.5	2.5	4.29	0.015	0.91
1	5	4.03	0.018	1.64
1.5	7.5	3.03	0.017	2.31
2	10	2.25	0.018	2.71

VITA

Manal W. Kaakani was born on the 30th of September, 1987, in Beirut, Lebanon. Her educational journey started in Aloma Public Elementary School and Munn's Public Elementary School in Ontario, Canada. She then moved back to Lebanon to continue middle school at the International School of Choueifat. She transferred to The International School of Choueifat in Qatar for a year of high school, and then transferred again to The International School of Choueifat in Dubai, United Arab Emirates, for her remaining high school years. She received her Bachelor of Science in Civil Engineering from the American University in Dubai, UAE, in the Fall of 2009. In January 2010, she joined the American University of Sharjah to earn her Master of Science in Civil Engineering, with an emphasis on Environmental Engineering. At the American University of Sharjah, she worked as a lab assistant and grader for Fluids Mechanics and Environmental Engineering Labs. She also performed research with her advisor, Dr Maruf Mortula and took part in a Conference that was organized at the university in November 2011. She graduated with a Master of Science in Civil Engineering Degree in the Fall of 2011.