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**Adsorption of organic compounds by microbial biomass**

**Selvakumar, Ariamalar, D.Eng.Sc.**

**New Jersey Institute of Technology, 1988**

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ADSORPTION OF ORGANIC COMPOUNDS  
BY MICROBIAL BIOMASS

BY

ARIAMALAR SELVAKUMAR

Dissertation submitted to the Faculty of the Graduate School  
of the New Jersey Institute of Technology in partial fulfillment  
of the requirements for the degree of  
Doctor of Engineering Science

1988

APPROVAL SHEET

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## ABSTRACT

**Title of Thesis: Adsorption of Organic Compounds by Microbial Biomass**

**Ariamalar Selvakumar, Doctor of Engineering Science, 1988**

**Thesis Directed by: Dr Hsin-Neng Hsieh**

The adsorption of hazardous organic compounds such as phenol, 2-chlorophenol, 2-nitrophenol, chlorobenzene, and ethylbenzene onto two types of inactive microbial biomass (activated sludge and nitrifying bacteria) was studied. The adsorption isotherms could be expressed by the Freundlich adsorption isotherm and were found to be nearly linear over the range of concentrations (50 - 200 mg/l) studied. Desorption studies showed that the adsorption process was partially reversible. Heat of sorption was estimated and indicate that the biosorption process involves a physical rather than a chemical mechanism. The adsorptive capacity of biomass is about two to three orders of magnitude less than activated carbon.

In bisolute systems, the uptake of each solute is reduced in the presence of a second solute, but the combined adsorptive capacity was greater than that for either of the individual substances from its pure solution. The compound with higher octanol/water partition coefficient was observed to be more favorably adsorbed. In the case of activated carbon, the more hydrophobic compound was observed to be more favorably adsorbed. The uptake of each solute is reduced, when the initial



concentration of other solute is increased.

In multi - solute systems, the equilibrium capacity for each solute is reduced significantly in the presence of other solutes and the effect of competition become more pronounced with the increase in number of solutes in solution. The overall adsorption capacity of biomass was barely affected by the presence of more solutes in solution.

Live and inactive biomass do not exhibit the same level of biosorptive uptake, and the differences appear to depend on the specific organic compound.

The extent of biosorption is directly related to the organic carbon content of the biomass. Octanol/water partition coefficient is a much better predictor of extent of adsorption on microbial biomass than aqueous solubility. Reasonable estimation of the sorption behavior of organic compounds can be made from a knowledge of organic carbon content of the biomass and octanol/water partition coefficient of the organic compound.

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"Economical Flow Velocity in Water Distribution System", Distribution System Symposium Proceedings, AWWA, September 1986.

To  
my beloved husband,  
respectable parents  
and loving sisters

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## I. INTRODUCTION

### A. General

Development of sophisticated industrial societies has led to proliferation of a vast number and variety of complex chemicals for industrial, agricultural and domestic use. Many of these compounds exhibit toxic, carcinogenic, mutagenic or teratogenic properties, and may have insidious effects on man and his environment in uncontrolled exposure situations.

Many compounds of such concern eventually find their way into municipal and industrial wastewaters, and, unless specifically removed by waste treatment processes, ultimately appear in receiving waters and drinking water supplies and can have harmful effects on human and other organisms in the environment. The release of toxic and potentially toxic organics, especially from among the 129 organic compounds which include 88 organics classified as non-pesticides, 26 pesticides and PCBs, 13 metals, cyanide, and asbestos identified by the U.S. Environmental Protection Agency as Priority Pollutants to the environment, has become an issue of prime concern in the last few years.

The fate of hazardous organic pollutants discharged into conventional biological wastewater treatment processes is not well understood. These compounds may be removed from the wastewater stream by biodegradation, volatilization (air stripping), sorption on the biomass, precipitation, hydrolysis,

etc. Of these processes, sorption would accumulate pollutants in the sludge and create potential environmental hazards when released back into the environment upon sludge landfilling or spreading the sludge on the land surface. Hence, the sludge from water and wastewater treatment plants presents not only a significant waste disposal problem but one that is growing. The wastes include lime-rich sludge from water treatment plants as well as sewage sludge from wastewater treatment plants. When the sludges are used as fertilizers, the soluble compounds may infiltrate and pollute groundwater resources, while the more insoluble compounds, many of which may consist of toxic metals, are removed and concentrated by plants.

Municipal sewage sludges applied to land are known to contain synthetic organics. Recent studies (Patterson and Kodukala, 1981; Tsezos, 1983; Lal and Saxena, 1982; Mac Rae, 1983) have shown that the microbial cells tend to concentrate chemicals from their aquatic environment. The presence of these chemicals in groundwater represents a health risk to consumers. These compounds are harmful to life and can destabilize the food chain. Furthermore, it has been shown that many toxic organic compounds that enter conventional biological wastewater systems with the domestic and industrial wastes accumulate in microbial sludge without substantial biodegradation occurring. The accumulation of toxic organics in the sludge raises questions whether the present practices for biological sludge management and disposal are appropriate.

A number of different mechanisms have been proposed as potentially responsible for the accumulation of organics by microbial biomass. Adsorption, however, has been shown to be the primary mechanism via which cations are accumulated by microbial biomass. The phenomenon of retention of cations from solution by microbial cells has been termed "biosorption". It is possible that adsorption is also the significant mechanism in the accumulation of organics by microbial biomass. Because adsorption is reversible, there must be concern for the potential desorption of the pollutants with the ultimate disposal of waste sludges to the environment. In order to study biosorption as a mechanism of organics uptake, the interference of active transport and biodegradation processes has to be eliminated by inactivating the microbial cells.

#### B. Fate of Hazardous Organic Compounds in Wastewater Treatment Plants

The Effluent Guidelines Division in the Environmental Protection Agency(EPA), Office of Water Regulations and Standards initiated a program to study the occurrence and fate of the 129 priority pollutants in 40 Publicly Owned Treatment Works (POTWs) and found many hazardous organic pollutants in the influents, effluents and sludges (Burns and Roe Industrial Services Corp., 1982). Table 1.1 gives the concentration ranges in influent, effluent and raw sludge samples from the POTWs for the compounds selected in this study.

**Table 1.1: Concentration Ranges in Influent, Effluent and Raw Sludge from 40 Publicly Owned Treatment Facilities in ug/l**

Compound	Influent	Effluent	Raw Sludge
Phenol	1 - 1400	1 - 89	5 - 17,000
2-Chlorophenol	1 - 5	1 - 5	11 - 72
2-Nitrophenol	5 - 64	5 - 14	-
Chlorobenzene	1 - 1500	1 - 9	1 - 687
Ethylbenzene	1 - 730	1 - 49	1 - 4200

Table 1.2 gives the pollutant treatability/removability range by activated sludge process( Martin and Johnson, 1987).

**Table 1.2: Pollutant Treatability/Removability by Activated Sludge Process**

Compound	Range of Removal in %	Range of Effluent Concentration in g/l
Phenol	8 - 99	ND - 1400
2-Chlorophenol	92 - 99	ND - 100
2-Nitrophenol	99 - 99	ND - BDL
Chlorobenzene	38 - 99	ND - 100
Ethylbenzene	16 - 99	0.9 - 250

ND = Not Detected

BDL = Below Detection Level

Lue-Hing et al. (1980) reported that hazardous organics were found in the influents, effluents, waste activated sludges and digested sludges of three large treatment facilities in the



Chicago area. Maximum concentrations found in the plant influents range from less than one ug/l to several thousand ug/l. Concentrations of hazardous organics in the sludges have been found in the range of a thousand ug/g of dry solids to less than one ug/g dry solids. Convery et al. (1980) reported that on removal of organic priority pollutants in three large combined-municipal treatment facilities, biosorption was observed for a number of pollutants. Concentrations of ethylbenzene, chlorobenzene and 2-nitrophenol in the sludge were found to be 22.8, 161.0, and 1.4 ug/l, respectively, whereas the influent concentrations of ethylbenzene and chlorobenzene were 177.3 and 148.3, ug/l respectively. Hence, it is apparent that many hazardous organics are removed from wastewater entering biological treatment systems by partitioning onto the sludges.

The Municipal Environmental Research Laboratory (MERL) in the EPA Office of Research and Development has conducted a pilot plant study to determine the fate of 22 toxic organic compounds discharged into an activated sludge pilot plant (Petrasek et al., 1983). Many compounds were found to accumulate in primary and secondary sludge. The fraction of the compounds removed by the primary sludge was reasonably well correlated with the octanol/water partition coefficient of the compound, however fraction removed by the secondary sludge was not well correlated. One of the compounds examined in the present study was included in the EPA study. Five percent of the phenol entering the plant was reported to be removed by the primary and activated sludge.

It should be noted that among the compounds studied, phenol has the lower octanol/water partition coefficient ( $\log K_{OW} = 1.46$ ). In the case of pentachlorophenol, ( $\log K_{OW} = 5.01$ ), 26% was removed in the primary sludge and 5% in the activated sludge. These studies confirm that the sorption of organic priority pollutants by the microorganisms is an important removal mechanism in biological waste treatment plants.

### C. Objectives and Scope of the Study

Significant amount of research has been conducted on the removals of heavy metals in activated sludge (Brown and Lester, 1979, Neufeld and Hermann, 1975, Oliver and Cosgrove, 1974). However, few studies were reported in the adsorption of hazardous organic compounds in biomass. With the increasing usage of organic compounds in household cleaners, office supplies, and industries more and more organic compounds will be discharged into domestic wastewater treatment plant. The fate of the hazardous organics will ultimately affect the concept and method of sludge disposal.

The overall aim of the present work is to develop better understanding of adsorption of organic compounds by microbial biomass in biological wastewater treatment systems. Also, develop an empirical equation using isotherm data and sorbate - sorbent properties to estimate the level of hazardous organics in the final effluent and the biological sludge of a biological wastewater treatment plant. Phenol, 2-chlorophenol, 2-

nitrophenol, chlorobenzene and ethylbenzene were selected for this study, because of their frequent presence in industrial wastewaters. Two types of microbial biomass (activated sludge and nitrifying bacteria) were chosen for investigation of the adsorption phenomenon. Inactive biomass was used because it is a stable sorbent and eliminates the potential for biodegradation. Comparative studies were done with live activated sludge biomass. The contact time of 4 hrs was used, which is too short for potential biodegradation to occur. Activated carbon, a known sorbent, was used to compare the sorption capacity of biomass. Hence, the objectives of this study are as follows:

1. Examination of the adsorptive capacity of several selected organic priority pollutants by microbial biomass and the factors influencing such an adsorption system.
2. Determination of adsorption and desorption isotherms for each sorbate.
3. Study the effect of fundamental molecular properties of the sorbate (such as aqueous solubility, octanol/water partition coefficient, molecular weight, etc.) on sorption capacity.
4. Comparison of the sorption capacity of biomass with activated carbon.
5. Investigation of the effect of competitive adsorption of liquid organic compounds on microbial biomass in multi solute solution systems.

## II. LITERATURE REVIEW

Tsezos and Seto (1986) studied the adsorptive capacity of 1,1,2 trichloroethane(TCE) and 1,1,2,2 tetrachloroethane(TTCE) onto mainly two types of microbial biomass: (1) pure culture inactive waste biomass from industrial fermentation processes and (2) inactive municipal wastewater biological treatment plant return sludge. They used inactive microbial cells in order to eliminate all active transport mechanisms that could contribute to the accumulation. Their results showed that the combination of a lower water solubility, higher octanol/water partition coefficient and the reduced volatility favors the uptake of TTCE by microbial biomass, a behavior in accordance with that of adsorption systems. Their results also suggest that the adsorption isotherm could be best described by a modified Freundlich adsorption isotherm.

They further studied the effect of competition on biosorption in mixed solute systems. Comparison of the single to the mixed solute in solution had a marked effect on the biosorption equilibrium especially for activated sludge. The presence of an additional adsorbate did result in a significant change of the biomass uptake capacity of the first one.

Bell and Tsezos (1987) studied the removal of five toxic organic compounds, namely lindane, diazinon, malathion, pentachlorophenol, and the PCB 2 - chlorobiphenyl from water by adsorption on inactive microbial biomass. They found that the

uptake capacity of biomass is generally less than that of activated carbon, but it is high enough to provide significant removal of trace quantities of hazardous compounds combined with domestic and industrial pollutants. They said that with the exception of malathion, the adsorptive uptake data fit the Freundlich equation and were very well correlated with the octanol/water partition coefficient but not as well correlated with water solubility of the compounds. Except for malathion, the adsorption was reversible. Malathion showed unusually high apparent uptake and the removal appeared to be irreversible.

The extent of biosorption by the microorganisms varies from species to species. One suggestion which has often been mentioned in describing biosorptive phenomena is that the bioaccumulation of highly hydrophobic organic compounds is directly related to the lipid content of the organism. Ware and Roan(1970) in their review of biosorption of pesticides by aquatic microorganisms suggested that lipid soluble organics, like many pesticides, would sorb more strongly to surfaces containing larger amounts of lipid materials. Lal and Saxena(1982) also reported that nonpolar compounds are accumulated in an organism according to their partitioning between the medium and the lipid content of the organism. Shin et al.(1970), on the other hand, studied adsorption of DDT by various soil fractions. They discovered that soil treated with ether and ethanol for the removal of lipid - like materials actually increased the adsorption of DDT. This suggested that other components may also play a role in

biosorption. At the present time, a clear understanding of the mechanism that controls microbial adsorption of non - ionic organic chemicals is not available.

Tsezos and Seto(1986) observed that organic carbon (TOC) that leached from microbial cells during contact with TCE or TTCE solutions correlates better to the observed biosorptive behavior than to the lipid content. The characteristic value of this TOC is dependent on the characteristics of each cell type. Hence, the more cells that rupture, the higher the uptake capacity that is observed, accompanied by increased leachable TOC.

Roman - Seda(1985) studied the potential of inert biological sludges for the removal of heavy metals such as Cd, Ni, Pb, and Cr at neutral pH's under batch conditions. They also studied the effects of the operational parameters of contact time, sludge concentration, and initial metal concentration on overall removal. Their conclusions are as follows:

1. Maximum removals are obtained for Cd, Ni, and Pb at the neutral pH region; for Cr at pH 4.5 to 5.5.
2. Optimum contact time lies between 2 and 4 hours for the metals tested.
3. Conventional adsorption models do not fit the data adequately.
4. The adsorptive capacity of the sludge is very high.

Tada and Suzuki (1982) carried out an adsorption experiment to determine the factors affecting the uptake of heavy metals by bottom mud in urban rivers. The adsorption of Cu, Zn, Cd, and Pb

was described using the Freundlich adsorption equation and the Freundlich Constant(K) was related to the grain size and organic matter content of bottom mud. They found that the main factor controlling the adsorption of metal was organic matter rather than surface area. The desorption experiment proved that the metals adsorbed by mud were extracted approximately 100% with dilute HCl.

Tsezos and Volesky (1981) studied the biosorption potential of waste biomass which could be used as an inexpensive material for the development of a wastewater treatment scheme for the decontamination of waste streams containing ions of high atomic number elements such as uranium, thorium, etc. They also compared the biosorptive capacity of biomass to an activated carbon and ion - exchange resin currently used in uranium production processes. They found that the biomass of *Rhizopus arrhizus* removed 2.5 and 3.3 times more uranium than the ion exchange resin and activated carbon, respectively, at pH 4 at an equilibrium concentration of 30 mg/l. Under the same conditions, *R. arrhizus* removed 20 times more thorium than the ion exchange resin and 2.3 times more than the activated carbon.

Mac Rae (1985) studied the removal of pesticides such as lindane, 2,4 - dichlorophenoxyacetic acid and 2,4,5 - trichlorophenoxyacetic acid in water by microbial cells immobilized on magnetite and reported that microbial cells adsorbed to magnetite can remove significant amounts of the above pesticides. It was assumed that lindane removal was by sorption since no evidence

was obtained to indicate biodegradation of lindane by any of the microorganisms studied. They further said that biological removal of lindane from water by bacterial cells immobilized on magnetite particles was much less effective than the removal obtained with activated carbon, but more effective than coagulation and filtration and chemical oxidation by chlorine and ozone. The equilibrium was found to be reached after one minute of mixing. Magnetite alone would remove significant amounts of lindane from water.

Adsorption of organic matter onto activated sludge particles was originally considered to be the major reason for the rapid removal of substrate during the contact period in a contact stabilization activated sludge process, which was named by Ullrich and Smith(1951) as the biosorption process. In the conventional activated sludge process, contact and stabilization occur in a single tank. Nevertheless, the sorption of specific organic chemicals onto the biomass could be an important removal mechanism in the activated sludge process. Leo et al.(1971) have shown that the octanol/water partition coefficient,  $K_{OW}$ , is a very useful tool in many situations where a substance's behavior is influenced by its partition into a lipid phase. The rationale behind this lies in the supposition that octanol is similar in polarity - hydrophobicity characteristics to glyceryl esters that comprise the principal components of the cell membrane.

Matter - Muller et al. (1980) have determined the partition coefficients,  $K_p$ , of several refractory organic compounds in a



batch activated sludge process and found a linear dependence of  $\log K_p$  upon  $\log K_{ow}$ . The compounds with high octanol/water partition coefficient were found to be sorbed in a greater extent onto the activated sludge process.

Petrasek et al. (1983) studied the quantification of the partitioning of 22 of the semivolatile organic priority pollutants in conventional wastewater systems. Removal in the primary clarifiers, computed from mass balances, was quite variable among groups but was relatively consistent within any given class of compounds. Partitioning to the primary sludge was shown to be an undefined function of the octanol/water partition coefficient.

Karickhoff et al. (1979) investigated the sorption of hydrophobic pollutants on natural sediments and found that the sorption isotherms were linear over a broad range of aqueous phase pollutant concentrations. The linear partition coefficients ( $K_p$ ) were directly related to organic carbon content for given particle size isolates in the different sediments. They demonstrated that on an organic carbon basis ( $K_{oc}$ ), the sand fraction was a considerably less effective sorbent than the fines fraction. Differences in sorption within the silt and clay fractions were largely the result of differences in organic carbon content. They further suggested that reasonable estimates of  $K_{oc}$ 's can be made from octanol/water partition coefficients, which are widely catalogued or easily measured in the laboratory.

Lambert (1968) has demonstrated that for a given soil type,

the sorption of neutral organic pesticides can be very well correlated with the organic matter content of the soil. He further suggested that the role of soil organic matter was similar to that of an organic solvent and that the partitioning of an organic solute between the soil material and water could be estimated by its tendency to partition between water and an immiscible organic solvent. A solvent system that has been used extensively since then is the n-octanol/water combination. Octanol is believed to best imitate the fatty structures in plants and the aqueous phases of living tissues.

Singer and Yen (1980) conducted a series of batch adsorption experiments to evaluate the effect of alkyl substitution on the adsorption of phenols by activated carbon with particular attention directed at the position, length and number of the alkyl substituents. Their data confirm to the Langmuir adsorption isotherm. They found that the alkyl substituted phenols are more strongly adsorbed than phenol itself, and adsorption increases as the length of the alkyl chain increases. While position of the substituted alkyl groups has no effect on the extent of adsorption, adsorption is enhanced when the number of substituents on the phenol molecule is increased. The substitution of alkyl groups on the phenol molecule would be expected to make the resulting alkyl phenols less polar and therefore less soluble in water. Their results are in accordance with adsorption theory and with the results of previous investigators who have reported that the extent of adsorption

increases as the solubility of the adsorbate decreases.

Lian - Pang Wei (1983) studied the fate of trace organic priority pollutants in an enriched continuous culture system and found that in general, the compounds with a higher octanol/ water partition coefficient tend to be sorbed in a greater extent onto the activated sludge. 1,2 - Dichlorobenzene, 2,4 - Dichlorophenol and Naphthalene were not found to be adsorbed appreciably onto the activated sludge and the extent of biosorption does not bear any relationship with . On the other hand, biosorption of pentachlorophenol and two phthalate esters was related to the amount of sludge present in the system. It increased with an increased sludge concentration obtained at a lower .

Weber and Morris (1964) studied the adsorption on activated carbon in binary solute systems and pointed out that each solute affects adversely both the rate of adsorption and the equilibrium capacity for adsorption of the other compound present. They also said that the degree of the mutual inhibition of competing adsorbates should be related to the relative sizes of the molecules being adsorbed, to the relative adsorptive affinities, and to the relative concentration of the solutes. They also noted that the total rates and adsorptive capacities (the sums of these quantities for the individual constituents) were greater than that for either of the individual substances from its pure solution.

Martin and Al-Bahrani (1977) investigated the effects of competitive adsorption in batch and column systems and reported

that the equilibrium adsorption capacity for each solute from a multi - solute solution on activated carbon was adversely affected by the presence of the other solutes. In the column system, some of the less favorably adsorbed compounds that were initially adsorbed were desorbed in favor of the more effectively adsorbed compounds at later stages of column operation until equilibrium was reached. The less effectively adsorbed the compound, the more adversely it was affected by the competitive adsorption. The effect of competitive adsorption became more pronounced with an increase in the number of solutes in solution, which emphasized the importance of this factor on the performance of activated carbon when used for the removal of complex mixtures of organic pollutants from waters and effluents.

In 1979, Martin and Al-Bahrani further studied the effects of competitive adsorption in bisolute systems. Compounds which possessed similar capacities for adsorption from their respective single solute aqueous solutions did not have similar capacities for adsorption from their bisolute solutions. In three of the four bisolute solutions studied, the higher molecular weight compound was more favorably adsorbed; this preferential adsorption cannot be attributed to differences in solubility or rates of adsorption but to the higher affinity of the larger molecule to the carbon surface. In the case of fourth bisolute system, that containing nitrobenzene and o-methoxyphenol, which are of virtually identical molecular weight, the more hydrophobic nitrobenzene was observed to be more favorably adsorbed.

### III. THEORETICAL CONSIDERATIONS

#### A. Adsorption Theory and Fundamentals

Adsorption is generally defined as the accumulation or concentration of a substance at an interface between two phases. Adsorption from solution is an extremely complicated phenomenon, and no single theory has yet been developed which adequately explains the process from a molecular standpoint. The main reasons for its complexity are:

(1) It involves not only the interaction of the adsorbent with the adsorbate, but also interactions between a solvent(water) with the adsorbate, and with the adsorbent.

(2) Molecular interactions in condensed systems differ from those occurring in the gaseous phase because distances between the interacting molecules are much smaller.

#### 1. Adsorption Isotherms and Models

Perhaps the most useful way to present equilibrium adsorption data is via an adsorption isotherm. The isotherm is a plot of the mass of solute adsorbed per unit mass (or surface area) of solid (i.e., adsorption capacity ) versus the equilibrium solute concentration (at constant temperature). According to Giles (1970), equilibrium adsorption data plotted as isotherms can potentially yield a surprising amount of information, including: the nature of the adsorption reaction; the heat, free energy, and

entropy of the reaction; the specific surface of the solid, its degree of porosity, and the size and shape of its pores; and the size of the adsorbate molecule, its orientation at the surface, and its degree of self association.

By the early part of this century, several theories/models have been derived to fit isotherm data (especially on gas - solid adsorption systems), but none were specifically applicable to liquid - solid adsorption systems. Many of the assumptions made in these theoretical derivations are not applicable to the case of adsorption from solution. For example, the Langmuir (1918) adsorption model was derived for the adsorption of gases onto nonporous solids, and the following assumptions were made:

- (1) Adsorption is limited to a single layer of solute molecules.
- (2) There are no interactions between adsorbed molecules, and they are not free to move on the surface.
- (3) The enthalpy of adsorption is the same for all molecules.

It is very unlikely that the above assumptions are true for the adsorption of solutes by microbial biomass. Nevertheless, the Langmuir adsorption isotherm is sometimes used to describe the experimental data for liquid - solid adsorption. (However, a successful fit of experimental data to the Langmuir equation does not imply that its underlying assumptions are valid). The Langmuir equation is:

$$q = \frac{q_m K_A C_e}{1 + K_A C_e} \quad (3.1)$$

where  $q$  = mass solute adsorbed/ mass adsorbent  
 $q_m$  = mass solute adsorbed/mass adsorbent for a complete monolayer  
 $C_e$  = concentration of solute in solution  
 $K_A$  = constant related to enthalpy of adsorption

The Langmuir isotherms can be rearranged to the following linear forms:

$$\frac{C_e}{q} = \frac{1}{K_A q_m} + \frac{C_e}{q_m} \quad (3.2)$$

or

$$\frac{1}{q} = \frac{1}{q_m} + \frac{1}{K_A q_m} \frac{1}{C_e} \quad (3.3)$$

Another equation that is much more widely used to describe liquid - solid adsorption data is the Freundlich equation, which is:

$$q = K_d C_e^{1/n} \quad (3.4)$$

where  $K_d$  and  $n$  are constants and  $1/n$  is usually less than or about equal to one. The major drawback of the Freundlich equation is that it predicts that adsorption increases indefinitely with solute concentration, and therefore, could never be applicable to the case of monolayer adsorption.

The Freundlich adsorption isotherm can be rearranged to the following form:

$$\log q = \log K_d + 1/n \log C_e \quad (3.5)$$

## 2. Factors Influencing the Sorption of Non - ionic, Organic Solutes in Biomass Solution

### a. Sorbent Characteristics

The soil components which account for virtually all sorption phenomena in soils are the clays, hydrous metal oxides, and organic matter. The most important of these components in "controlling" the sorption of non - ionic, organic compounds is the soil organic matter. In fact, many studies have found that the soil organic matter content is essentially the only soil property which affects the sorption of these compounds. Hence, one can expect the same concept with microbial biomass too.

Many studies have established strong correlation between sorption and soil organic matter content, that the sorption distribution coefficient( $K_d$ ) is normalized to the fraction of organic carbon ( $f_{OC}$ ) present in the sorbent, as indicated in the following equation:

$$K_{OC} = K_d/f_{OC} \quad (3.6)$$

where  $K_{OC}$  = normalized distribution coefficient  
 $f_{OC}$  = organic carbon content  
 $K_d$  = sorption distribution coefficient

Karickhoff and others (1979) reasoned that if the  $1/n$  term of



the Freundlich adsorption equation was equal to one,  $K_d$  reduced to a simple partition coefficient based on concentration, hence

$$q = K_d C_e \quad (3.7)$$

#### b. Sorbate Properties

The two most popular sorbate properties used in sorption correlation studies have been aqueous solubilities and octanol/water partition coefficients. The general rule for the inverse correlation between sorption and a compound's solubility was first expounded by Lundelius (1920). The rule serves as a guide, but numerous exceptions have been reported. The use of a compound's octanol/water partition coefficient ( $K_{ow}$ ) as a correlating parameter probably originated with the works of Lambert (1967, 1968) and Hance (1967).

Other correlating parameters which are used less often are the sorbate's bioconcentration factor and parachor. A compound's parachor,  $p$ , is a function of molecular structure and, for liquids, is defined as,

$$p = \frac{M \sigma^{1/4}}{\rho_l - \rho_v} \quad (3.8)$$

where  $M$  = molecular weight

$\sigma$  = surface tension

$\rho_l$  = liquid density

$\rho_v$  = vapor density

Since  $\rho_l \gg \rho_v$ , the equation reduces to

$$p = \frac{M \sigma^{1/4}}{\rho_1} = V \sigma^{1/4}. \quad (3.9)$$

where V is the molar volume.

Regression equations developed between the sorption and the above sorbate properties normally take the form:

$$\log K_{OC} = A \log r + B \quad (3.10)$$

where A and B are regression coefficients, and r is the particular sorbate property (i.e., solubility,  $K_{OW}$ , or bioconcentration factor).

It should be noted that these correlations were developed primarily for pesticides and, to a lesser extent for aromatic and polynuclear aromatic hydrocarbons. Furthermore, it appears that virtually no research studies attempt to correlate sorption to more fundamental sorbate properties such as polarizability, dipole moment, and molecular weight.

### c. Solution Properties

Properties of the solution which may affect the sorption of organic compounds in microbial biomass are temperature, pH, sorbate concentration, solids concentration and the presence of other sorbates.

Since adsorption is an exothermic reaction, it should decrease with increasing temperature. However, only adsorption from the gas phase is strictly exothermic. Sorption from solution is a different matter, since the presence of a third component,

the solvent, must be reckoned with. Studies by Tsezos et al. (1987) on the sorption of lindane by inactive activated sludge biomass do indicate that biosorption is an exothermic reaction.

The pH of the solution has a strong influence on sorption for ionizing sorbate species. Myers and Zolandz (1980) said that considerably less adsorption occurs from basic solution than either the acidic or the "Natural pH" solutions. Adsorption under acidic conditions was only slightly lower than that under the natural pH conditions. However, in the case of non - ionic sorbate molecules, the literature (La Poe, 1985) indicates that the pH has virtually no effect. However, pH effect will not be investigated in this research, as pH doesn't change very much in biological wastewater treatment plants.

Sorbate concentration always influences the amount sorbed. As the sorbate concentration increases, the amount sorbed increases (but there is not necessarily a linear correspondence), until the sorbent becomes "saturated" with the sorbate. Beyond this point, increasing sorbate concentration will not further increase the quantity sorbed, and the isotherm should become flat. However, it appears that this saturation point is rarely attained in batch sorption studies.

As the solid concentration or water content of a biomass suspension is altered, the amount of solute sorbed and its equilibrium solution concentration will, in general, change. However, the distribution coefficient,  $K_d$ , should theoretically

remain the same.

The presence of a mixture of solutes in a sorption system may mutually enhance sorption, may act independently, or may compete with one another for sorption. The studies on the sorption of organic compounds by activated carbon (Martin and Al-Bahrani) do indicate that the equilibrium capacity for each sorbate from a multi solute solution was adversely affected by the presence of other solutes. The effect of competition on sorption by biomass will be verified experimentally.

#### B. Desorption and Reversibility

Very few desorption studies have been performed, but those that have generally indicate that the desorption process is slower to reach equilibrium than sorption. Also, it is frequently observed that a portion of the sorbed compound is very difficult to remove. That means, sorption is partially irreversible.

#### IV. MATERIALS AND METHODS

##### A. Materials

The microbial biomass types that were used in this study are dewatered activated sludge and nitrifying bacteria from the Stony Brook Regional Sewerage Authority River Road Treatment Plant, Princeton, New Jersey, which serves Hopewell Township, Princeton Township, West Windsor Township, and South Brunswick Township. The treatment processes include grit removal, activated sludge, final sedimentation, nitrification (suspended growth), and chlorination. According to the test, heavy metals and organics in sludge were all below E P Toxicity Standard. The biomass (sludge) contains various elements. Water comprises the major portion of a microorganisms (75 to 90%). The elemental composition of microorganisms varies, depending on the environmental conditions and species of microorganisms. Generally, 75 percent of the dry weight of the cell is composed of elements carbon, hydrogen, oxygen, and nitrogen. The composition of these biomasses taken from Stony Brook Treatment Plant are as follows:

Biomass type	% C	% H	% N	% O
Activated Sludge Biomass	36.73	5.24	3.43	28.17
Nitrifying Bacteria	36.24	5.68	6.49	30.77

The analysis was done by Galbraith Laboratories Inc., Knoxville, Tennessee using an infrared absorption method.

Filtrisorb 400 type activated carbon with a specific area of 1000 m<sup>2</sup>/g produced by Calgon Corporation, Pittsburgh, PA was used for comparison studies.

Phenol, 2-chlorophenol, 2-nitrophenol, chlorobenzene and ethylbenzene were selected as "target compounds". The selection was based on their frequent presence in industrial wastewaters. The physical properties of target compounds are given in Table 3.1. The organic compounds used in the experiments were of 99+% purity. Water solutions were made with distilled/deionized water prepared in the laboratory.

#### Phenol (P)

Sources: Phenol is used in the production or manufacture of explosives, fertilizer, coke, illuminating gas, paints, paint removers, rubber, asbestos goods, wood preservatives, synthetic resins, textiles, drugs, pharmaceutical preparations, perfumes, etc. Phenol also finds wide use as a disinfectant in the petroleum, leather, paper, soap, tanning, dye and agricultural industries.

Physical and Chemical Properties: It is a white crystalline mass which turns pink or red if not perfectly pure. It has a burning taste and a distinct aromatic, acrid odor.

Toxicity: The available data for phenol indicate that acute and chronic toxicity to fresh water aquatic life occur at concentrations as low as 10,200 ug/l and 2560 ug/l, respectively.

Table 3.1: Physical Properties of Test Organic Compounds

Compound	Molecular Weight (g/mol)	Dipole Moment (debye)	Electronic Polarizability ( $10^{-24} \text{ cm}^3$ )	Molar Volume ( $\text{cm}^3/\text{mol}$ )	Pargchor $(\text{cm}^3 \text{ dyne}^{1/4} \text{ mol}^{-1} \text{ cm}^{1/4})$	Aqueous Solubility (mg/l)	Octanol - Water Partition Coeff. $K_{ow}$	Dielectric Constant
Phenol	94.11	1.45	3.72	87.77	221.96	82000	28.84	9.78
2-Chlorophenol	128.56	2.11	162.0	101.59	259.0	28500	147.91	6.31
2-Nitrophenol	139.11	-	153.6	93.67	-	2100	57.54	17.3
Chlorobenzene	112.56	1.69	155.0	101.79	245.0	480	691.83	5.71
Ethylbenzene	106.17	0.59	178.0	122.46	284.67	152	1412.54	2.41

Based on available toxicity data, for the protection of human health from phenol ingested through water and through contaminated aquatic organisms, the concentration in water should not exceed 3500 ug/l. But for the prevention of adverse effects due to the organoleptic(affecting one or more organs of special sense) properties of chlorinated phenols inadvertently formed during water purification processes, the phenol concentration in water should not exceed 300 ug/l.

Phenol is very toxic by ingestion, inhalation or skin absorption. It is a powerful irritant to mucous membranes and skin tissues. When it comes in contact with the eyes it may cause severe damage and blindness. Systematic effects may occur from any route of exposure. These include weakness, paleness, sweating, headache, ringing in the ears, shock and death. If death doesn't occur, kidney damage may occur.

## 2-Chlorophenol (CP)

Sources: Industrial occurrences of 2 - chlorophenol include iron and steel manufacturing, aluminium forming, foundries, soap and detergent manufacturing, textile mills, auto and other laundries, etc.

Physical and Chemical Properties: It is a colorless liquid, having melting and boiling points of 7°C and 175.6°C, respectively.

Toxicity: The available data for 2 - chlorophenol indicates that



acute toxicity to fresh water aquatic life occurs at concentrations as low as 4,380 ug/l. Sufficient data are not available for 2 - chlorophenol to derive a level which would protect against the potential toxicity for human health. But for controlling undesirable taste and odor quality of ambient water, the estimated level is 0.1 ug/l. 2 - chlorophenol is not likely to bioaccumulate since it is slowly degraded in aquatic and soil environments. There is a slight potential for adsorption by lipophilic and clay minerals. 2-chlorophenol is toxic by ingestion, inhalation and skin absorption.

#### 2-Nitrophenol(NP)

Sources: It is used in the synthesis of dye stuffs and other intermediates and pesticides. Presence of 2 - nitrophenol has been detected in the raw wastewater of industries such as iron and steel manufacturing, foundries, metal finishing, petroleum refining, etc.

Physical and Chemical Properties: It is slightly yellowish crystals with an aromatic to sweetish odor. It's melting and boiling points are 45°C and 214°C, respectively.

Toxicity: The available data indicate that acute toxicity to fresh water aquatic life occurs at concentrations as low as 230 ug/l. 2 - nitrophenol is not likely to bioaccumulate, it is resistant to biodegradation under natural conditions and inhibits microbial growth at higher concentration. It is adsorbed to a moderate degree by clay minerals. 2-nitrophenol is toxic by

inhalation, skin absorption of liquid.

#### Chlorobenzene (CB)

Sources: It is used in the manufacture of aniline, phenol, chlorobenzene and as an intermediate in the manufacture of dye stuffs and many pesticides. Industrial occurrences of chlorobenzene include foundries, metal finishing, pharmaceutical manufacturing, paint and ink formulation, textile mills, etc.

Physical and Chemical Properties: It is a colorless liquid, having an almond like odor. It's normal melting and boiling points are  $-45^{\circ}\text{C}$  and  $132^{\circ}\text{C}$ , respectively.

Toxicity: It has a low acute local or chronic toxicity. The available data for chlorobenzene indicate that acute toxicity to fresh water aquatic life occurs at 250 ug/l. Based on available toxicity data, for the protection of human health or prevention of adverse toxicological effects, the concentration in water should not exceed 480 ug/l. But to prevent adverse organoleptic effects, the concentration should not exceed 20 ug/l.

Chlorobenzene is toxic by ingestion, inhalation or eye and skin contact. It is a fairly strong narcotic and possesses but slight irritant qualities. It causes irritation of the eyes and nose, drowsiness, skin irritation, liver damage, incoherence, etc.

## Ethylbenzene(EB)

Sources: It is used in the manufacture of cellulose acetate, styrene, and synthetic rubber. It is also used as a solvent or diluent and as a component of automotive and aviation gasoline. Industrial occurrences of ethylbenzene include auto and other laundries, metal finishing, gum and wood chemicals, pharmaceutical manufacturing, pulp and paperboard mills, etc.

Physical and Chemical Properties: It is a colorless liquid with an aromatic odor. It's boiling and melting points are 136.2°C and -94.97°C, respectively.

Toxicity: The available data for ethylbenzene indicate that acute toxicity to fresh water aquatic life occurs at concentrations as low as 32,000 ug/l. For the protection of human health from the toxic properties of ethylbenzene ingested through water and contaminated aquatic organisms, the ambient water criterion is determined to be 1.4 mg/l. Ethylbenzene is an irritant to the skin mucous membranes. A concentration of 0.1% of the vapor in air is an irritant to the eyes of humans, and a concentration of 0.2% is extremely irritating at first, then causes dizziness, irritation of the nose and throat and a sence of constriction of the chest.

## B. Methods

### 1. Preparation of Inactive Biomass

Sludge containing 18% solids was obtained from the Stony Brook Regional Sewerage Authority River Road Treatment Plant and

it was filtered to remove most of the water and it was dried under the sun light. Then dried sludge was ground using a hand mill and passed through a U.S. No. 40 sieve. Powdered sludge was washed well with distilled, deionized water and then filtered to remove most of the wash water and subsequently dried at room temperature. The resulting biomass had the physical appearance of a fine powder. Here the microbial biomass is inactivated to eliminate the interference of active transport and biodegradation processes in order to study the adsorption as a mechanism of organic uptake. Oxygen uptake measurements were done, which confirmed that the biomass was really inactive. Further, biomass was put in Lauryl Tryptose Broth and incubated at 35°C for 48 hours and no cloudiness was observed. However when incubation was further carried out for three more days, under the same condition, some cloudiness appeared. This also confirmed that the biomass was inactive, but not dead. In this thesis, this biomass will be referred to as "inert" or "inactive" biomass. Figure 3.1 shows the photograph of inactive biomass taken from ZEISS microscope.

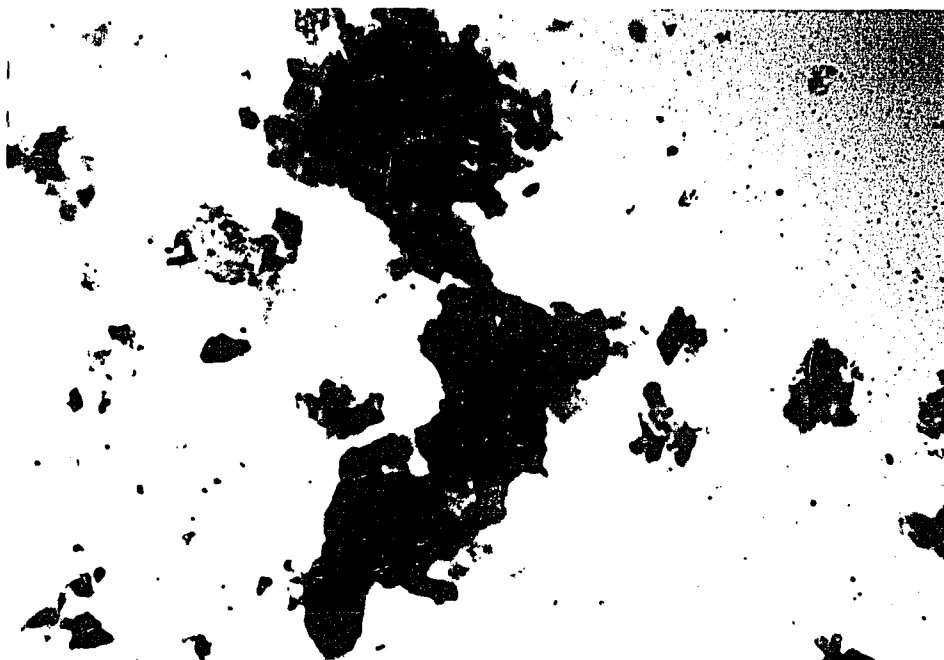
## 2. Sorption Study with Inactive Biomass

### a. Rate Study

The batch technique was used to evaluate both the rate and equilibrium of adsorption. The study was conducted in a series of 50 ml screw cap test tubes. Initially a constant weight of biomass was added in each test tubes. Then equal volumes of a specified concentration of liquid organic compound solution were



(a) Activated Sludge



(b) Nitrifying Bacteria

Figure 3.1: Photograph of Inactive Biomass taken from ZEISS Microscope.

added to each test tubes. The tubes were sealed immediately by screwing the teflon - lined caps and the caps were sealed using parafilms in order to cut down any evaporation of the organic compound during the experiment. The test tubes were placed on an electrically operated shaker and shaken at 300 rpm at a constant room temperature. The test tubes were withdrawn one by one at specific interval of time for the analysis of residual concentration of the organic compound in the liquid phase.

During this study, one tube was introduced without the biomass to serve as blank to see whether there is any loss of organic compound to the glassware or to the environment.

The test tubes were centrifuged at 1500 rpm for about ten minutes to allow the biomass to settle and the supernatants were decanted carefully. Then the samples were analyzed for the residual concentration of the organic compound in the liquid phase using a Varian 3700 Gas Chromatograph with a flame ionization detector system using the direct injection of aqueous solution. A Varian CDS 111 integrator was used to determine the peak area. One ul of samples were injected into a 2 m \* 2 mm ID glass columns containing 1% SP - 1240 DA on 100/120 Supelcoport packed with poleyester and 10% SP - 2100, 100/120 Supelcoport packed with methyl silicane used for phenolic and benzenic compounds respectively.

Oxygen - free nitrogen was used as a carrier gas. In the experimental work that was carried out, the following different operating conditions of chromatography were employed.

a) For analysing phenolic compounds, when each was present alone in the solutions or in the multi solute solutions used in this study, the following conditions were used:

Column temperature : 80°C - 180°C.

Injector temperature : 100°C.

Detector Temperature : 220°C.

Nitrogen flow rate : 30 cc/min.

Air flow rate : 300 cc/min.

Hydrogen flow rate : 30 cc/min.

b) For the analysis of benzene compounds, when each was present alone in the solutions or in the multi solute solutions used in this study, the following conditions were used:

Column temperature : 50°C - 120°C.

Injector temperature : 100°C.

Detector Temperature : 200°C.

Nitrogen flow rate : 20 cc/min.

Air flow rate : 300 cc/min.

Hydrogen flow rate : 30 cc/min.

The difference between the amount of organic compound in the supernatant and the amount initially present in the solution was taken as the amount of organic compound adsorbed by the biomass. For the compounds we studied, it was found that a rapid adsorption was taken place in the first 30 minutes and the complete adsorption was in the range of one to two and a half

hours (Figure 3.2).

b. Adsorption Equilibrium Study

The procedure for this analysis was similar to the rate study. The isotherm was run at "as is" pH (i.e. at natural pH). Measured quantities of biomass was placed in each test tube. Then equal volumes of different concentration (ranging from 50 - 200 mg/l) of liquid organic compound solution (mono or multi solute) was added to each test tube. The test tubes were shaken for approximately 4 hrs. In the conventional activated sludge plant, a hydraulic detention time of 4 to 8 hrs is used.

c. Consecutive Desorption Equilibrium Study

The centrifuged tubes of the adsorption equilibrium study were subjected to the desorption study. This study was done by decanting all the supernatant and adding 25 ml of organic free distilled water. The new mixture was shaken on the shaker similar to the adsorption equilibrium study. The amount of organic compound desorbed from the biomass was determined by measuring the increase of concentration of organic compound in the liquid phase.

3. Live Biomass Experiments

Adsorption and desorption experiments with live activated sludge biomass were performed in essentially the same way as experiments with inactive biomass. Live activated sludge was obtained from Stony Brook Regional Sewerage Authority River Road



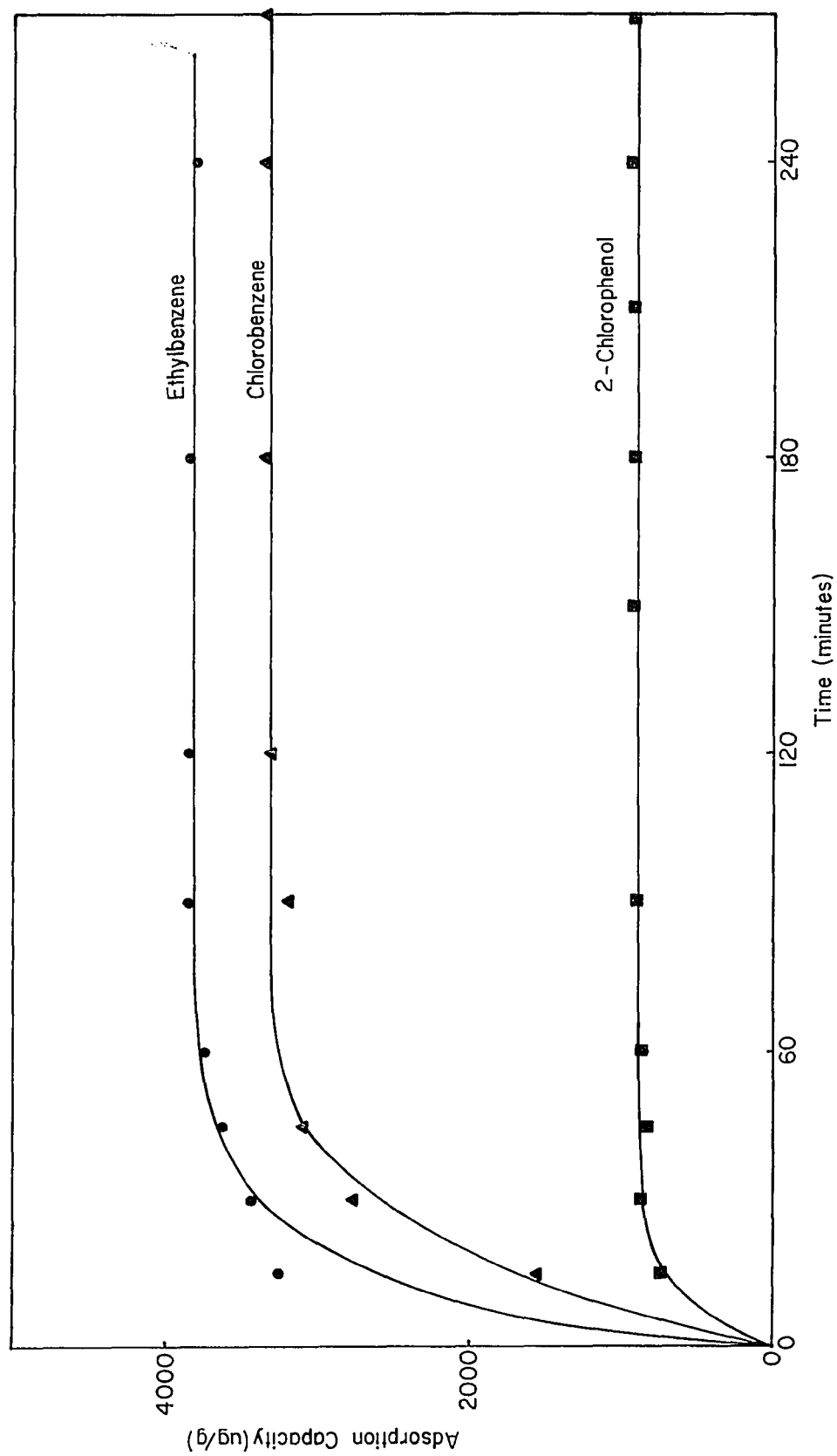


Figure 3.2: Time Effect on Adsorption of Organic Compounds.

Treatment Plant located in Princeton, New Jersey. The sludge was washed well with distilled/deionized water and dewatered by vacuum filtration.

Samples of the filtered sludge were placed in preweighed weighing dishes which were then weighed. The dishes were placed in an oven for drying at 105°C. After the samples were dried, they were reweighed and the percentage of dry weight in wet filtered sludge was determined. This was the basis for determining dry solids concentration in each adsorption tube. Measured quantities of wet biomass were added to test tubes. The remainder of the experiments proceeded as for the inactive biomass.

#### 4. Sorption Study with Activated Carbon

The batch technique was used to evaluate the equilibrium adsorption. The study was conducted in a series of 500 ml conical flasks with screw caps. 0.2 gm of filtrasorb 400 type activated carbon was placed in each flask. Then 500 ml of different concentration (ranging from 50 - 200 mg/l) of liquid organic compound solution was added to each tube. The remainder of the experiments proceeded as for the biomass.

## V. RESULTS AND DISCUSSION

### A. Equilibrium Adsorption Study with Inactive Biomass

For the equilibrium adsorption study, different quantities of microbial biomass were used with 25ml of liquid organic contaminant solutions of various concentrations. Phenol, 2-chlorophenol, 2-nitrophenol, chlorobenzene, and ethylbenzene were selected as the organic contaminants. The results are expressed in the form of equilibrium adsorption isotherms, which present the distribution of the solute between the adsorbent (biomass) and the solvent (water solution) at equilibrium.

Two of the most widely accepted adsorption isotherm models, namely, those of Langmuir and Freundlich, were used to fit the available organic uptake data. Both models fit the data reasonably well, with linear regression coefficients(r) greater than 0.94.

Freundlich adsorption is the most useful for dilute solutions over small concentration ranges.

$$q = X/m = K_d C_e^{1/n} \quad (5.1)$$

where  $X$  = weight of contaminant adsorbed (ug)

$$= V (C_i - C_e)$$

$V$  = volume of contaminant used (ml)

$C_i$  = initial concentration of the contaminant (mg/l)

$C_e$  = concentration of solute remaining in the solution

$m$  = weight of adsorbent(biomass) (g)

$q$  = adsorption capacity of sorbent(ug/g)

$K_d$  and  $1/n$  are constants depending on temperature, the characteristics of sorbent and the substance to be adsorbed.

The Freundlich adsorption isotherm can be rearranged to the following form:

$$\log q = \log K_d + 1/n \log C_e \quad (5.2)$$

From the above equation, both the value of  $K_d$  and  $1/n$  give the adsorption capacity as a function of effluent concentration. The higher values of  $K_d$  and  $1/n$ , the better the adsorption capacity. However, the value of  $K_d$  is only a linear function of the concentration, whereas  $1/n$  is an exponential function. That means, if the value of  $K_d$  is small and that of  $1/n$  is large (greater than one), the adsorption capacity is highly dependent on the equilibrium concentration. Conversely, if  $K_d$  is large and  $1/n$  is small (smaller than one) then the adsorption will be favored by a lower effluent concentration. It has been found that the concentration levels of the toxic organic compounds in the hazardous waste stream are low.

Freundlich adsorption isotherms for activated sludge biomass with phenol, chlorophenol, nitrophenol, chlorobenzene and ethyl benzene are shown in Figures 5.1 through 5.5 respectively. The summary of the values of the parameters for the Freundlich adsorption isotherm and the adsorption capacity at 100 ppm equilibrium concentration are presented in Table 5.1. Figure 5.6

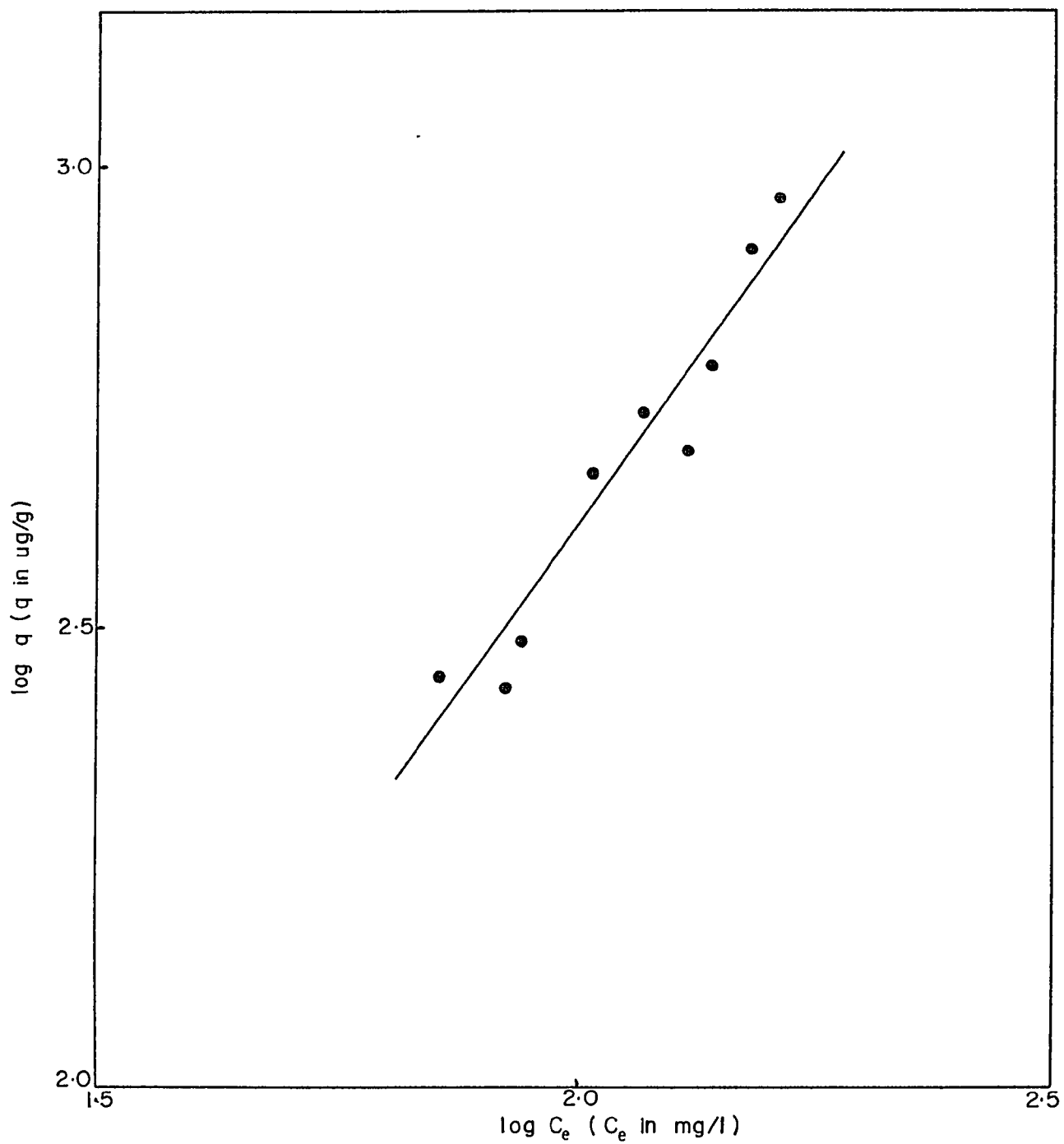


Figure 5.1: Freundlich Adsorption Isotherm for Phenol-Activated Sludge Biomass.

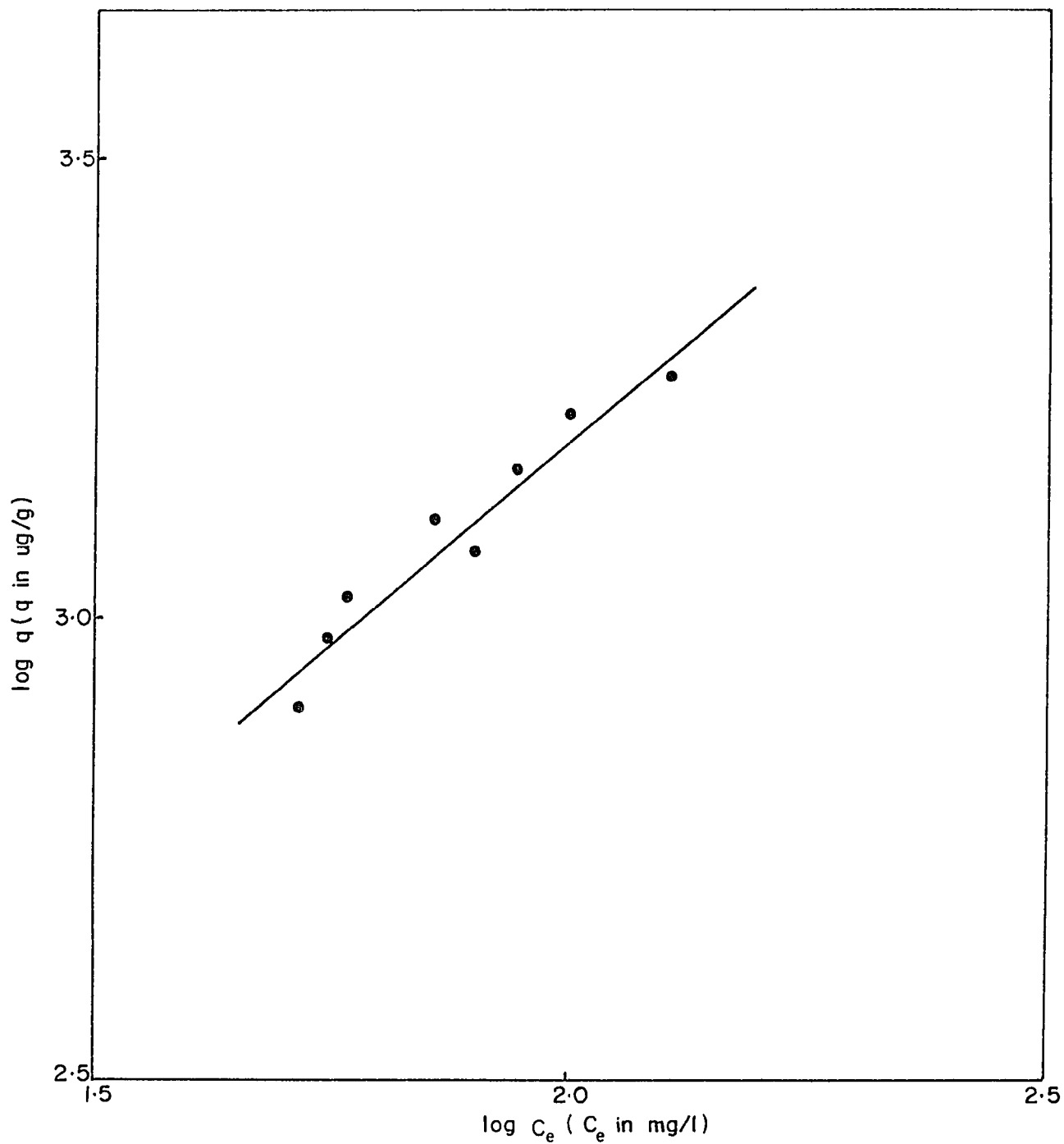


Figure 5.2: Freundlich Adsorption Isotherm for Chlorophenol-Activated Sludge Biomass.

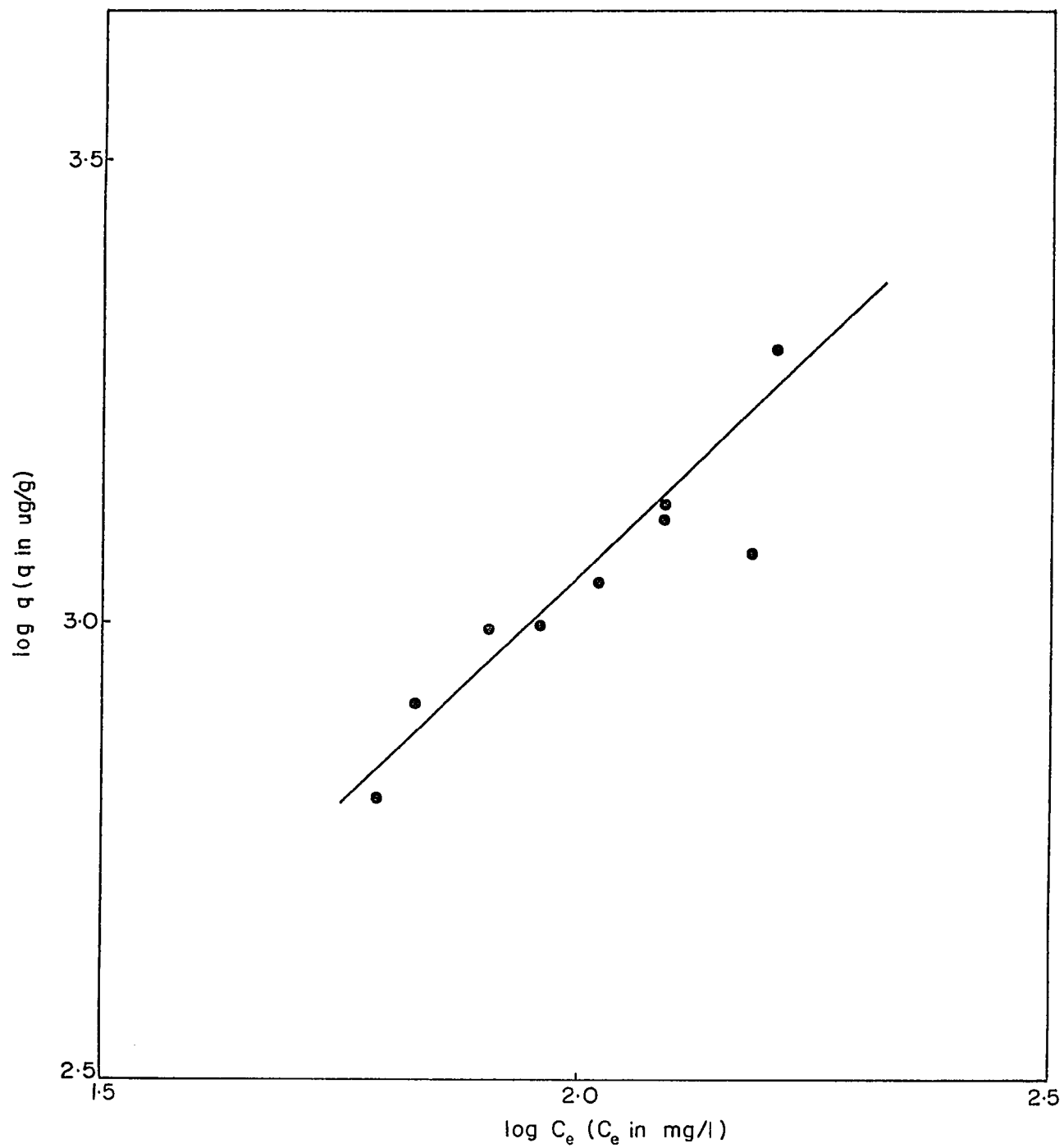


Figure 5.3: Freundlich Adsorption Isotherm for Nitrophenol-Activated Sludge Biomass.

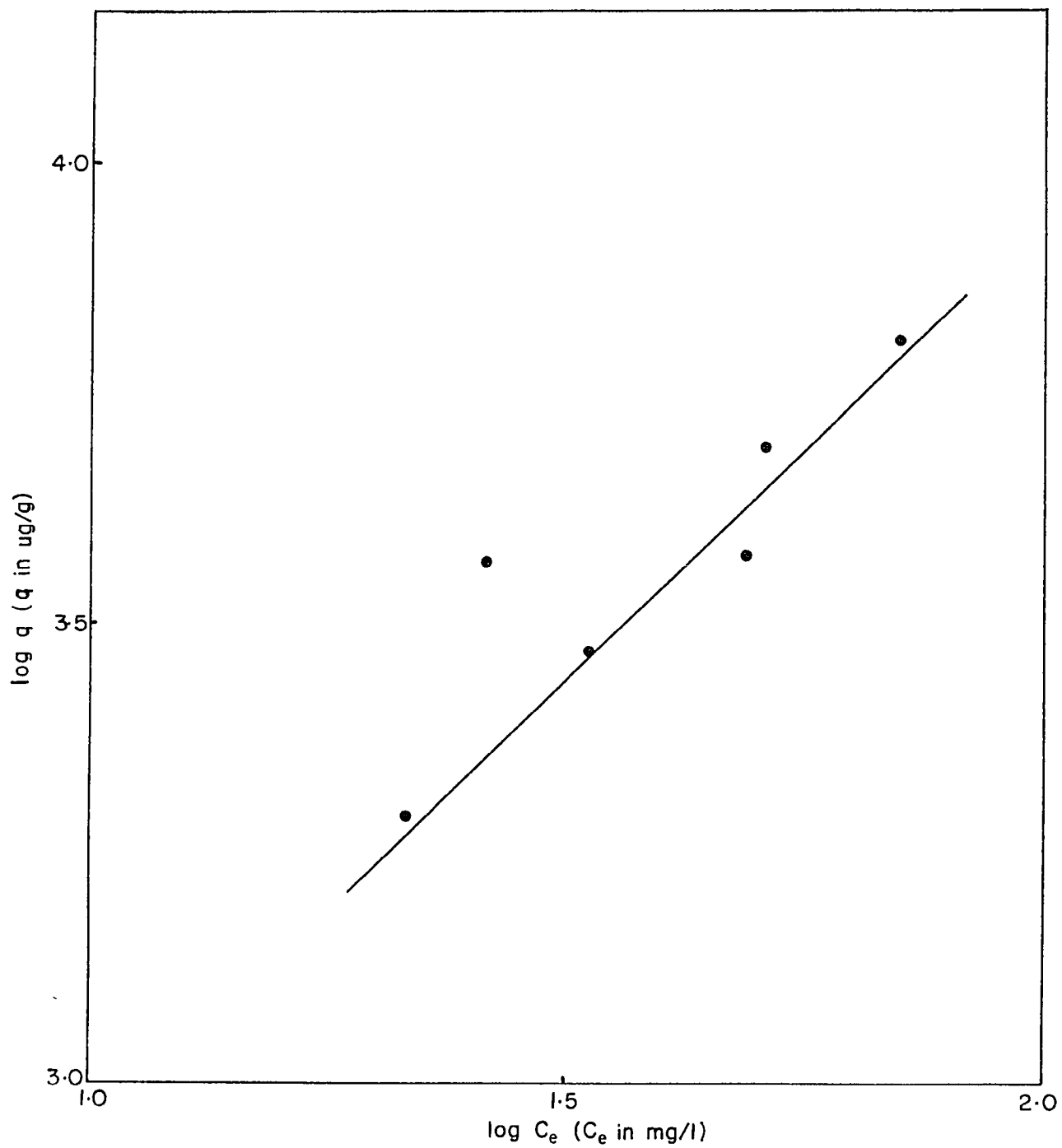


Figure 5.4: Freundlich Adsorption Isotherm for Chlorobenzene-Activated Sludge Biomass.



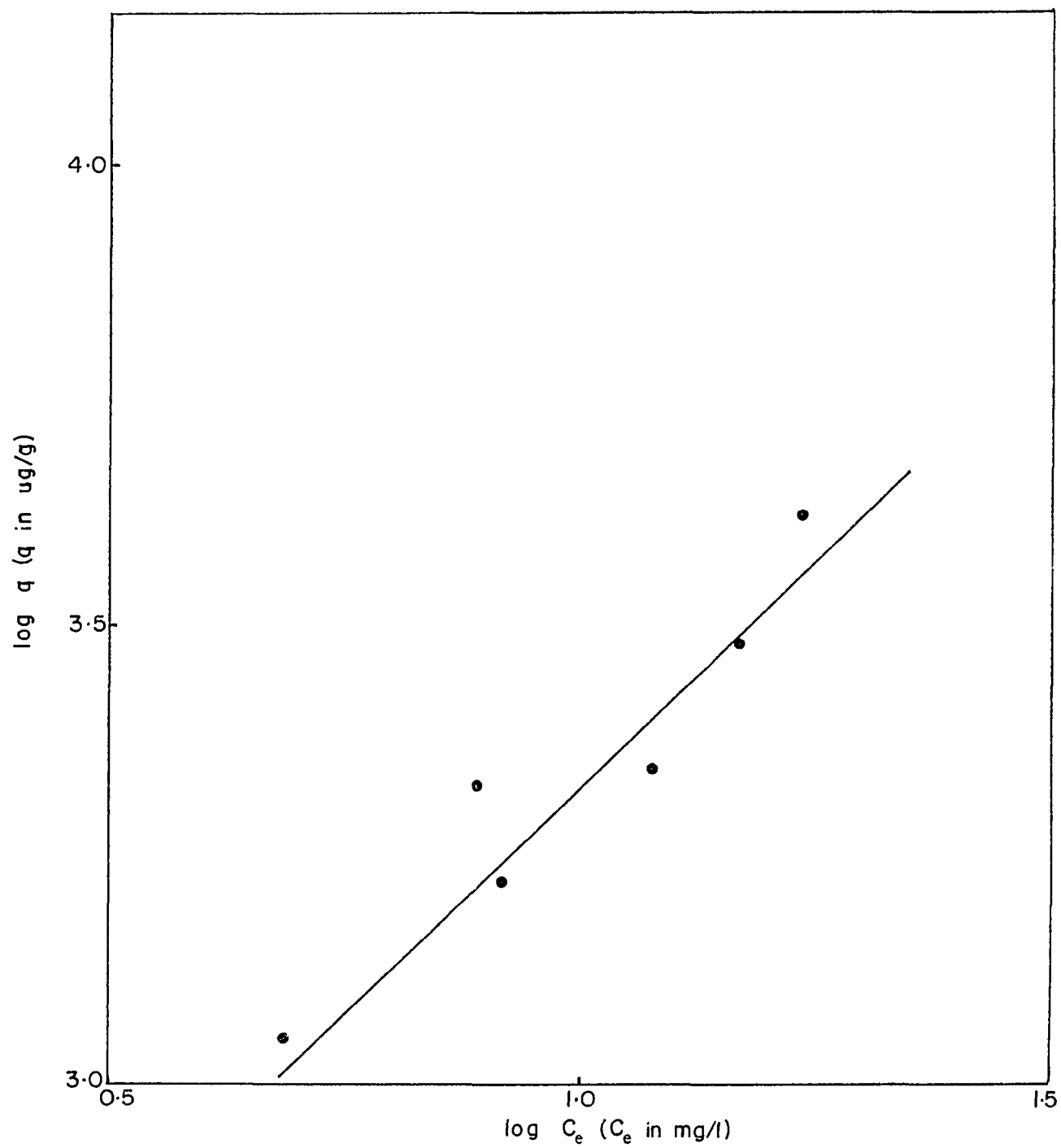


Figure 5.5: Freundlich Adsorption Isotherm for Ethylbenzene-Activated Sludge Biomass.

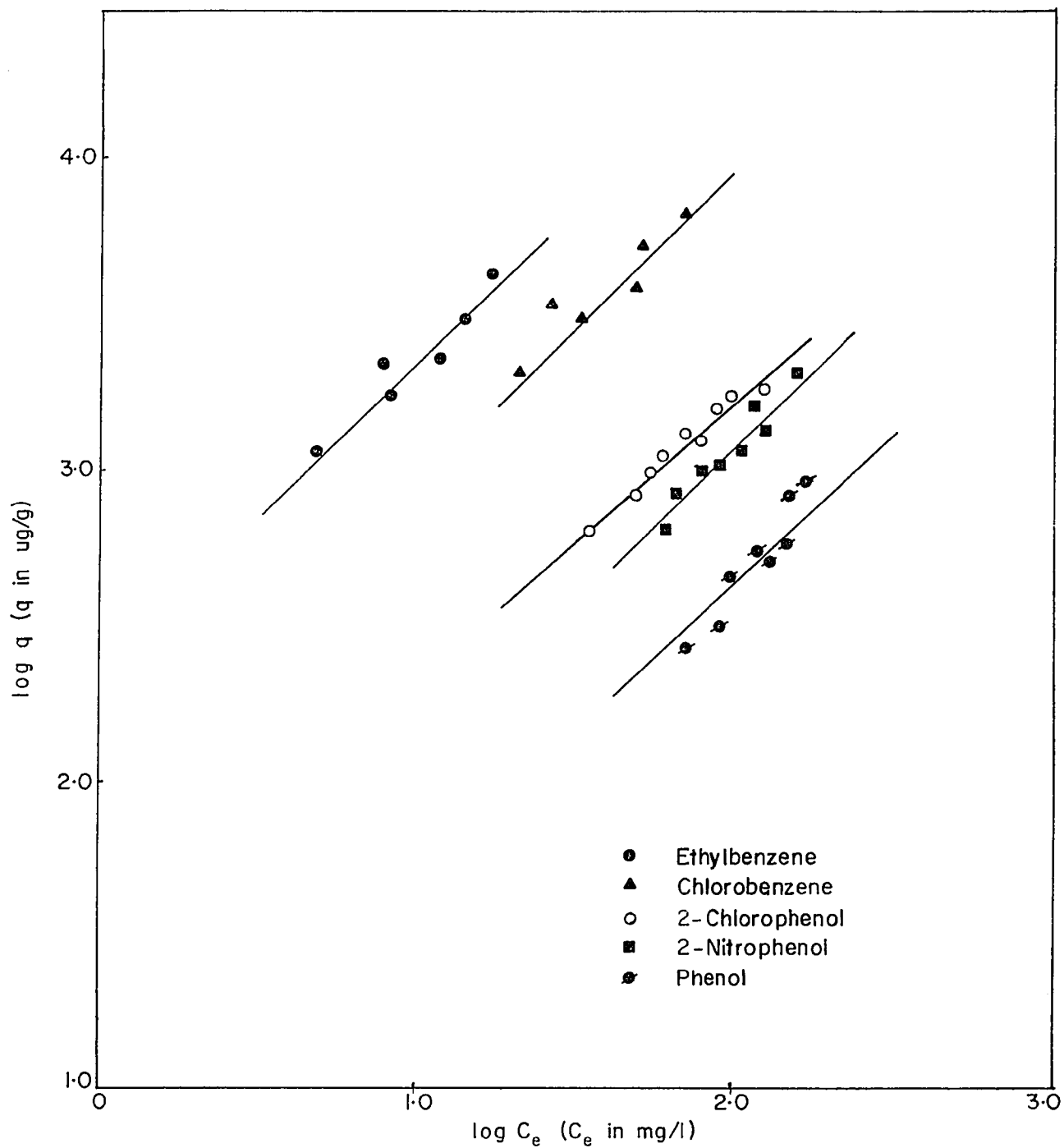


Figure 5.6: Freundlich Adsorption Isotherms for all Compounds with Activated Sludge Biomass.

summarizes the Freundlich adsorption isotherms for the five compounds with activated sludge biomass.

**Table 5.1: Freundlich Adsorption Isotherm for Inactive Activated Sludge Biomass**

Compound	Equation	Adsorption Capacity at 100 ppm (ug/g)
Phenol	$q = 0.53 C_e^{1.443}$	407.64
2-Chlorophenol	$q = 26.33 C_e^{0.886}$	1557.58
2-Nitrophenol	$q = 11.49 C_e^{0.993}$	1112.55
Chlorobenzene	$q = 88.51 C_e^{0.998}$	8769.95
Ethylbenzene	$q = 223.10 C_e^{0.977}$	20067.79

Adsorption isotherms for nitrifying bacteria with all five compounds are shown in Figures 5.7 through 5.11 with the fitted Freundlich equation lines. The summary of the values of the parameters for the Freundlich adsorption isotherm is presented in Table 5.2. Figure 5.12 summarizes the Freundlich adsorption isotherm for the five compounds with the nitrifying bacteria.

**Table 5.2: Freundlich Adsorption Isotherm for Nitrifying Bacteria**

Compound	Equation	Adsorption Capacity at 100 ppm (ug/g)
Phenol	$q = 7.05 C_e^{0.831}$	323.59
2-Chlorophenol	$q = 13.97 C_e^{1.013}$	1483.50
2-Nitrophenol	$q = 17.39 C_e^{0.855}$	891.86
Chlorobenzene	$q = 104.29 C_e^{0.948}$	8208.10
Ethylbenzene	$q = 183.06 C_e^{1.039}$	21907.77

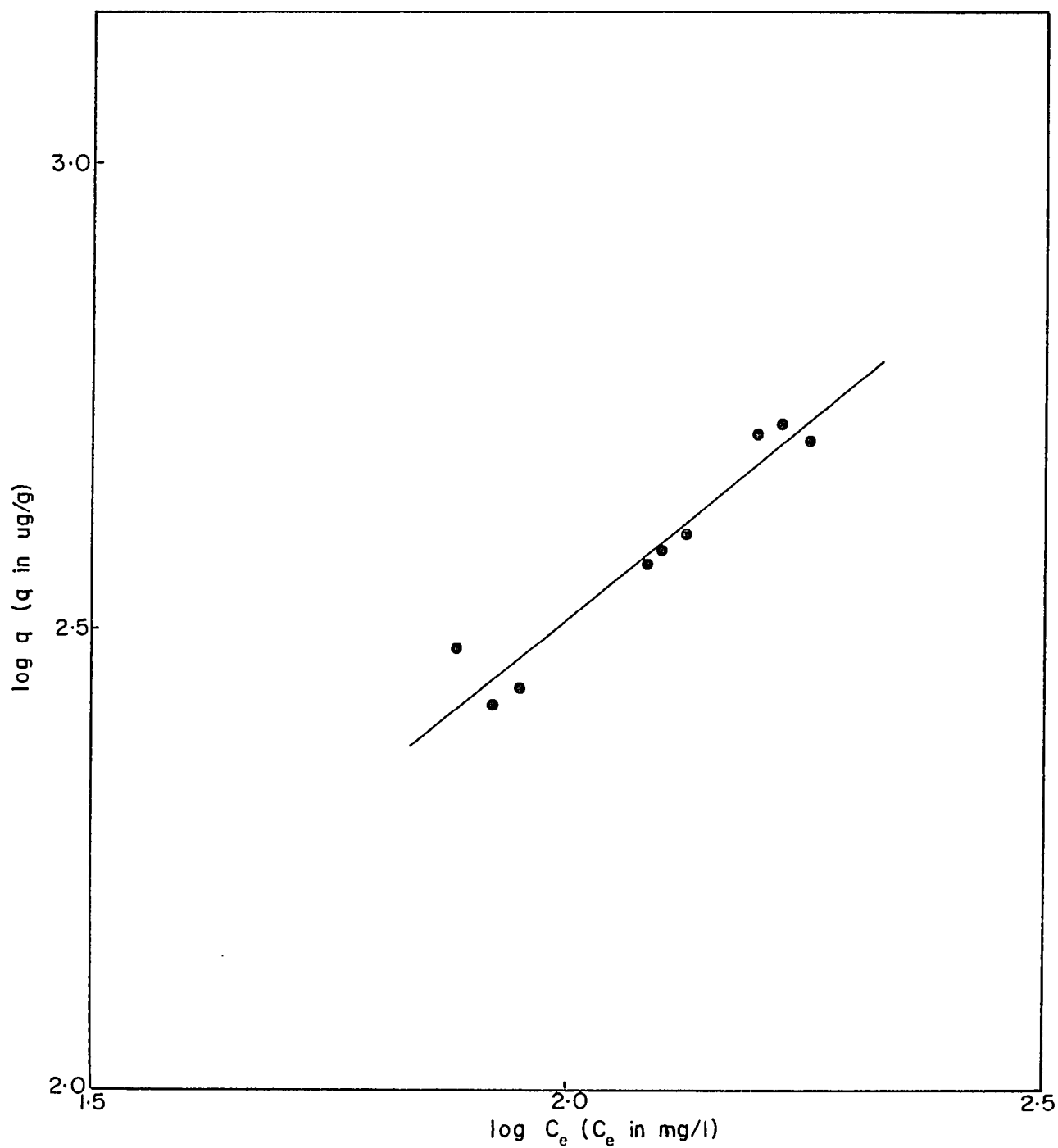


Figure 5.7: Freundlich Adsorption Isotherm for Phenol - Nitrifying Bacteria.

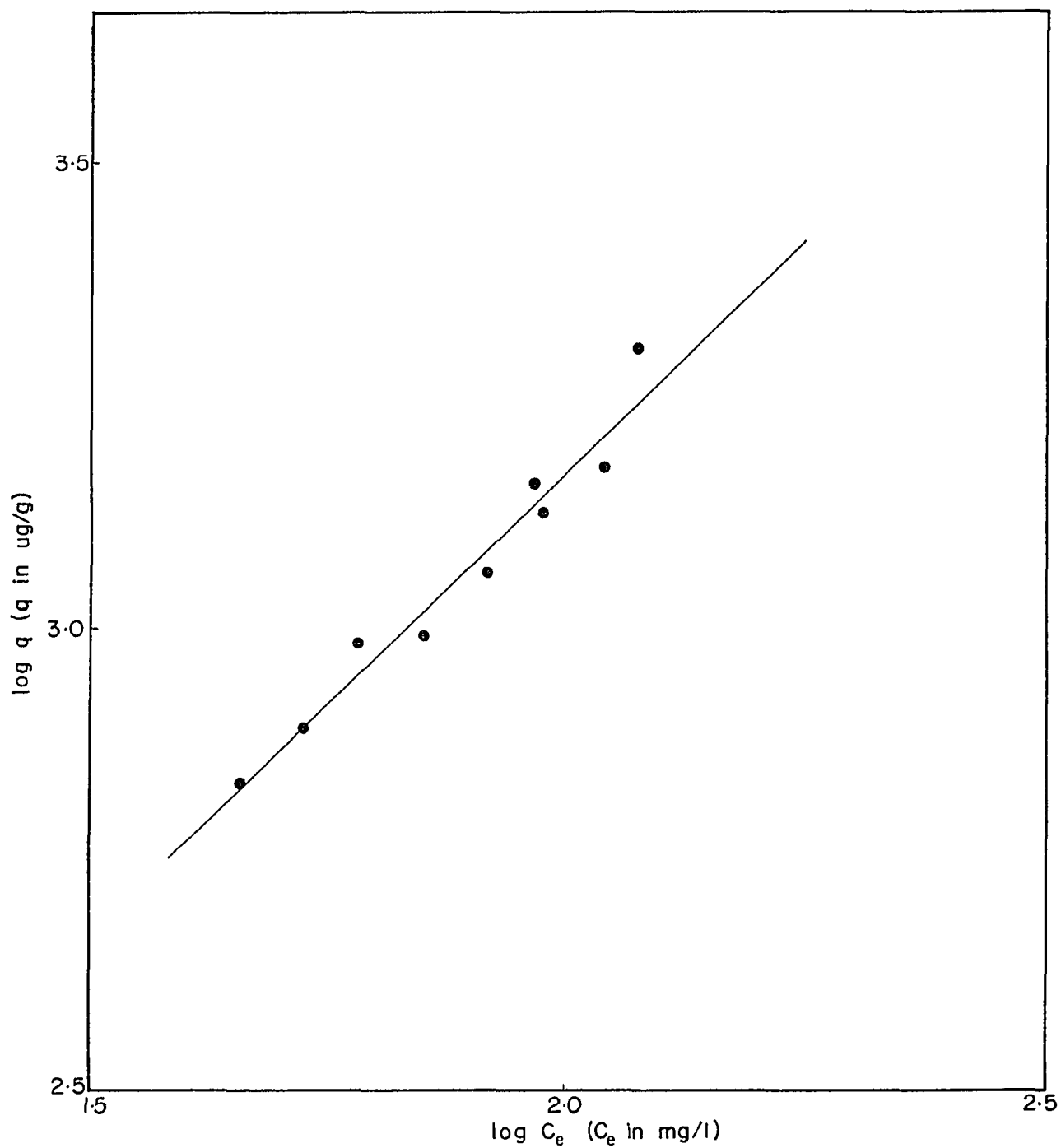


Figure 5.8: Freundlich Adsorption Isotherm for Chlorophenol-Nitrifying Bacteria.

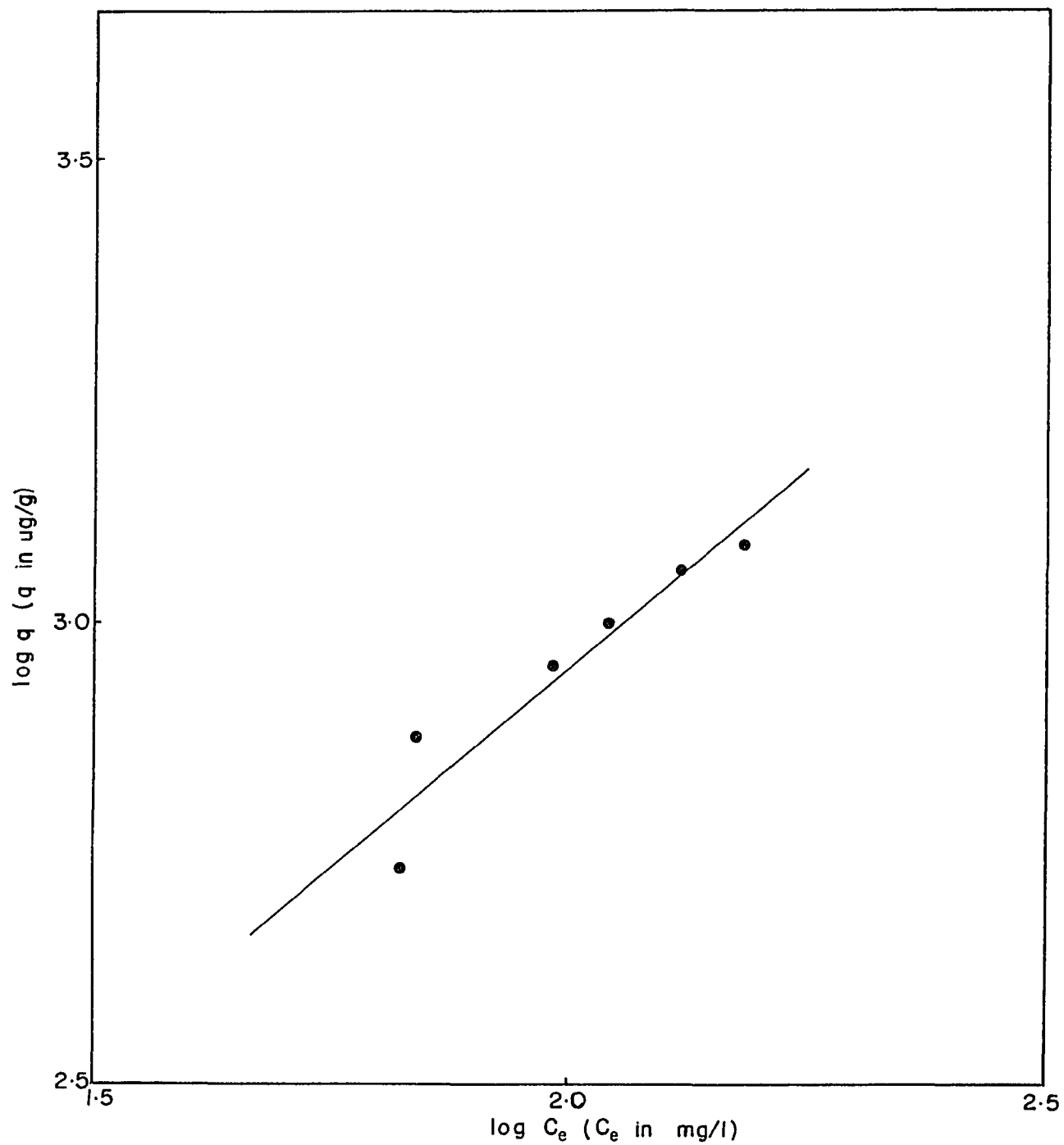


Figure 5.9: Freundlich Adsorption Isotherm for Nitrophenol  
-Nitrifying Bacteria.

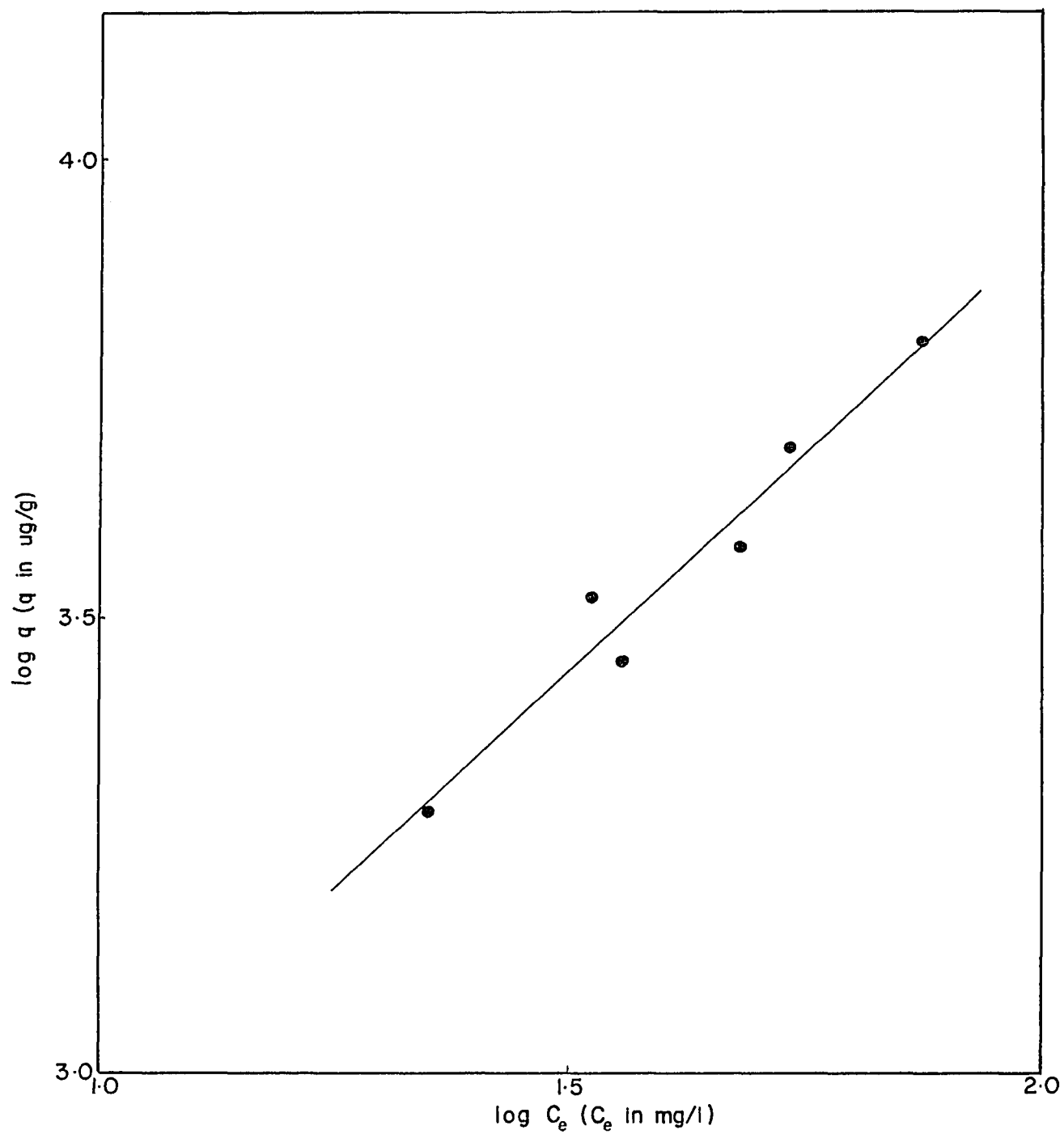


Figure 5.10: Freundlich Adsorption Isotherm for Chlorobenzene-Nitrifying Bacteria.

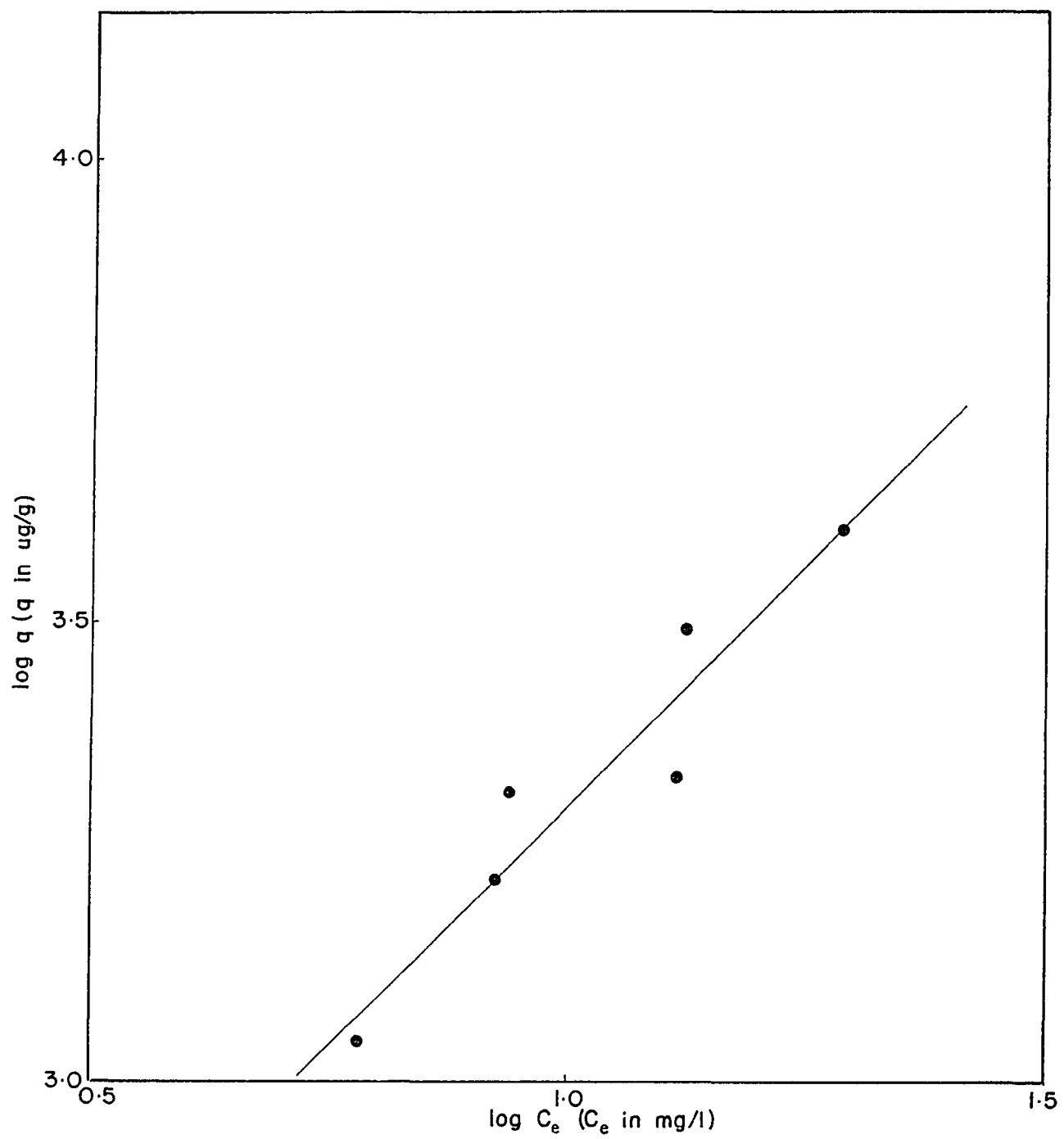
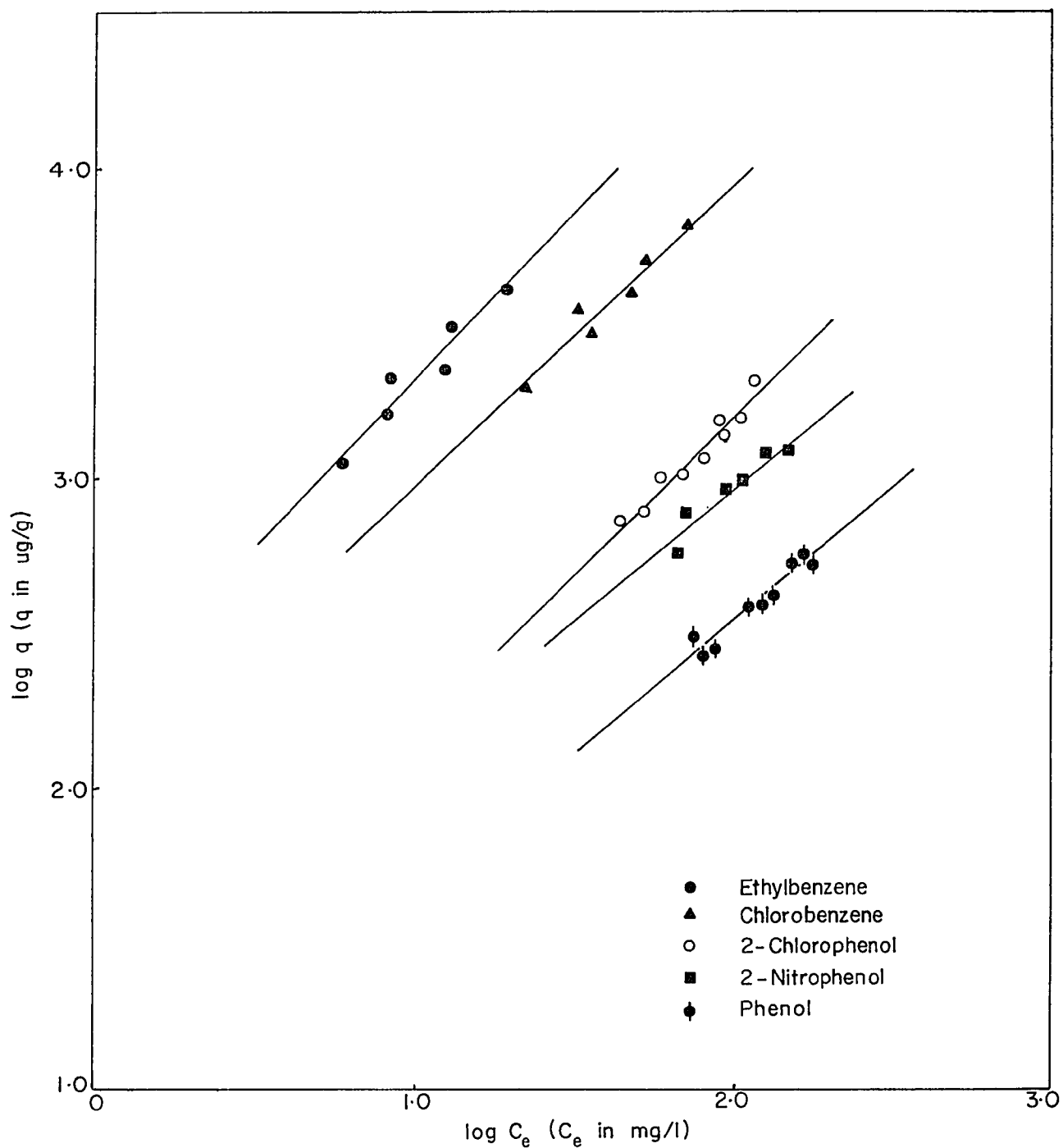


Figure 5.11: Freundlich Adsorption Isotherm for Ethylbenzene-Nitrifying Bacteria.





**Figure 5.12: Freundlich Adsorption Isotherms for all Compounds with Nitrifying Bacteria.**

Adsorption capacities ( $q$ ) at 100 ppm equilibrium concentration of the compounds used are also tabulated in Table 5.1 and 5.2 for activated sludge and nitrifying bacteria respectively. Note that the order of sorptive strength is:

Ethylbenzene > Chlorobenzene > 2-Chlorophenol > 2-Nitrophenol > Phenol.

Adsorption in biological systems has frequently been represented by the Freundlich equation or by a linear relationship which the Freundlich equation reduces to when the exponential parameter equals to one (Tsezos and Bell, 1987). At low concentrations, where only a small fraction of the ultimate adsorption capacity may be used, a nearly linear isotherm is expected. At higher concentrations, where a larger portion of the available adsorption capacity might be used, a nonlinear isotherm is expected. In that case, the exponent in the Freundlich equation should be less than one. For most of the systems tested in this study, the isotherms are close to linearity, indicating that saturation of the adsorption capacity of the biomass was not approached.

The equilibrium adsorptive uptake appears to be independent of the initial concentration of liquid organic compounds and biomass concentration because data obtained with different starting concentrations and biomass concentrations fit the same isotherm.

It can be seen from the results that the extent of

biosorption by the microorganisms depends on the type of biomass. Activated sludge biomass showed a relatively higher biosorptive uptake capacity than the nitrifying bacteria. One suggestion that has often been mentioned in the literature in describing biosorptive phenomena is that the bioaccumulation of highly hydrophobic organic compounds is directly related to the lipid content of the organism (Ware and Roan, 1970; Lal and Saxena, 1982). But experimental results of Tsezos and Seto (1986) did not confirm this. However, a comparison of the relative adsorptive capacities with the organic carbon content indicated a trend.

In order to determine whether the experimental results of this study has any correlation to organic carbon content, the fraction of organic carbon ( $f_{OC}$ ) of the activated sludge biomass and the nitrifying bacteria were determined. The fraction of organic carbon was determined using an infrared absorption method. The analysis was done by Galbraith Laboratories Inc., Knoxville, Tennessee. The  $f_{OC}$  of activated sludge and nitrifying bacteria were found to be 0.3673 and 0.3624, respectively. A comparison of the relative adsorption capacities with the organic carbon content indicated a trend. Activated sludge biomass showed the higher uptake capacity and also had the larger organic carbon content.

Two physical - chemical properties, aqueous solubility and octanol/water partition coefficient, play an important role in determining the partitioning behavior of chemicals in the environment. The adsorption - solubility relationship may be

understood by considering the physical adsorption of a chemical from an aqueous solution. As adsorption is an exothermic process in which the adsorbate condenses from the bulk phase onto the adsorbed phase, an increase in solubility with increasing temperature results in a reduction of the amount adsorbed. For compounds of comparable molecular size with different solubilities, the one with lower solubility, i.e., lower hydrophilicity, tends to be adsorbed more favorably at a given equilibrium concentration. Likewise, the one with the higher octanol/water partition coefficient tends to be adsorbed more favorably at a given equilibrium concentration. The above phenomena occurred in this study.

The least soluble compound studied, namely ethylbenzene, showed the highest uptake with both activated sludge and nitrifying bacteria. Although chlorophenol is more soluble (one order of magnitude greater) than nitrophenol, it is adsorbed more significantly. This implies that aqueous solubility offers only a very rough prediction of adsorption by biomass. The octanol/water partition coefficient of chlorophenol, however, is three times greater than that of nitrophenol. Hence, the octanol/water partition coefficient is a better predictor of the extent of adsorption on microbial biomass than the aqueous solubility. Lambert(1968) said that the partitioning of a neutral organic compound between soil organic matter and water should correlate well with its octanol/water partition coefficient if the role of soil organic matter is similar to that of an organic solvent. Hence it is demonstrated here that the sorption of

organic compounds by microbial biomass is related to the organic content of the biomass as octanol/water partition coefficient is a better predictor than the aqueous solubility.

Langmuir Adsorption Isotherms for activated sludge biomass with phenol, chlorophenol, nitrophenol, chlorobenzene and ethylbenzene are shown in Figures 5.13 to 5.17 and the experimental equation is tabulated in Table 5.3.

**Table 5.3: Langmuir Adsorption Isotherm for Activated Sludge Biomass**

Compound	Equation	Regression Coefficient
Phenol	$q = \frac{2.802 C_e}{1 - 0.002783 C_e}$	0.96
2-Chlorophenol	$q = \frac{18.3 C_e}{1 + 0.00174 C_e}$	0.98
2-Nitrophenol	$q = \frac{11.34 C_e}{1 + 0.000187 C_e}$	0.97
Chlorobenzene	$q = \frac{90.83 C_e}{1 + 0.000842 C_e}$	0.99
Ethylbenzene	$q = \frac{248.51 C_e}{1 + 0.0129 C_e}$	0.96

Langmuir adsorption isotherms for nitrifying bacteria with all five compounds are shown in Figures 5.18 to 5.22 and the experimental equation is tabulated in Table 5.4.

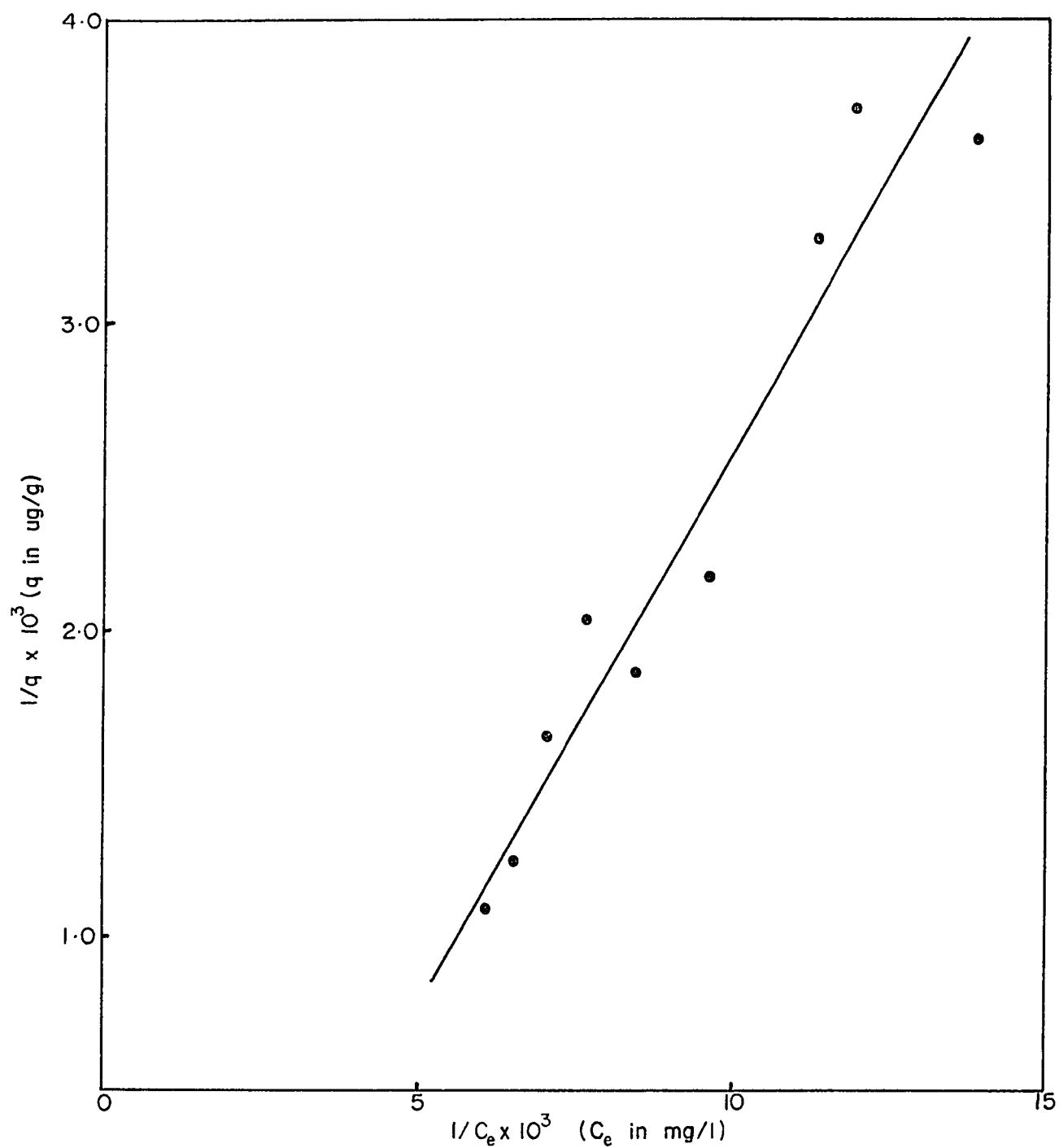


Figure 5.13: Langmuir Adsorption Isotherm for Phenol - Activated Sludge Biomass.

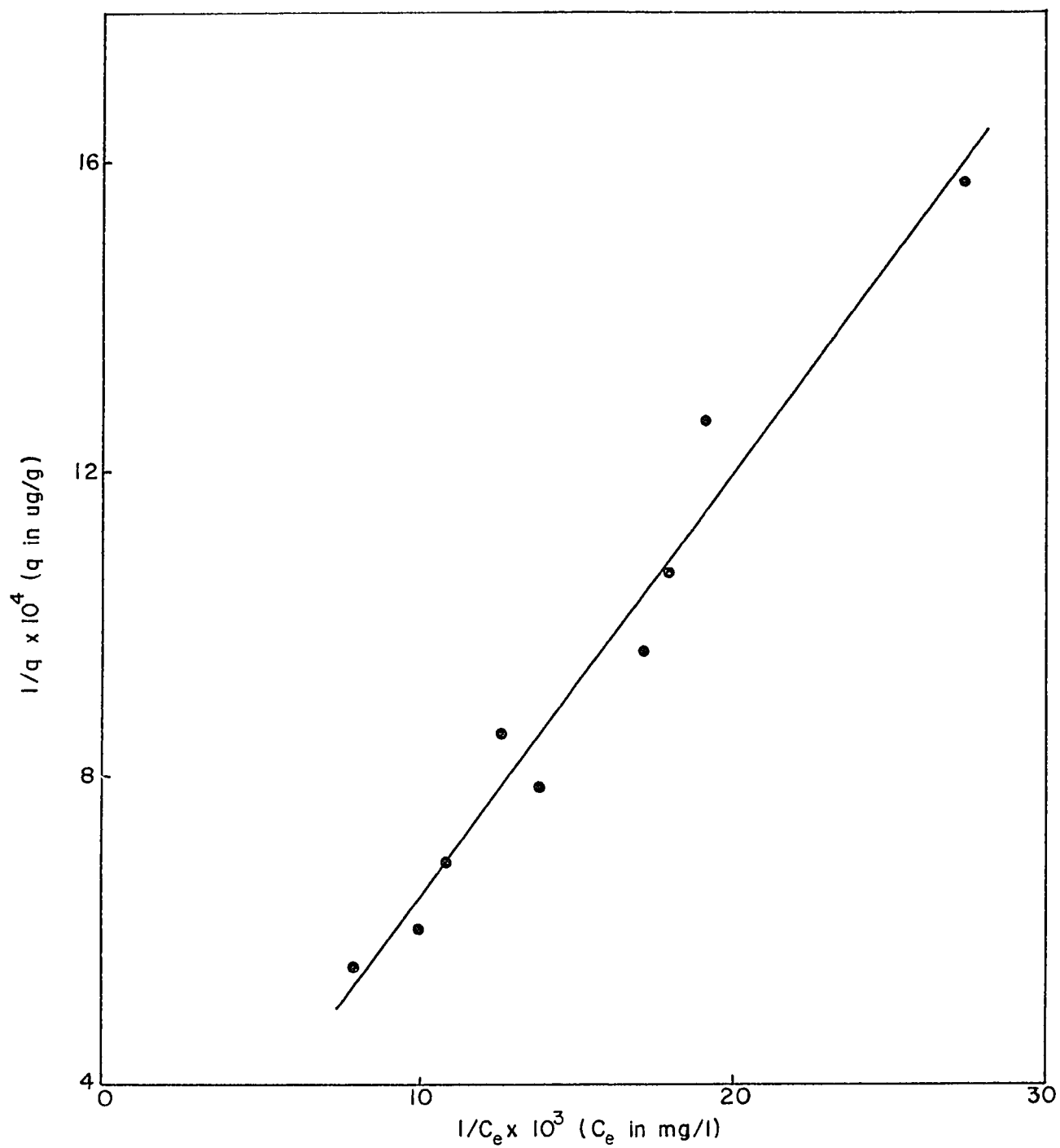


Figure 5.14: Langmuir Adsorption Isotherm for Chlorophenol - Activated Sludge Biomass.

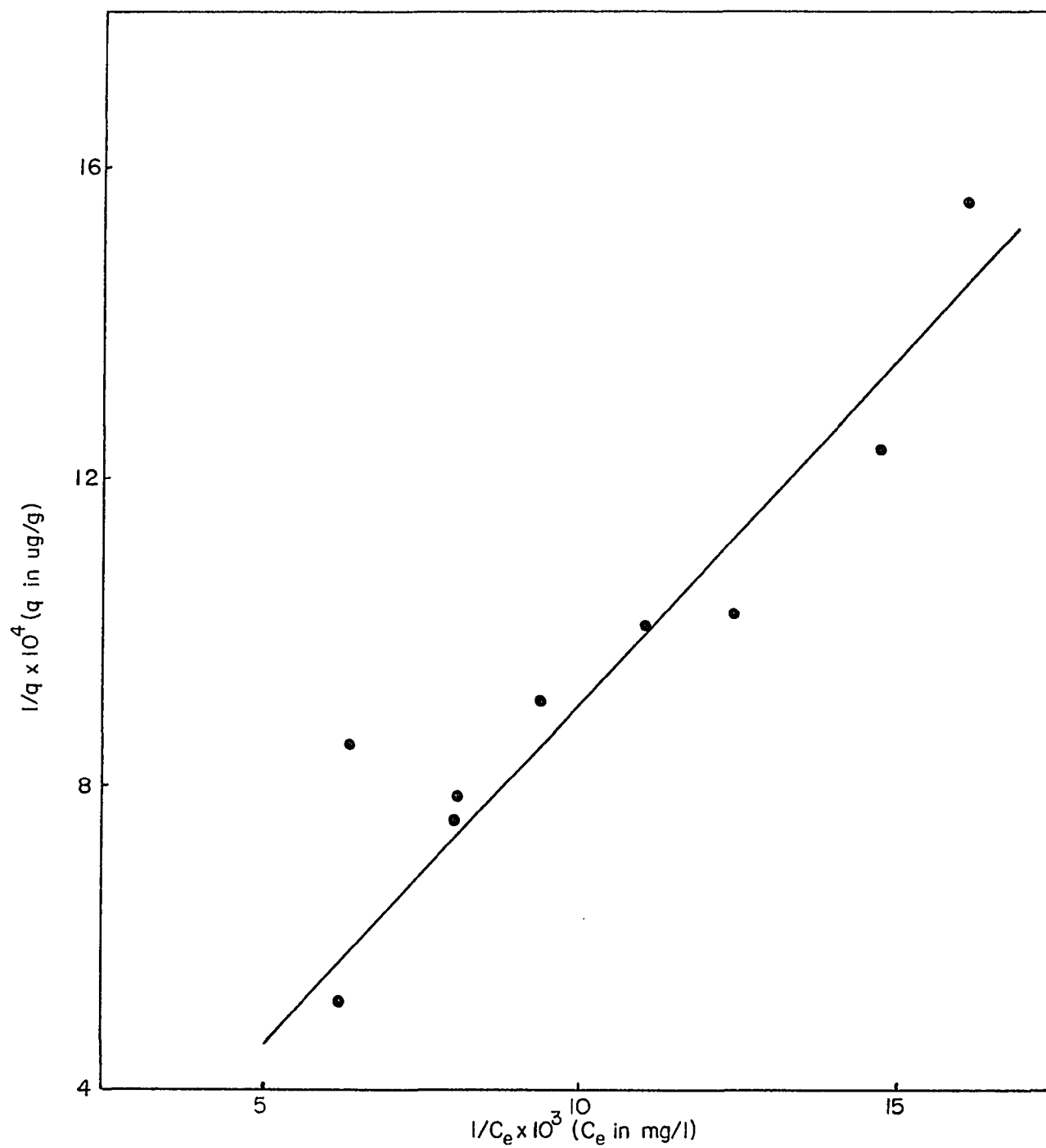


Figure 5.15: Langmuir Adsorption Isotherm for Nitrophenol-Activated Sludge Biomass.



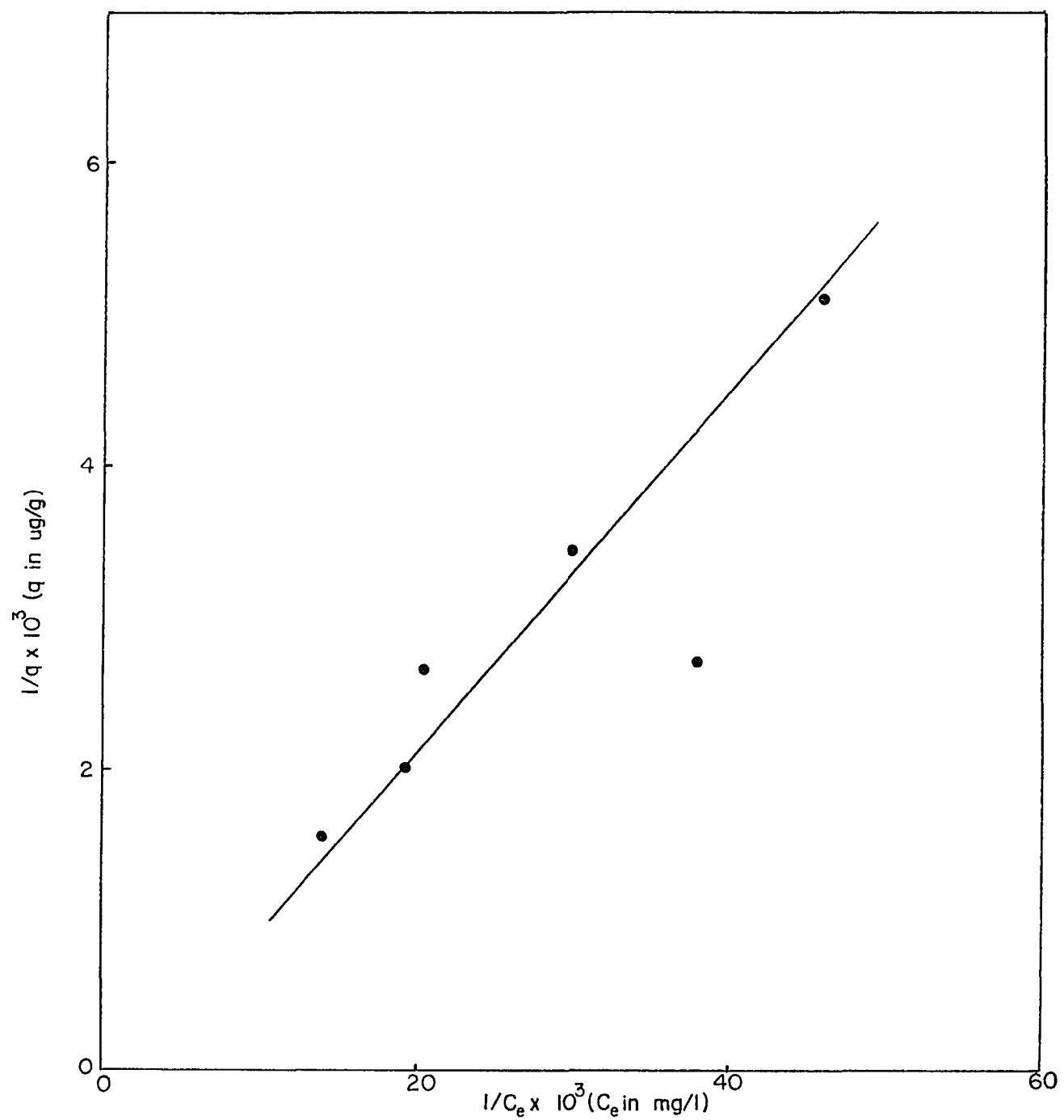


Figure 5.16: Langmuir Adsorption Isotherm for Chlorobenzene-Activated Sludge Biomass.

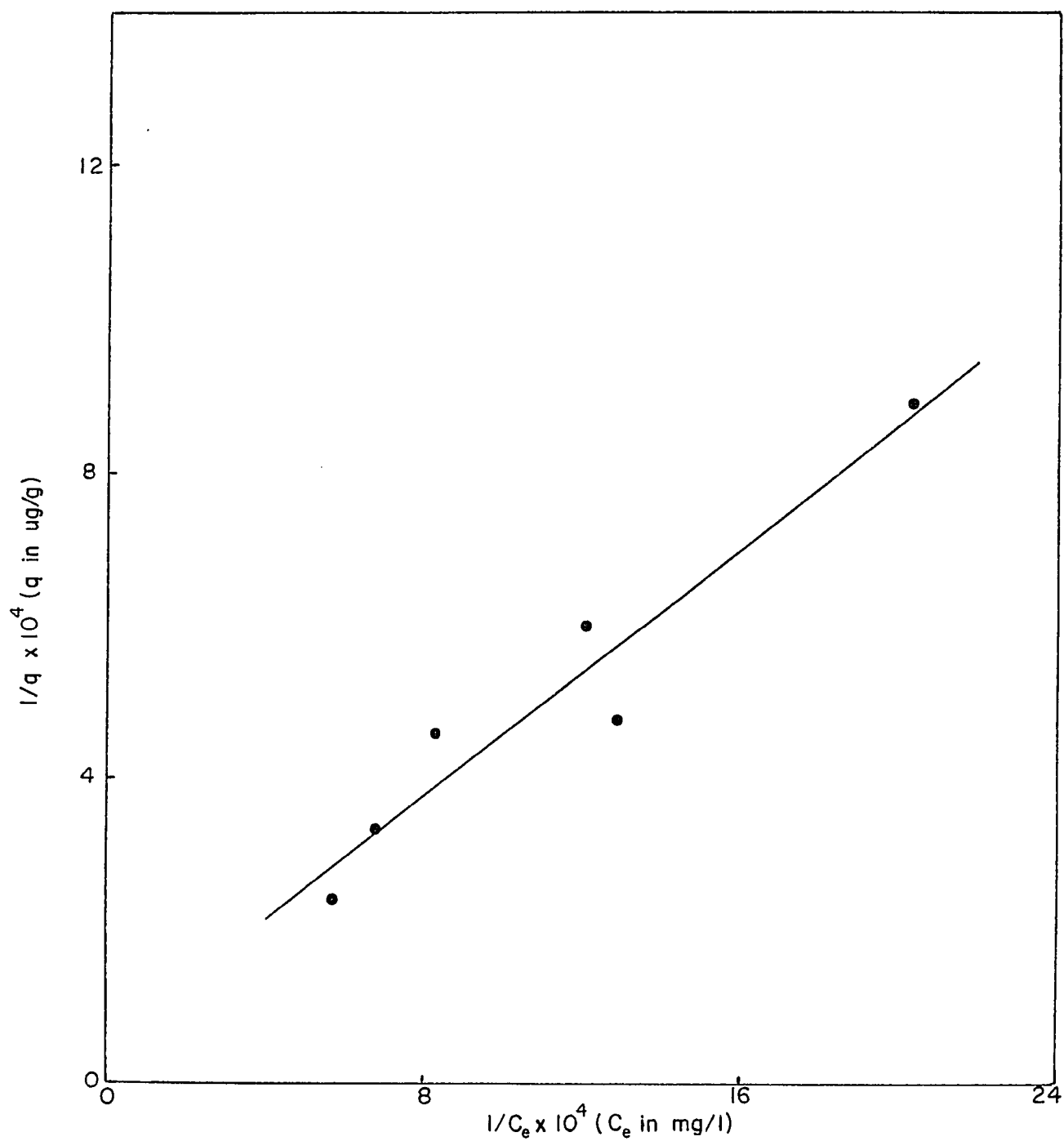


Figure 5.17: Langmuir Adsorption Isotherm for Ethylbenzene-Activated Sludge Biomass.

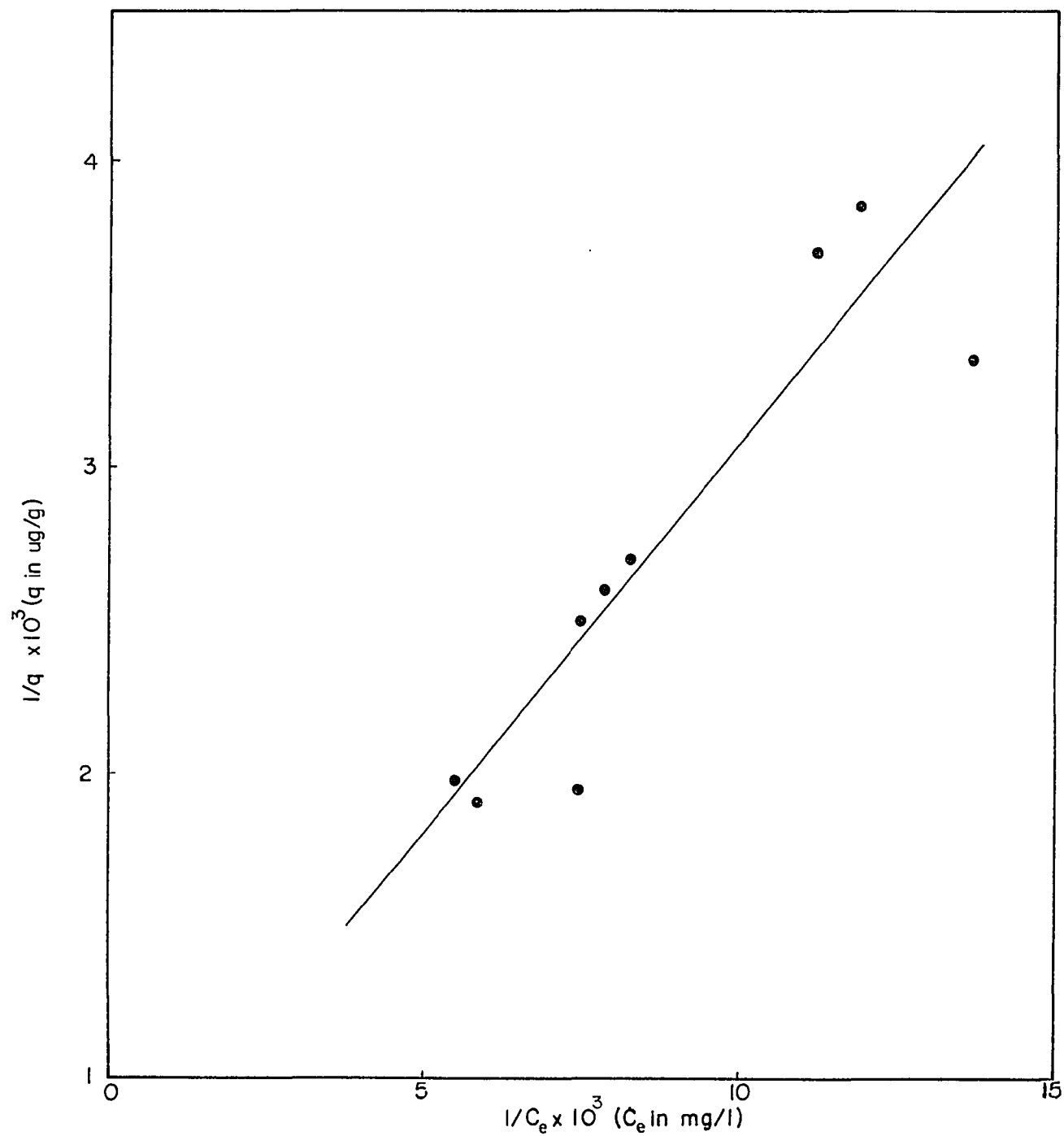


Figure 5.18: Langmuir Adsorption Isotherm for Phenol - Nitrifying Bacteria.

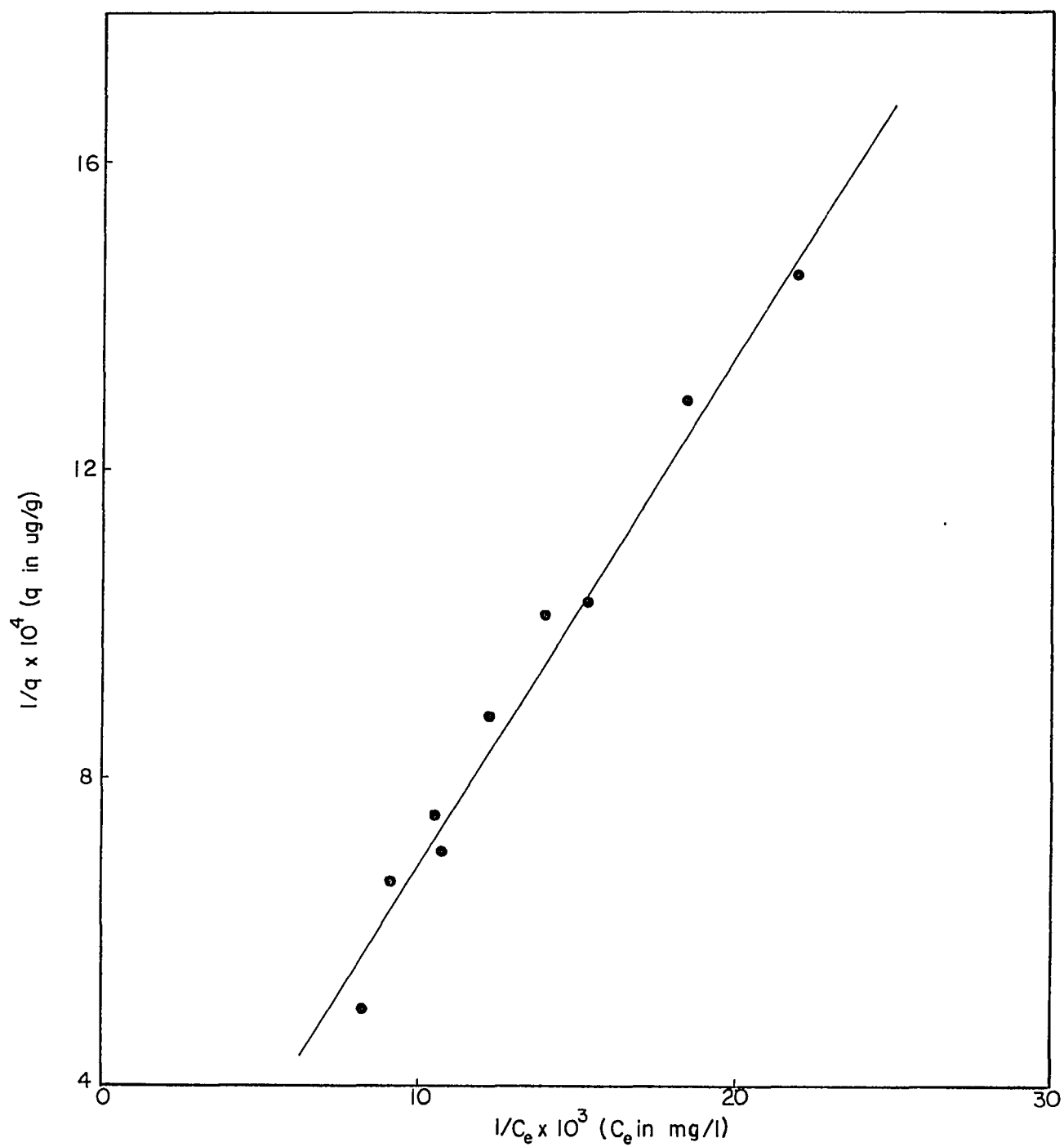


Figure 5.19: Langmuir Adsorption Isotherm for Chlorophenol-Nitrifying Bacteria.

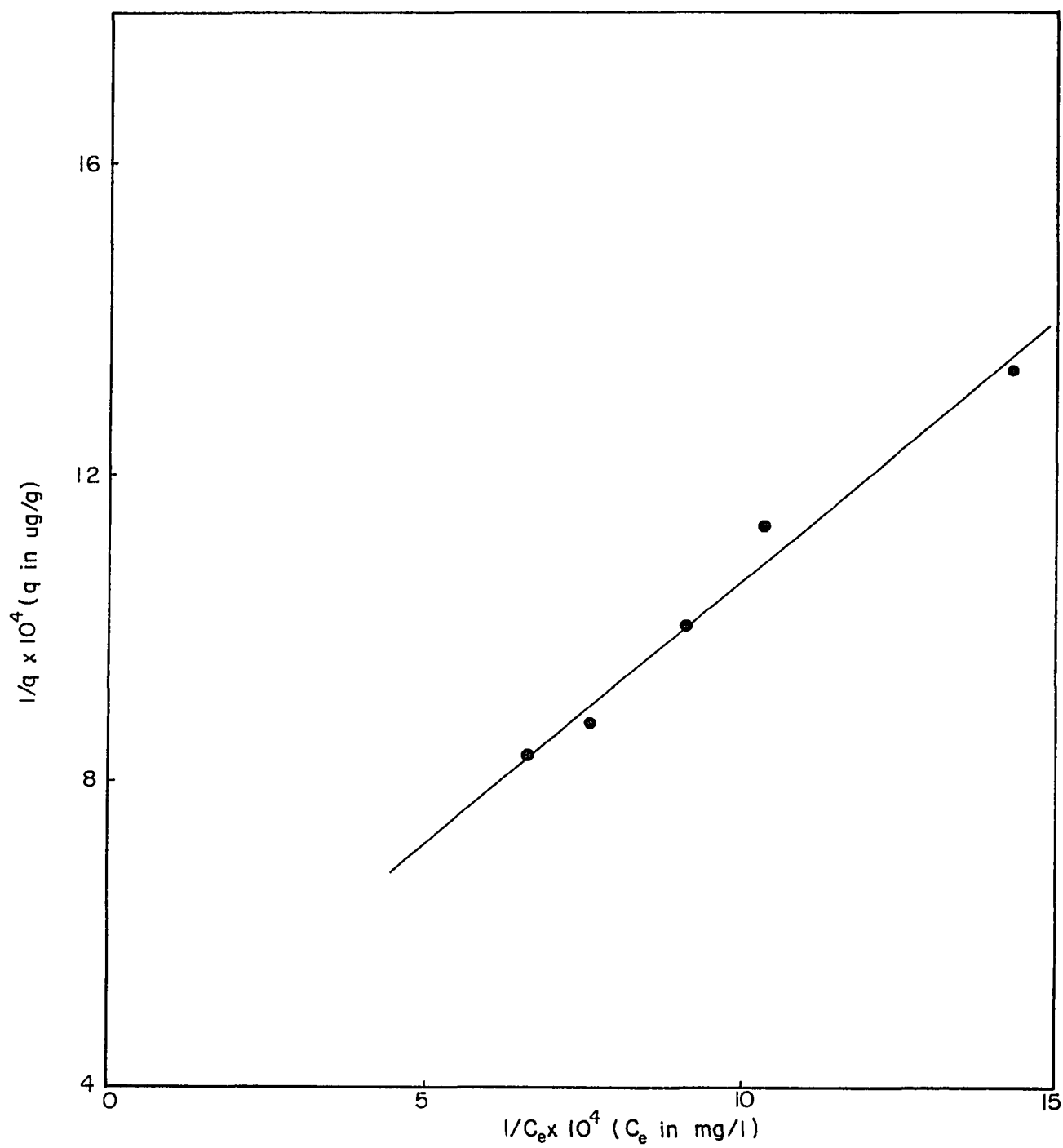


Figure 5.20: Langmuir Adsorption Isotherm for Nitrophenol  
-Nitrifying Bacteria.

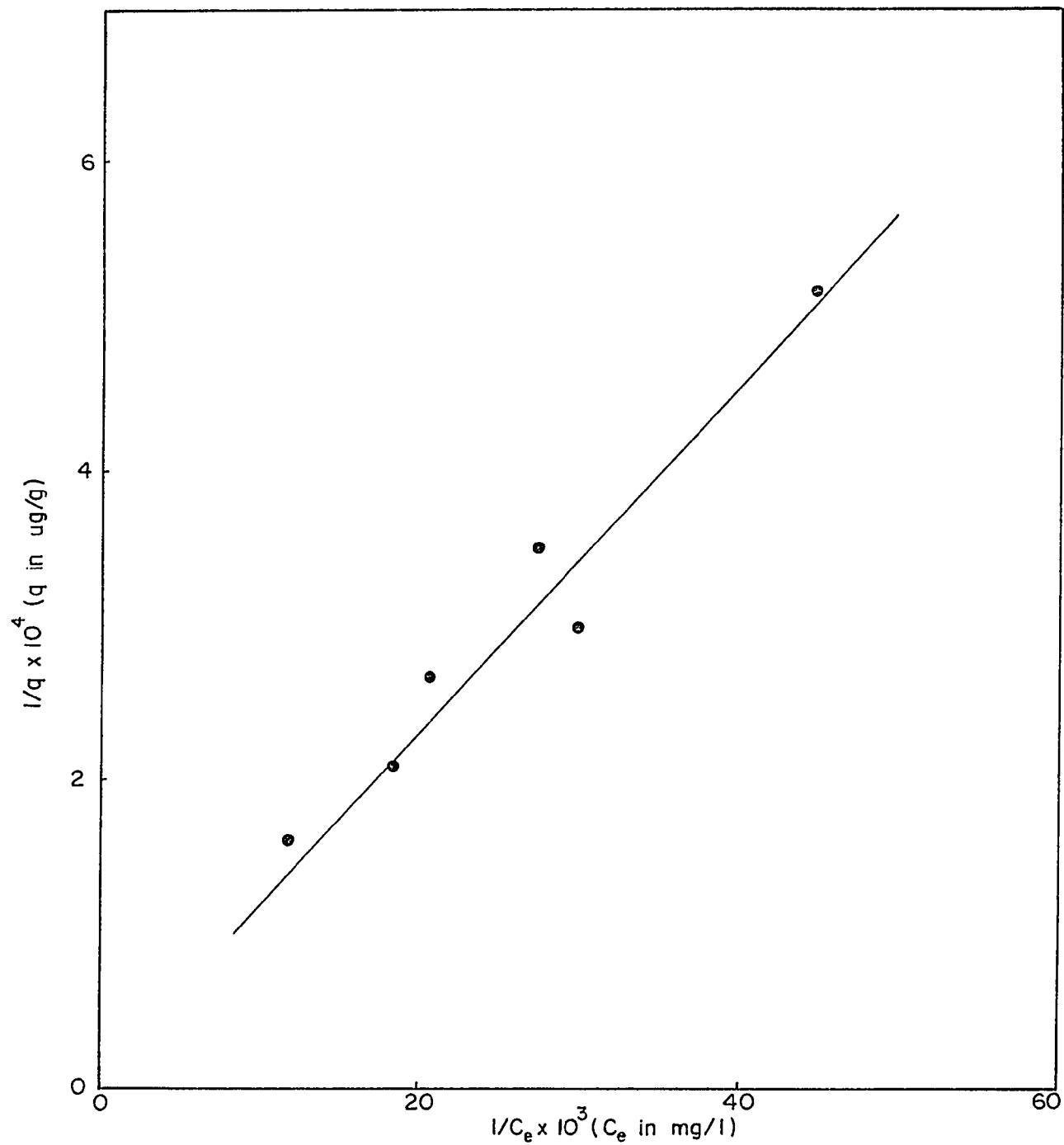


Figure 5.21: Langmuir Adsorption Isotherm for Chlorobenzene-Nitrifying Bacteria.

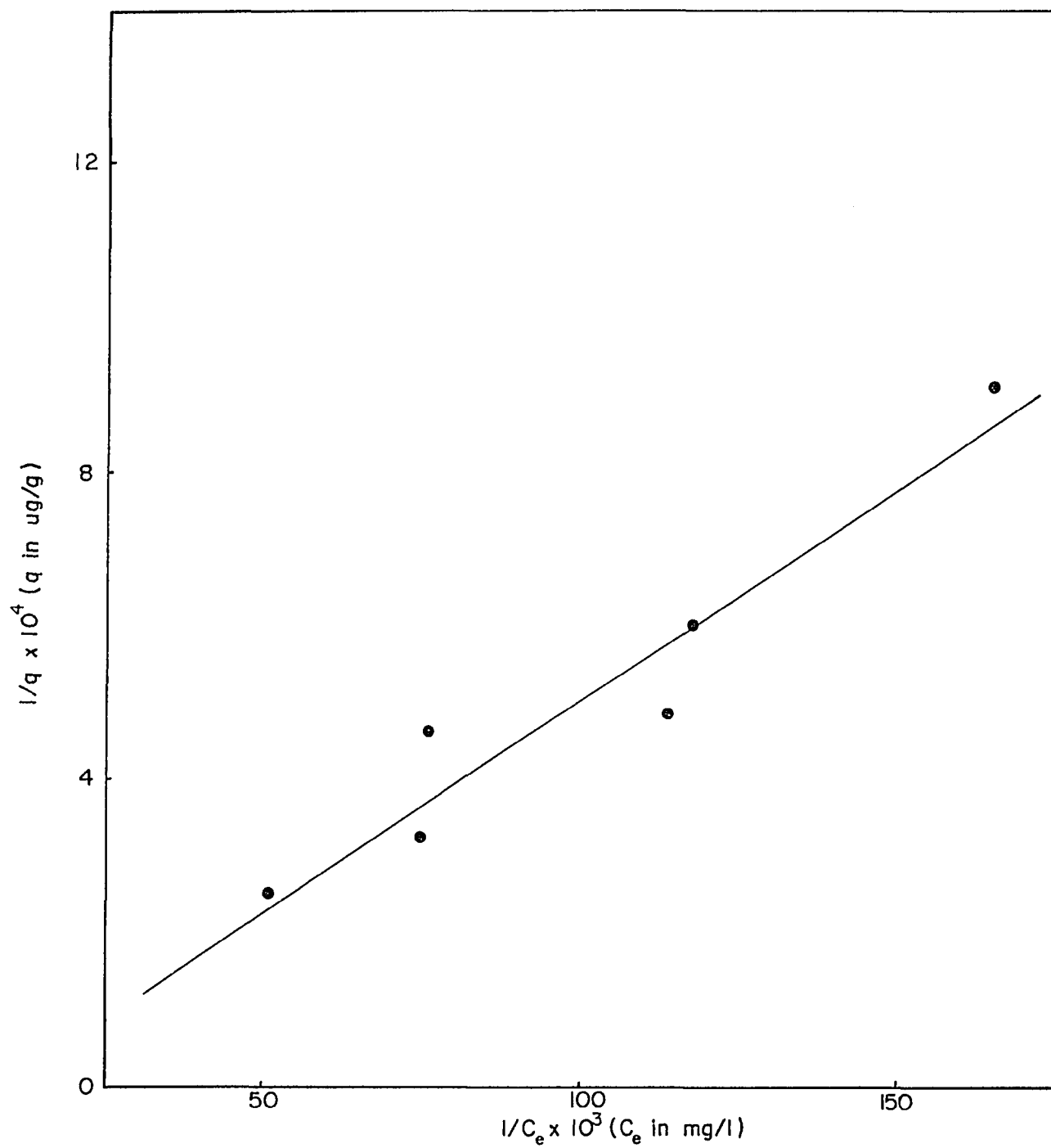


Figure 5.22: Langmuir Adsorption Isotherm for Ethylbenzene-Nitrifying Bacteria.

Table 5.4: Langmuir Adsorption Isotherm for Nitrifying Bacteria

Compound	Equation	Regression Coefficient
Phenol	$q = \frac{3.953 C_e}{1 + 0.00215 C_e}$	0.94
2-Chlorophenol	$q = \frac{15.2 C_e}{1 + 0.00334 C_e}$	0.98
2-Nitrophenol	$q = \frac{14.687 C_e}{1 + 0.0056 C_e}$	0.99
Chlorobenzene	$q = \frac{90.711 C_e}{1 + 0.0013 C_e}$	0.98
Ethylbenzene	$q = \frac{181.795 C_e}{1 - 0.00824 C_e}$	0.96

It can be seen that both Freundlich and Langmuir adsorption isotherms fit the results with a coefficient of regression greater than 0.94.

#### B. Equilibrium Desorption Study with Inactive Biomass

Once the adsorption was completed, the study of desorption of the contaminated microbial biomass was started by washing the adsorbed organic contaminant with contaminant free distilled water. The removal of the contaminants by washing depends on the nature of the liquid organic contaminant. The graphical representation of retained capacities for activated sludge biomass are given in Figures 5.23 to 5.27. Figure 5.28 summarizes



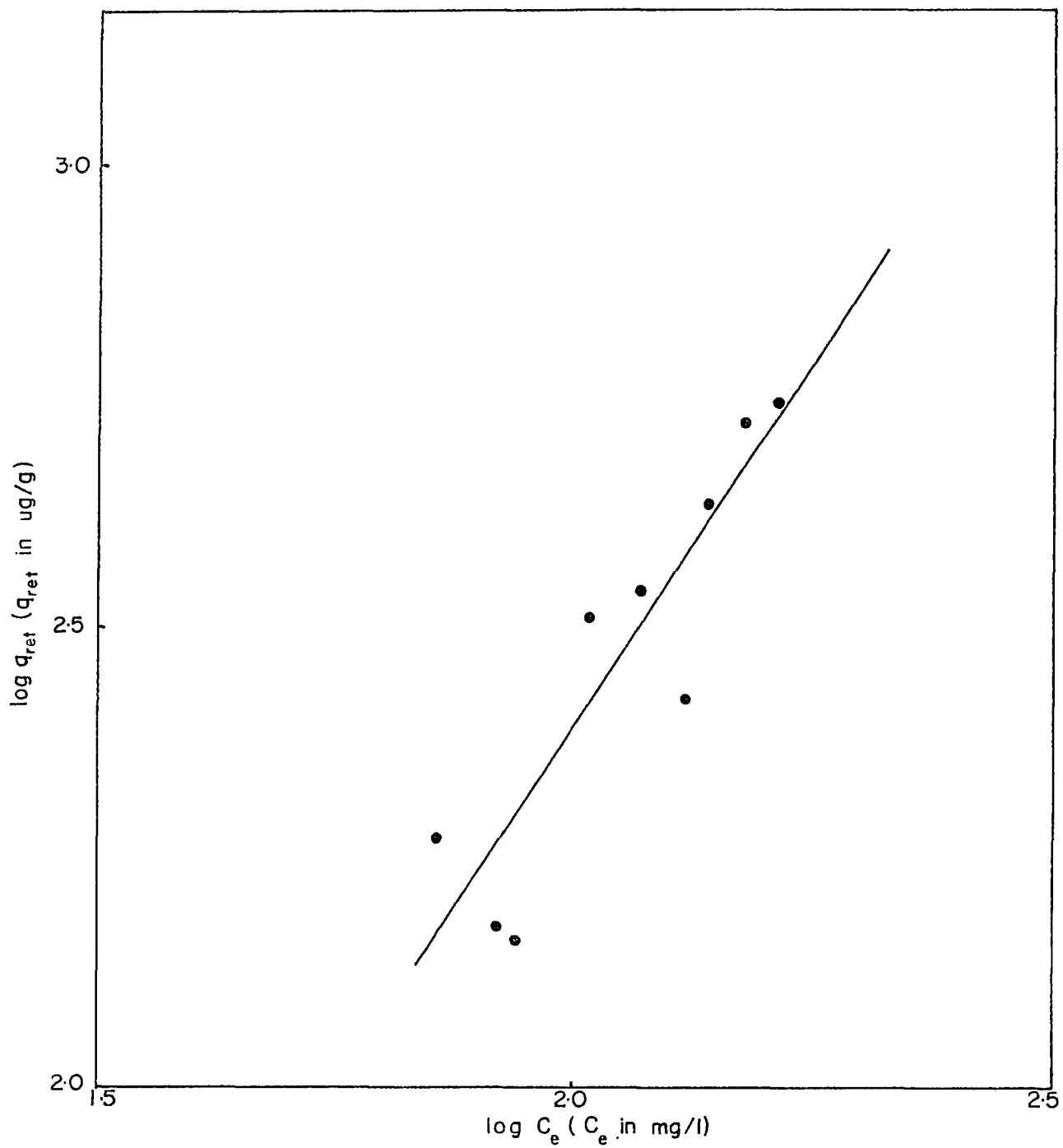


Figure 5.23: Freundlich Retained Isotherm for Phenol - Activated Sludge Biomass.

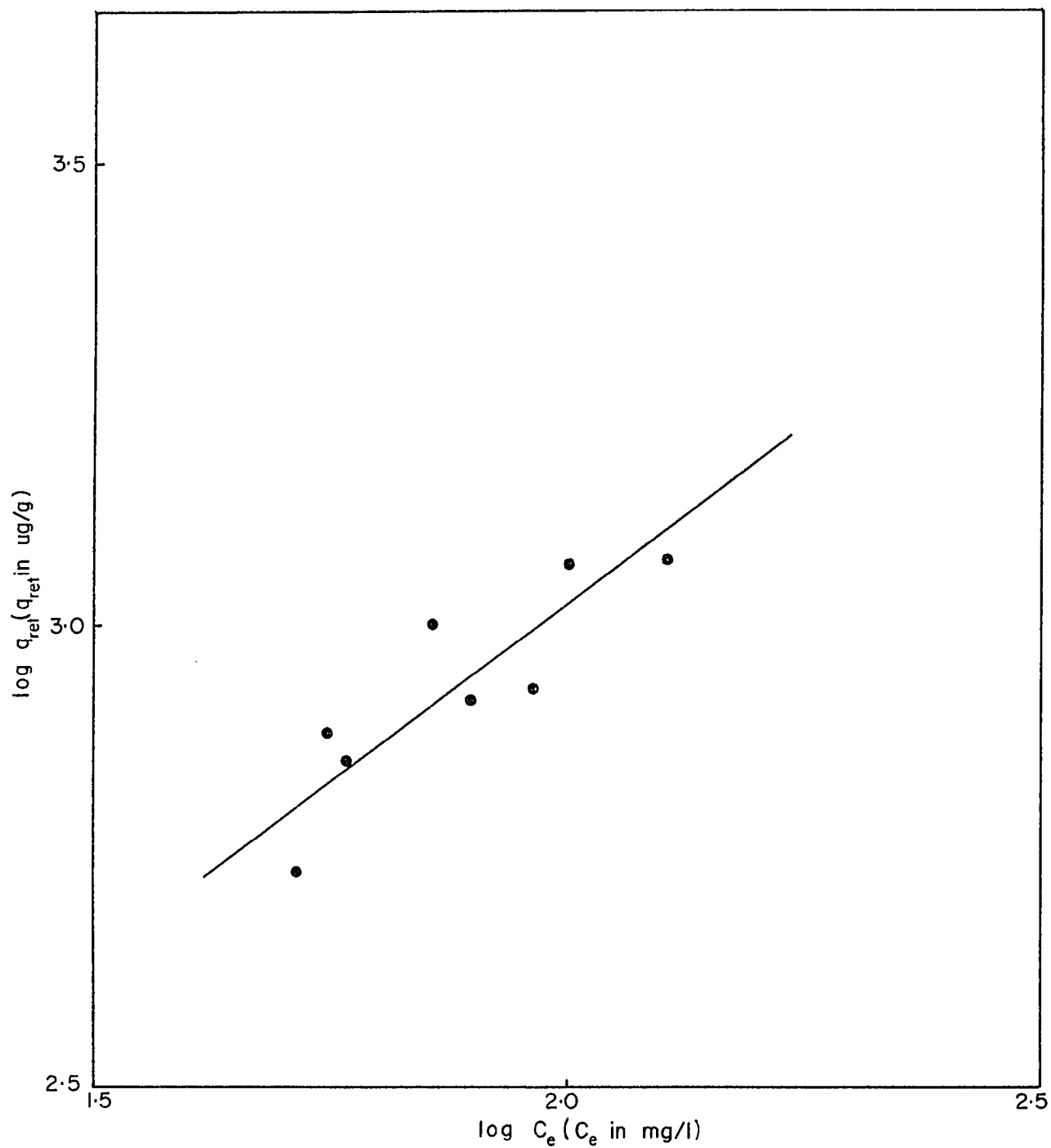


Figure 5.24: Freundlich Retained Isotherm for Chlorophenol-Activated Sludge Biomass.

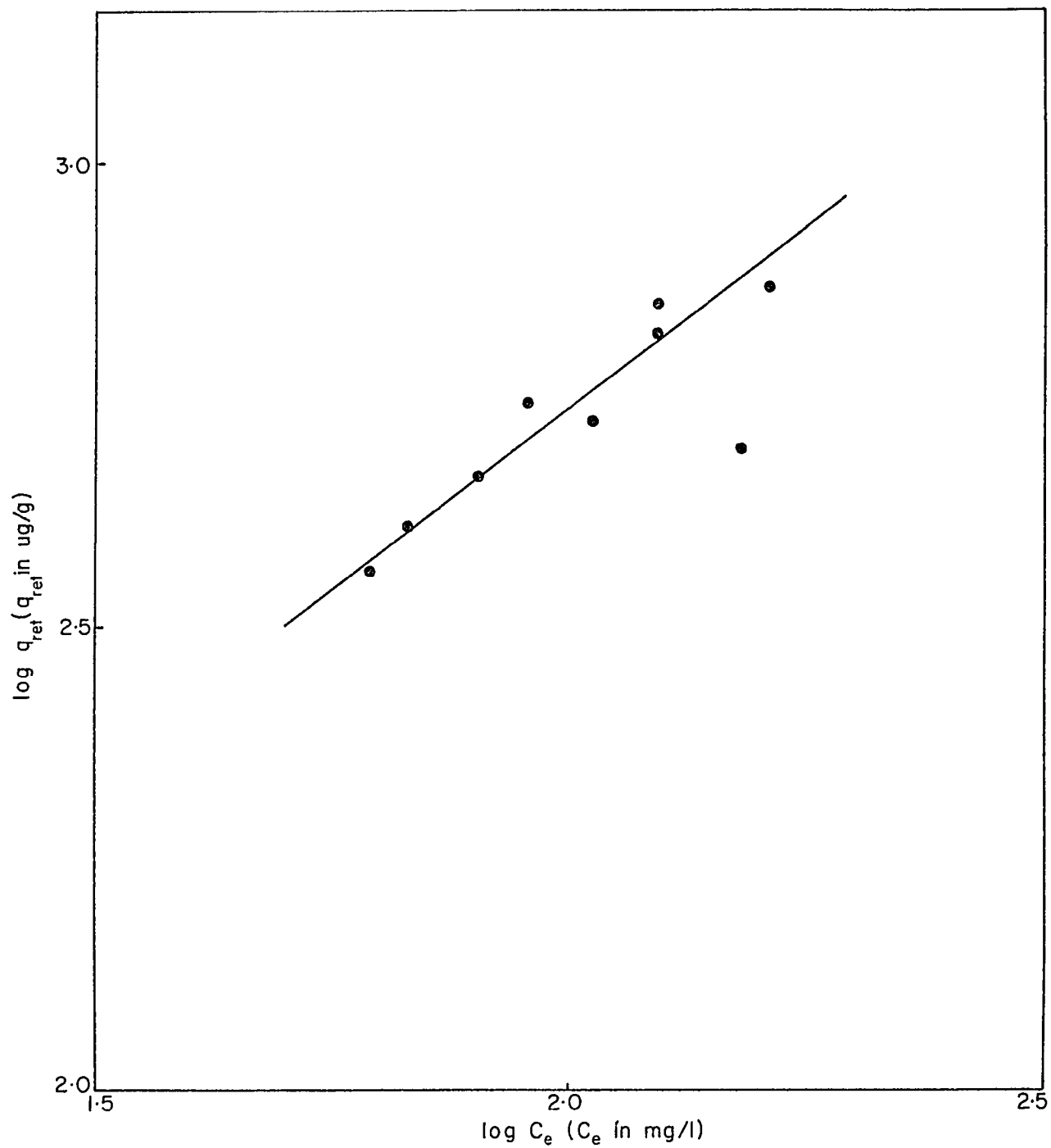


Figure 5.25: Freundlich Retained Isotherm for Nitrophenol-Activated Sludge Biomass.

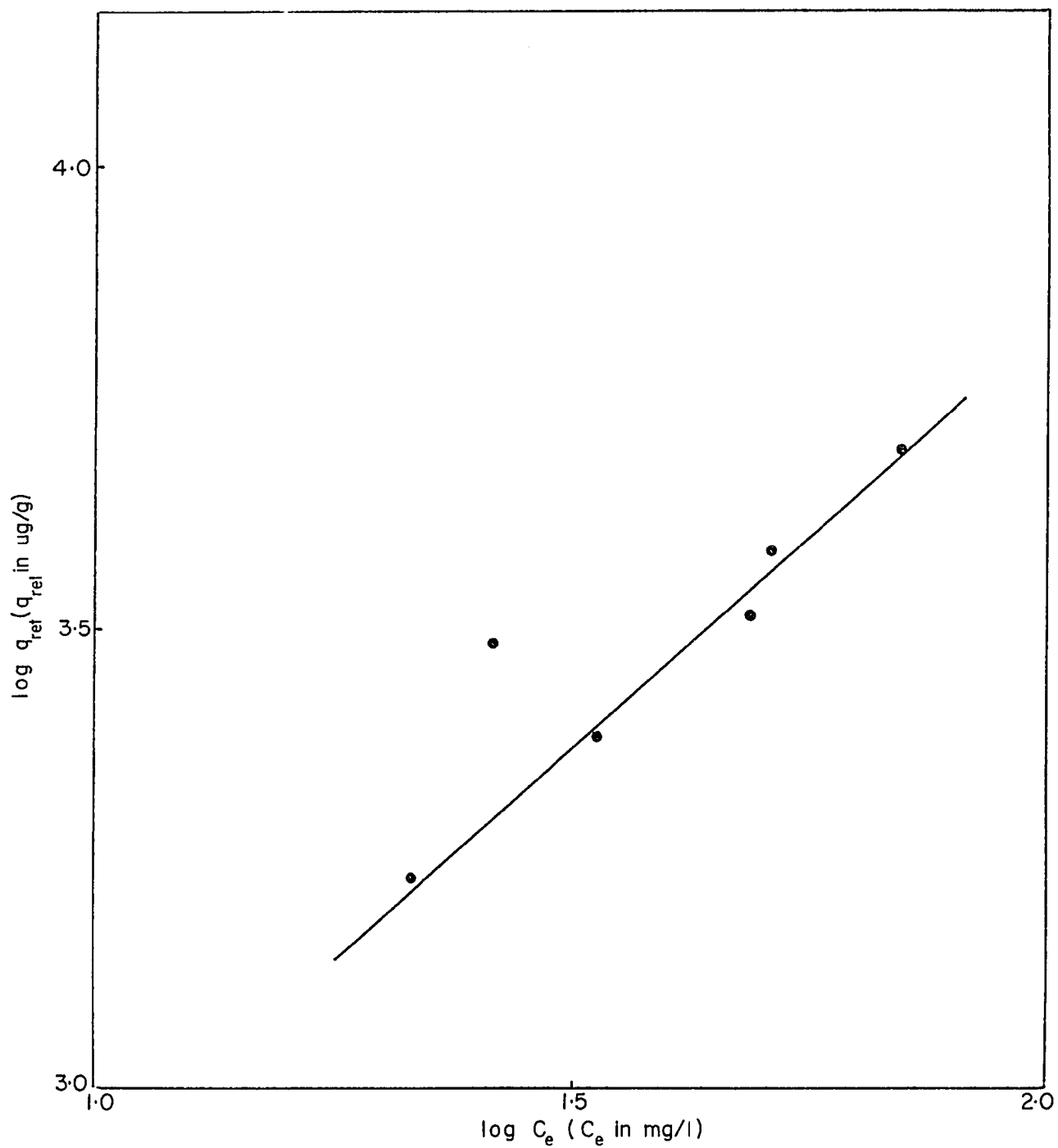


Figure 5.26: Freundlich Retained Isotherm for Chlorobenzene-Activated Sludge Biomass.

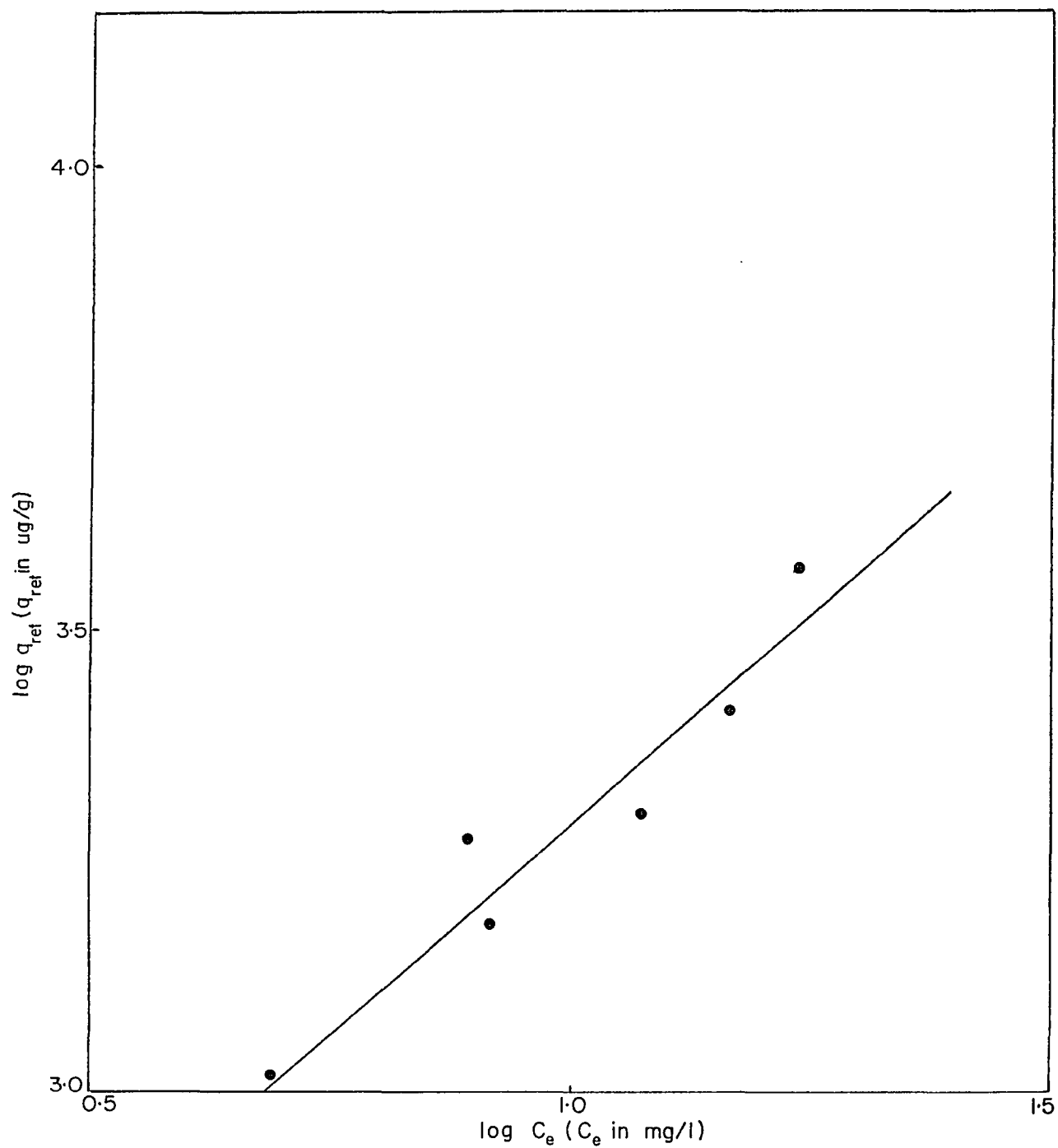


Figure 5.27: Freundlich Retained Isotherm for Ethylbenzene-Activated Sludge Biomass.

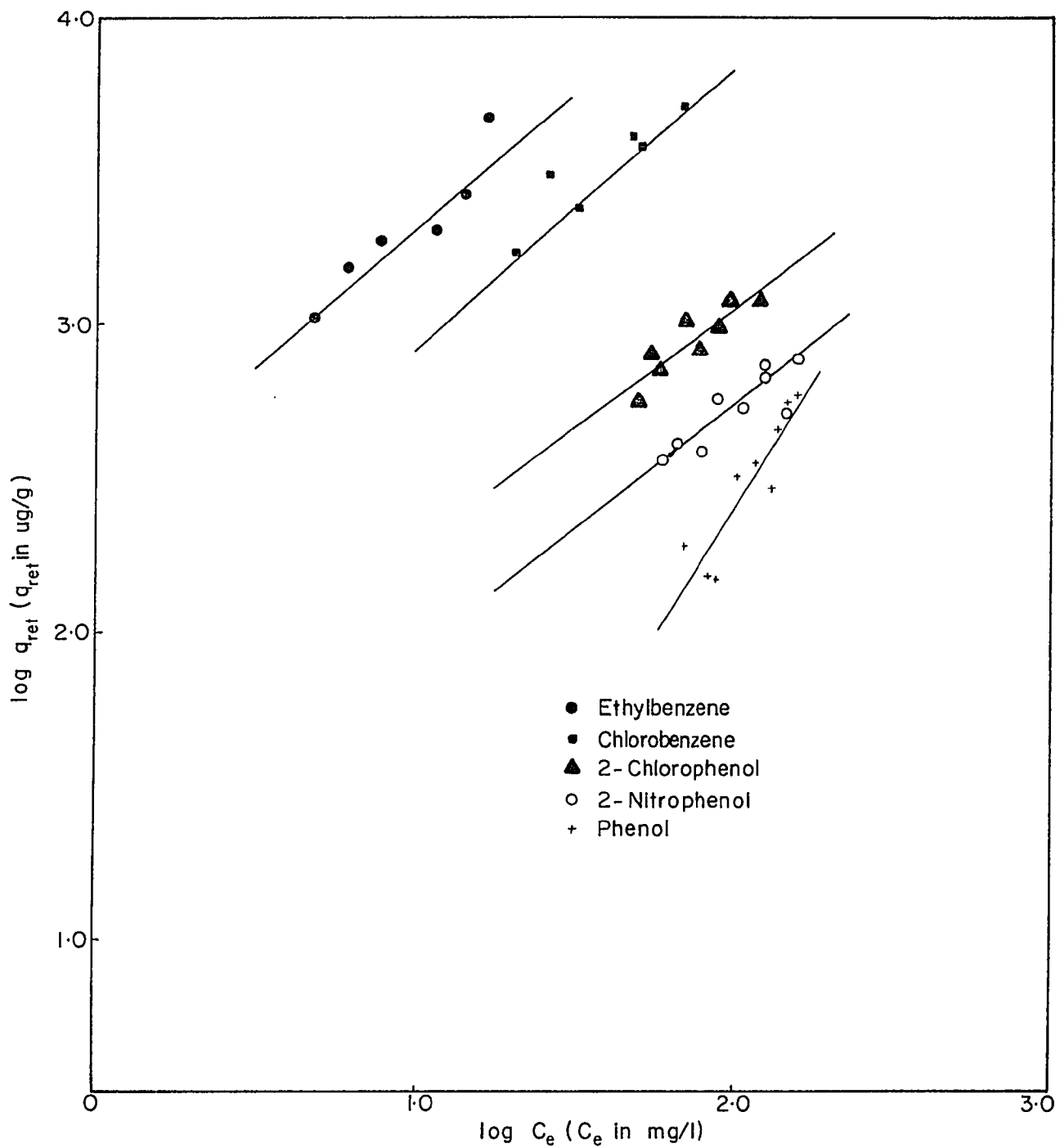


Figure 5.28: Freundlich Retained Isotherms for all Compounds with Activated Sludge Biomass.

the Freundlich retained isotherms for the five compounds with activated sludge biomass. When the retained capacity and equilibrium concentrations are plotted as the ordinates and abscissa respectively in a log - log paper, the data can be linearized with a fairly good straight line fit with a coefficient of regression greater than 0.89.

From the straight line plot, one can write the  $(X/m)_{\text{retained}}$  as a function of equilibrium concentration  $C_e$  as follows:

$$q_{\text{ret}} = (X/m)_{\text{ret}} = AC_e^s \quad (5.3)$$

where  $(X/m)_{\text{ret}}$  = retained capacity of sorbent (ug/g)

$C_e$  = equilibrium concentration (mg/l)

$A, s$  = empirical constants

The empirical constants are tabulated in Tables 5.5 and 5.6 for activated sludge and nitrifying bacteria respectively.

Table 5.5: Freundlich Retained Isotherm for Inactive Activated Sludge Biomass

Compound	Equation	Regression Coefficient
Phenol	$q_{\text{ret}} = 0.127 C_e^{1.639}$	0.92
2-Chlorophenol	$q_{\text{ret}} = 32.433 C_e^{0.757}$	0.89
2-Nitrophenol	$q_{\text{ret}} = 12.784 C_e^{0.811}$	0.94
Chlorobenzene	$q_{\text{ret}} = 100.460 C_e^{0.911}$	0.99
Ethylbenzene	$q_{\text{ret}} = 255.860 C_e^{0.886}$	0.95

Retained isotherms for all five compounds with nitrifying bacteria are shown in Figures 5.29 to 5.33. Figure 5.34 summarizes the Freundlich retained isotherms for all five compounds with nitrifying bacteria.

**Table 5.6: Freundlich Retained Isotherm for Nitrifying Bacteria**

Compound	Equation	Regression Coefficient
Phenol	$q_{ret} = 3.041 C_e^{0.867}$	0.86
2-Chlorophenol	$q_{ret} = 8.689 C_e^{1.011}$	0.86
2-Nitrophenol	$q_{ret} = 16.144 C_e^{0.768}$	0.96
Chlorobenzene	$q_{ret} = 118.980 C_e^{0.837}$	0.98
Ethylbenzene	$q_{ret} = 189.670 C_e^{0.964}$	0.96

Retained capacity of microbial biomass to the liquid organic compounds follows a similar pattern as adsorption capacity.

Ethylbenzene > Chlorobenzene > 2-Chlorophenol > 2-Nitrophenol > Phenol.

Tables 5.7 and 5.8 below gives the values of retained capacity, adsorbed capacity and the desorbed capacity at 100 ppm concentration of liquid organic contaminant for activated sludge biomass and nitrifying bacteria respectively. It can be seen that the more the compounds get adsorbed, the less they get desorbed. In the case of phenol, activated sludge biomass retained only 59% of the amount adsorbed, whereas it retained 75% of the



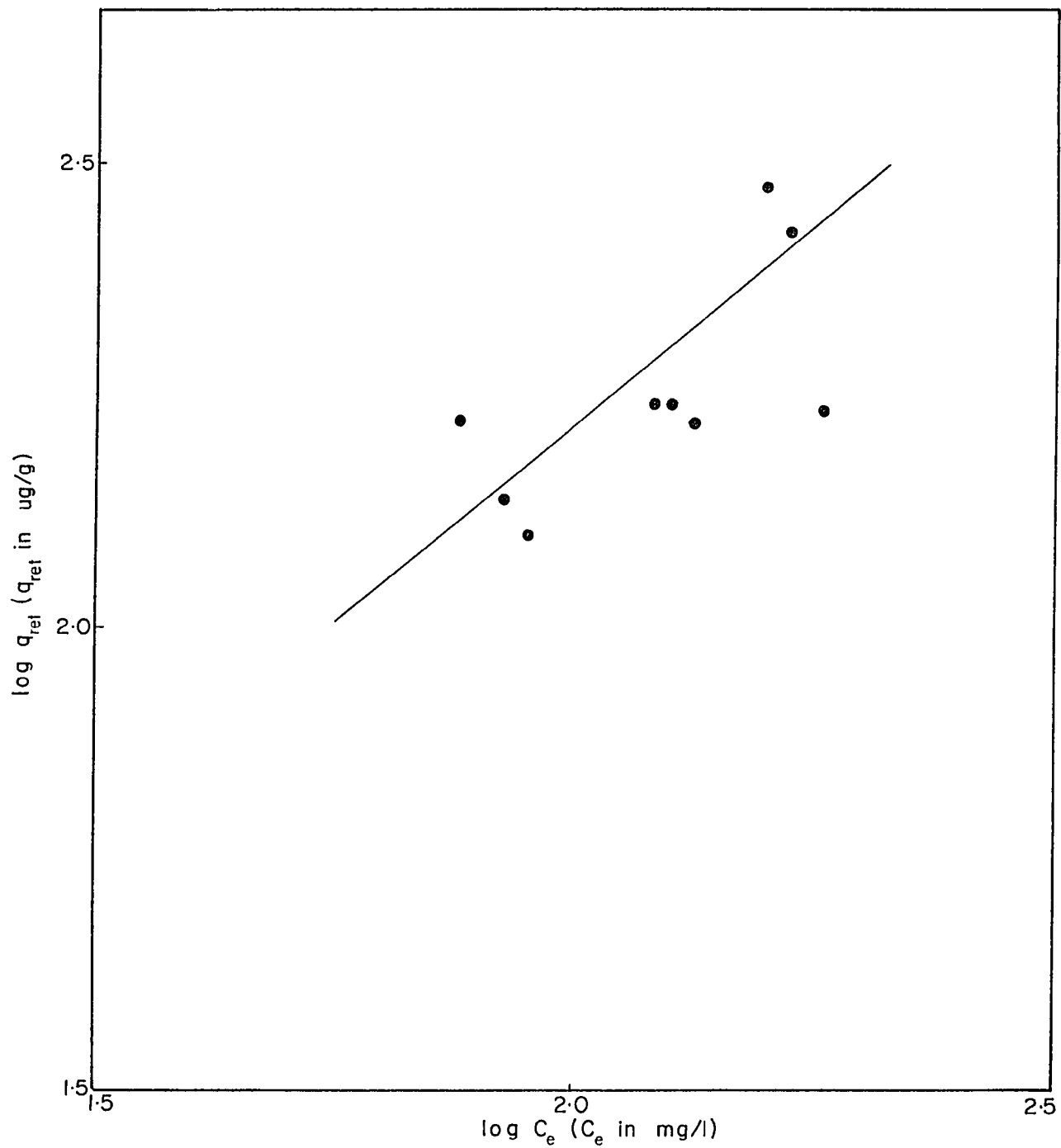


Figure 5.29: Freundlich Retained Isotherm for Phenol - Nitrifying Biomass.

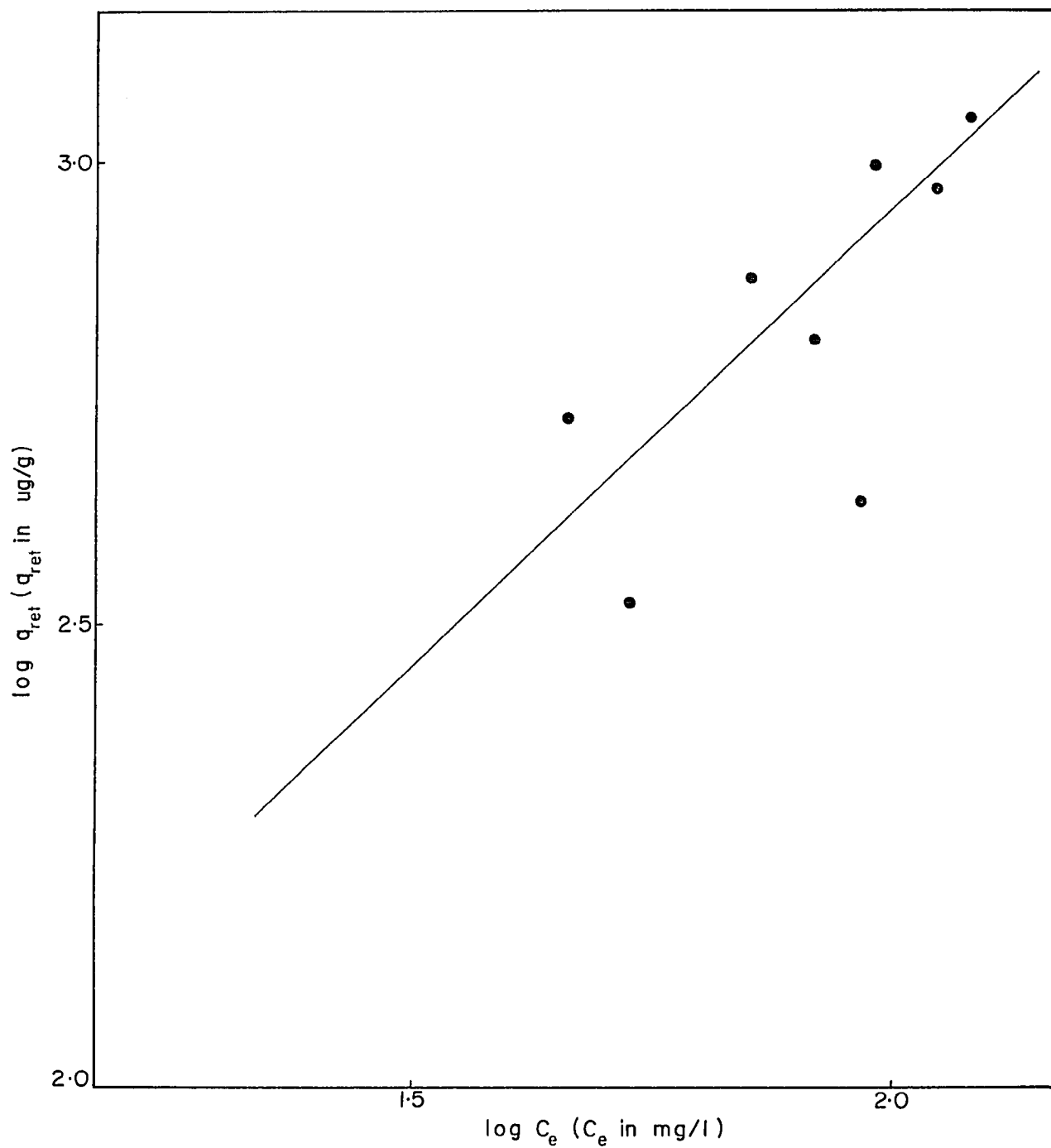


Figure 5.30: Freundlich Retained Isotherm for Chlorophenol-Nitrifying Bacteria.

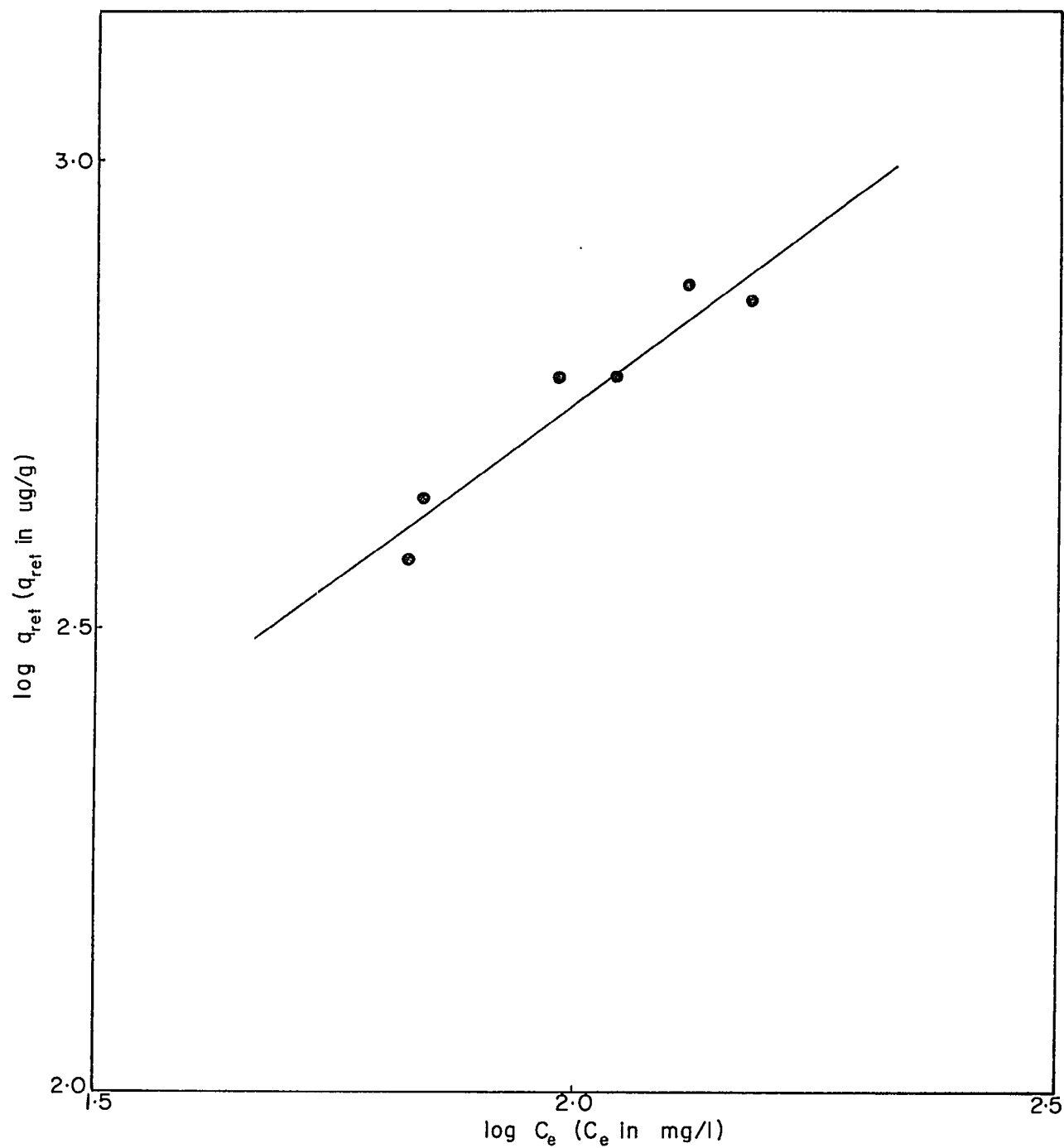


Figure 5.31: Freundlich Retained Isotherm for Nitrophenol-Nitrifying Bacteria.

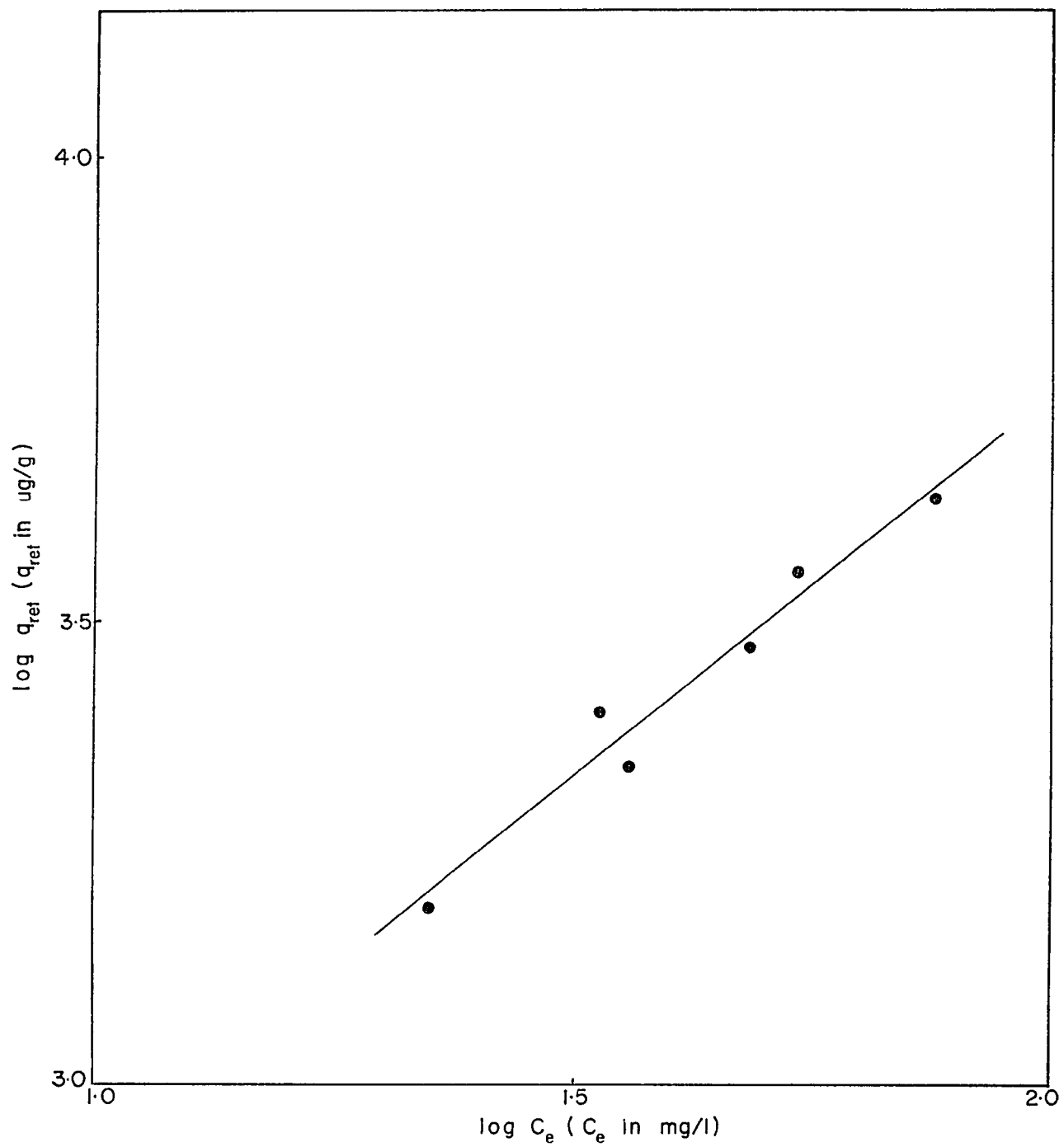


Figure 5.32: Freundlich Retained Isotherm for Chlorobenzene-Nitrifying Bacteria.

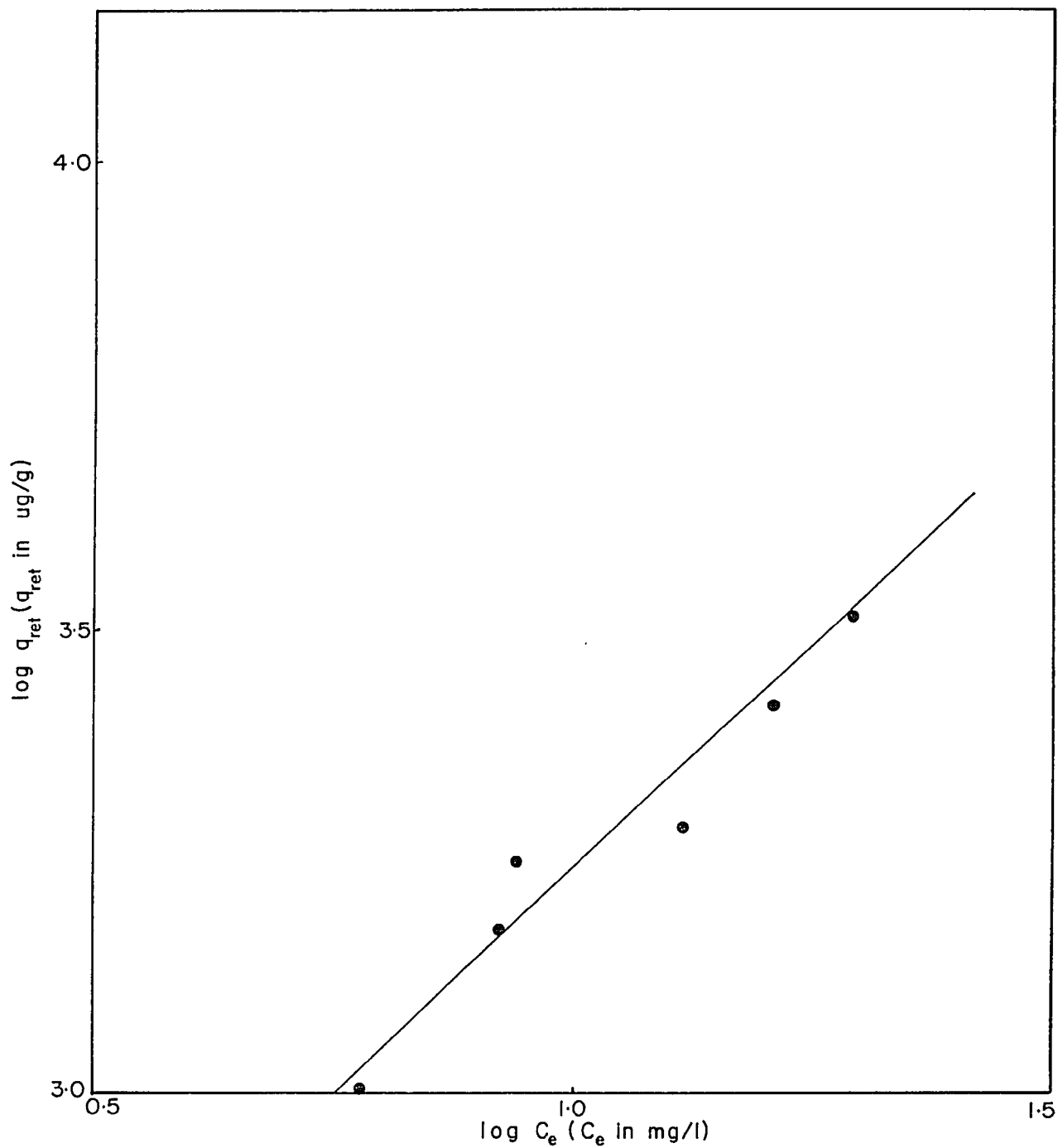


Figure 5.33: Freundlich Retained Isotherm for Ethylbenzene-Nitrifying Bacteria.

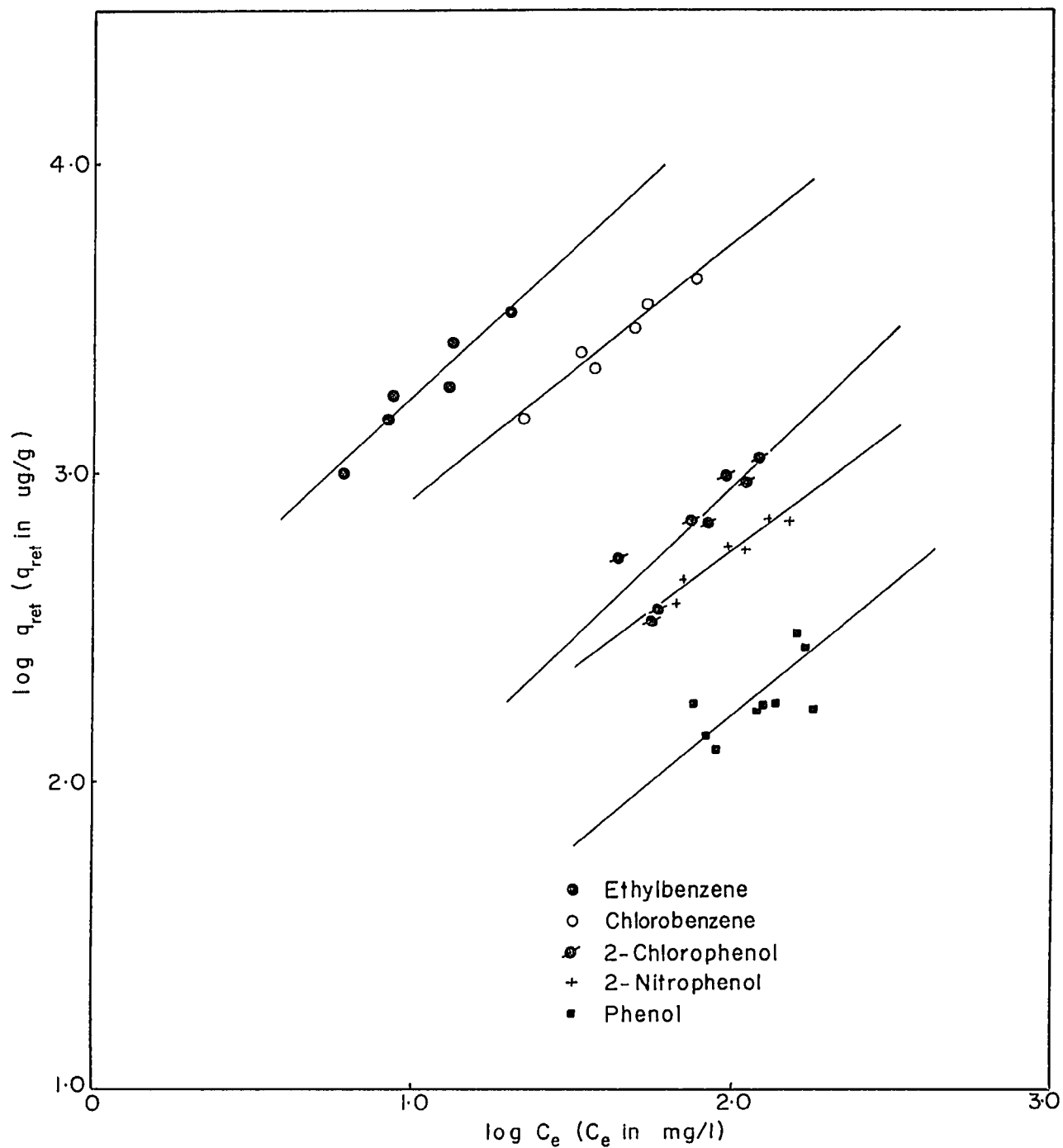


Figure 5.34: Freundlich Retained Isotherms for all Compounds with Nitrifying Bacteria.

ethylbenzene adsorbed. It is also interesting to note that the activated sludge biomass retained more than the nitrifying bacteria as one would expect according to their organic carbon contents.

**Table 5.7: Adsorbed Capacity, Retained Capacity and Percentage Desorbed at 100 ppm Equilibrium Concentration for Inactive Activated Sludge Biomass**

Compound	Adsorbed Capacity in ug/g	Retained Capacity in ug/g	Desorbed Capacity in ug/g	Percentage Desorbed in %
Phenol	407.26	241.83	165.43	40.62
2-Chlorophenol	1561.17	1057.76	503.41	32.24
2-Nitrophenol	1113.13	535.38	577.75	51.98
Chlorobenzene	8769.95	6667.96	2101.99	23.97
Ethylbenzene	20067.79	15135.57	4932.21	24.58

**Table 5.8: Adsorbed Capacity, Retained Capacity and Percentage Desorbed at 100 ppm Equilibrium Concentration for Nitrifying Bacteria**

Compound	Adsorbed Capacity in ug/g	Retained Capacity in ug/g	Desorbed Capacity in ug/g	Percentage Desorbed in %
Phenol	323.59	164.83	158.77	49.06
2-Chlorophenol	1483.50	914.05	569.45	38.38
2-Nitrophenol	891.86	554.64	337.22	37.81
Chlorobenzene	8208.10	5616.61	2591.49	31.57
Ethylbenzene	21907.77	16069.36	5848.41	26.65

### C. Comparison of Sorption Capacity with Activated Carbon

Activated carbon removes organic contaminants from water by the process of adsorption or the attraction and accumulation of one substance on the surface of another. In general, high surface area and pore structure are the prime considerations in adsorption. Adsorption from wastewater onto activated carbon occurs as a result of high affinity of a particular solute for the activated carbon. Because adsorption is a surface phenomenon, the ability of activated carbon to adsorb large quantities of organic molecules from solution stems from its highly porous structure, which provides a large surface area. In this study, activated carbon is used to compare its sorption capacity with the sorption capacities of biomass. The summary of the values of the parameters for the Freundlich adsorption isotherm is presented in Table 5.9.

Table 5.9: Freundlich Parameters for Activated Carbon

Compound	$K_d$	$1/n$	Regression Coefficient
Phenol	34723.98	0.286	0.97
2-Chlorophenol	61795.81	0.302	0.99
2-Nitrophenol	74371.86	0.393	0.98
Chlorobenzene	16058.30	0.779	0.99
Ethylbenzene	42648.13	0.660	0.88

Sorption capacity at 100 ppm equilibrium concentration for



activated sludge, nitrifying bacteria, and activated carbon are given in the Table 5.10 below.

**Table 5.10: Adsorption Capacity at 100 ppm Equilibrium Concentration**

Compound	Adsorption Capacity in ug/g		
	Activated Sludge	Nitrifying Bacteria	Activated Carbon
Phenol	407	323	129607
2-Chlorophenol	1561	1483	248290
2-Nitrophenol	1113	891	454369
Chlorobenzene	8769	8208	580352
Ethylbenzene	20067	21907	891046

It can be seen that compared to activated carbon, the adsorptive uptake of biomass was significantly less. Uptake by activated carbon was about three orders of magnitude greater for phenol, chlorophenol, and nitrophenol and about two orders of magnitude greater for chlorobenzene and ethylbenzene adsorbed onto activated sludge and nitrifying bacteria at 100 ppm equilibrium concentration. The higher uptake by activated carbon may be partly explained by its significantly greater specific surface area. Activated carbon used in this study (Filtrisorb 400) has a specific surface area of  $1000 \text{ m}^2/\text{g}$ . Tsezos and Bell(1987) reported that the activated sludge has a specific surface area of  $1.1 \text{ m}^2/\text{g}$ . It is interesting to note, however, that the uptake per unit surface area is greater for the biomass than for activated carbon.

#### D. Temperature Effects of Biosorption

The primary objective of the study of temperature effects was to determine whether the sorption process involves a physical or chemical mechanism. The effect of temperature on biosorptive uptake was examined by running biosorption experiments for 2-chlorophenol and chlorobenzene at different temperatures. Table 5.11 gives the Freundlich parameters for biosorption isotherm at 21°C and 37°C.

**Table 5.11: Freundlich Parameters for Biosorption at 21°C and 37°C**

Compound	Temp. in °C	K <sub>d</sub>	1/n
2-Chlorophenol	21	26.33	0.886
	37	11.97	0.977
Chlorobenzene	21	88.51	0.998
	37	90.77	0.897

The enthalpy or heat of sorption is given by van't off equation:

$$\Delta H = \frac{-R d(\ln K_d)}{d(1/T)} \quad (5.5)$$

where  $\Delta H$  = heat of sorption (kcal/g-mole)

R = gas constant ( $1.987 \times 10^{-3}$  kcal/g-mole °K)

T = absolute temperature (°K)

If the enthalpy of sorption is assumed to be relatively independent of temperature over 21°C to 37°C range in this

study, then the enthalpy of sorption can be determined using the simplified equation developed by Tsezos and Bell (1988). They used and used the following equation to determine  $\Delta H$  from liquid phase equilibrium concentration at constant loadings, at two different temperatures.

$$\Delta H = \frac{-R \ln (C_1/C_2)}{(1/T_2 - 1/T_1)} \quad (5.6)$$

where  $C_1$  = equilibrium concentration of solute at  $T = T_1$

$C_2$  = equilibrium concentration of solute at  $T = T_2$

$T_1, T_2$  = absolute temperature

Using the Freundlich equations from Table 5.11 to determine the equilibrium concentrations at different loadings, the heats of sorption shown in Table 5.12 were calculated.

Table 5.12: Estimated Heats of Sorption

Compound	$\Delta H$ at Stated Loading (kcal/g-mole)		
	1000 ug/g	2500 ug/g	5000 ug/g
2-Chlorophenol	-12.46	-13.41	-14.12
Chlorobenzene	+ 3.03	+ 4.08	+ 4.87

The heat of sorption is a measure of energy released or taken up in forming the bonds between the sorbent and the sorbate and breaking the bonds between the sorbate and the solvent. The magnitude of the heat of sorption is related to the strength of those bonds. In general, chemical bonds are stronger than bonds

resulting from physical attractive forces such as van der Waals forces. For chemical bonds or chemisorption, the magnitude of the heat of sorption would be expected to be greater than 10 kcal/g-mole. Physical sorption processes would be expected to have heat of sorption less than 10 kcal/g-mole. The estimated heat of sorption for 2-chlorophenol and chlorobenzene are in the range where a physical rather than a chemical mechanism would be expected to dominate.

#### E. Competitive Adsorption

The problem of possible competitive adsorption from aqueous solution to biomass has had little review in the literature. There is, thus, little fundamental background to allow one to predict the behavior of biomass with mixed aqueous solutions, which are often encountered in treatment plants. Some effects, at least on biosorptive capacity should be anticipated, unless the solutes are being adsorbed on completely separate areas of the biomass. Studies conducted herein related to competitive adsorption from aqueous solutions are presented below.

##### 1. Adsorption from Bisolute Systems

###### a. Ratio of Initial Concentration of Solutes equal to 1.0

Because of its slightly higher biosorptive capacity, activated sludge biomass was selected in order to study the effect of competition on biosorption. As a first step,

competitive effect on bisolute solutions was studied. Phenol-chlorophenol, phenol-nitrophenol, chlorophenol-nitrophenol and chlorobenzene-ethylbenzene systems were selected for the analysis. Bisolute solutions were prepared with the ratio of initial concentration of the solutes equal to 1.0. The equilibrium data for adsorption for the compounds correlated well with the Freundlich equation (with regression coefficient greater than 0.88) in the range of concentrations (50 to 200 mg/l) studied. The competitive effect of each solute in a bisolute system on the biosorption of other is shown in Figures 5.35 to 5.39. The summary of the parameters of the Freundlich equation and the adsorption capacity at 100 ppm equilibrium concentration are presented in Table 5.13.

**Table 5.13: Freundlich Constants and Adsorption Capacity at 100 ppm Equilibrium Concentration in Bisolute Systems**

Bisolute system	Compound	$K_d$	$1/n$	Adsorption Capacity at 100 ppm in ug/g
P - CP	Phenol	0.075	1.78	267.50
	2-Chlorophenol	4.920	1.23	1418.90
P - NP	Phenol	0.024	2.03	269.30
	2-Nitrophenol	8.910	1.01	933.20
CP - NP	2-Chlorophenol	9.560	1.08	1390.20
	2-Nitrophenol	0.011	2.32	471.30
CB - EB	Chlorobenzene	98.170	0.88	5754.11
	Ethylbenzene	187.720	0.98	17119.80

The experimental results under competitive condition in

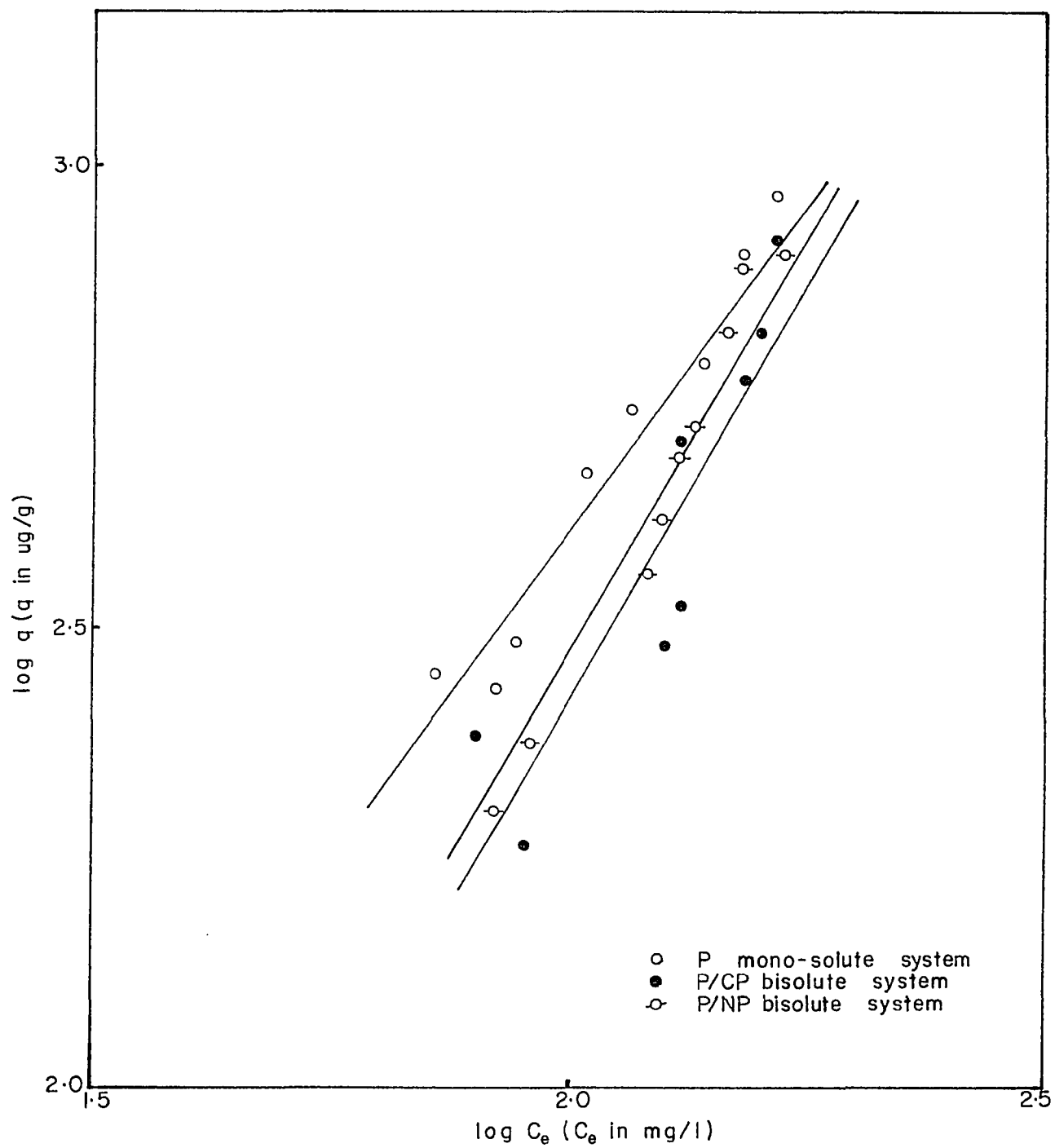


Figure 5.35: Adsorption Isotherms for Phenol on Activated Sludge Biomass.

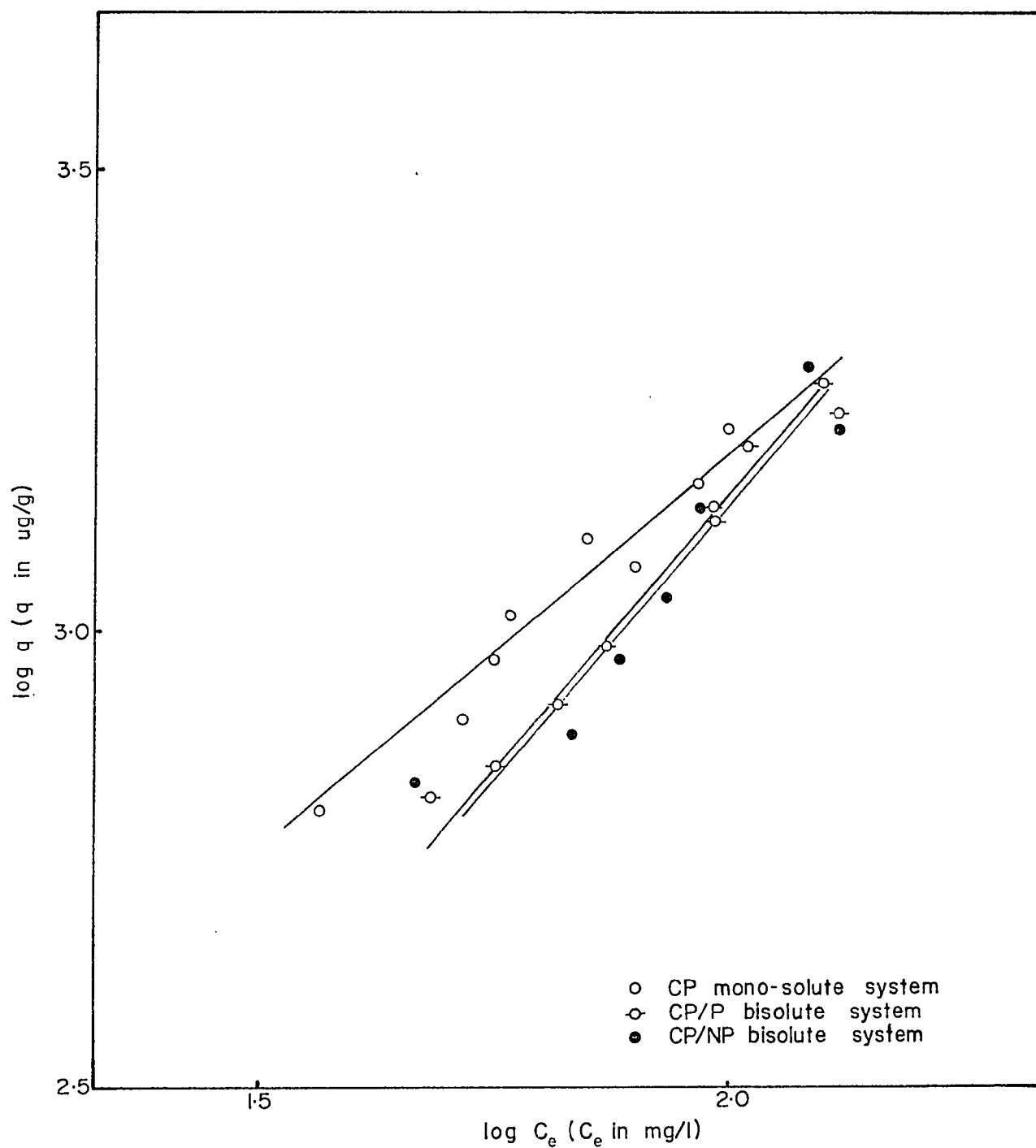


Figure 5.36: Adsorption Isotherms for Chlorophenol on Activated Sludge Biomass.

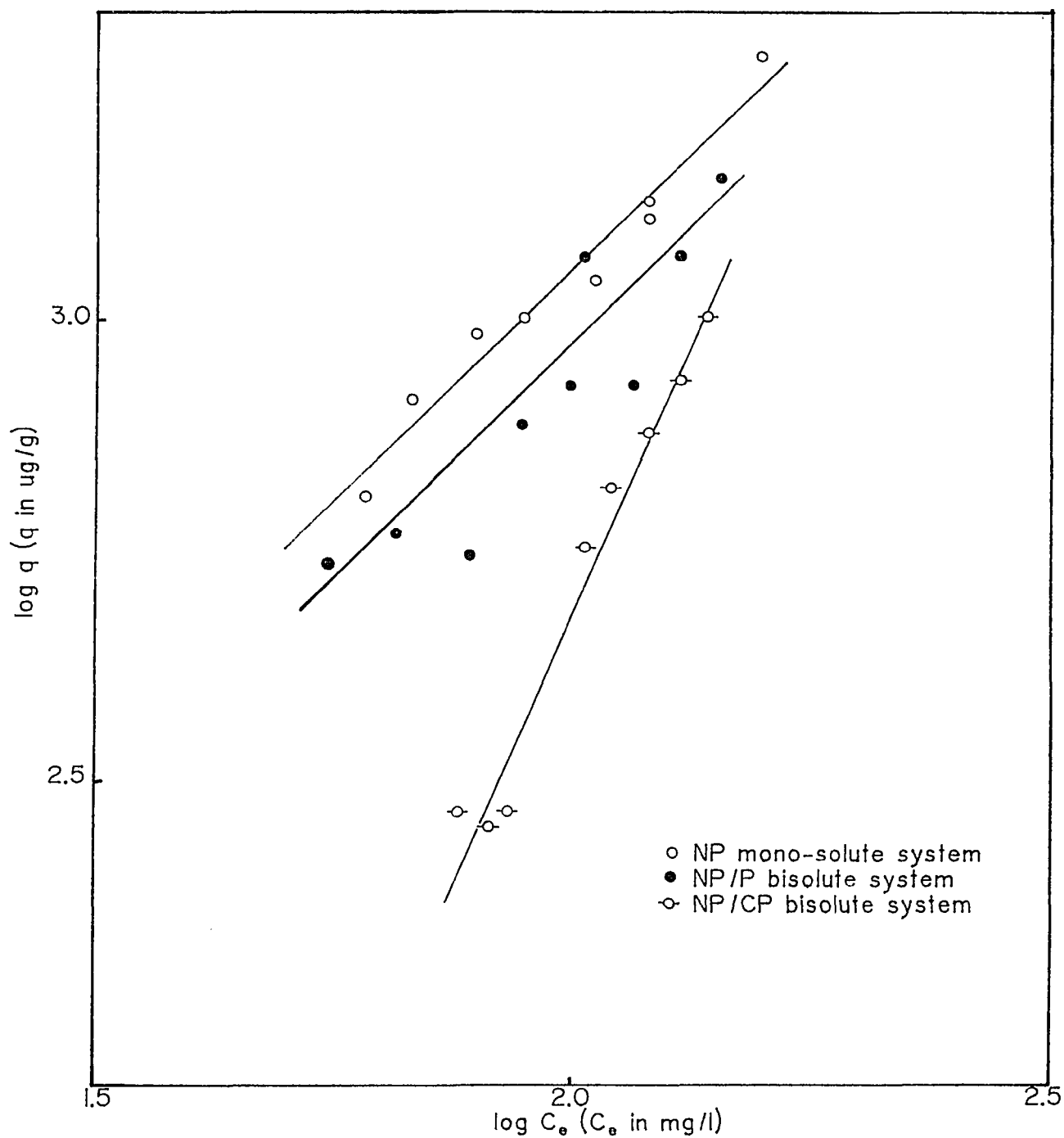


Figure 5.37: Adsorption Isotherms for Nitrophenol on Activated Sludge Biomass.



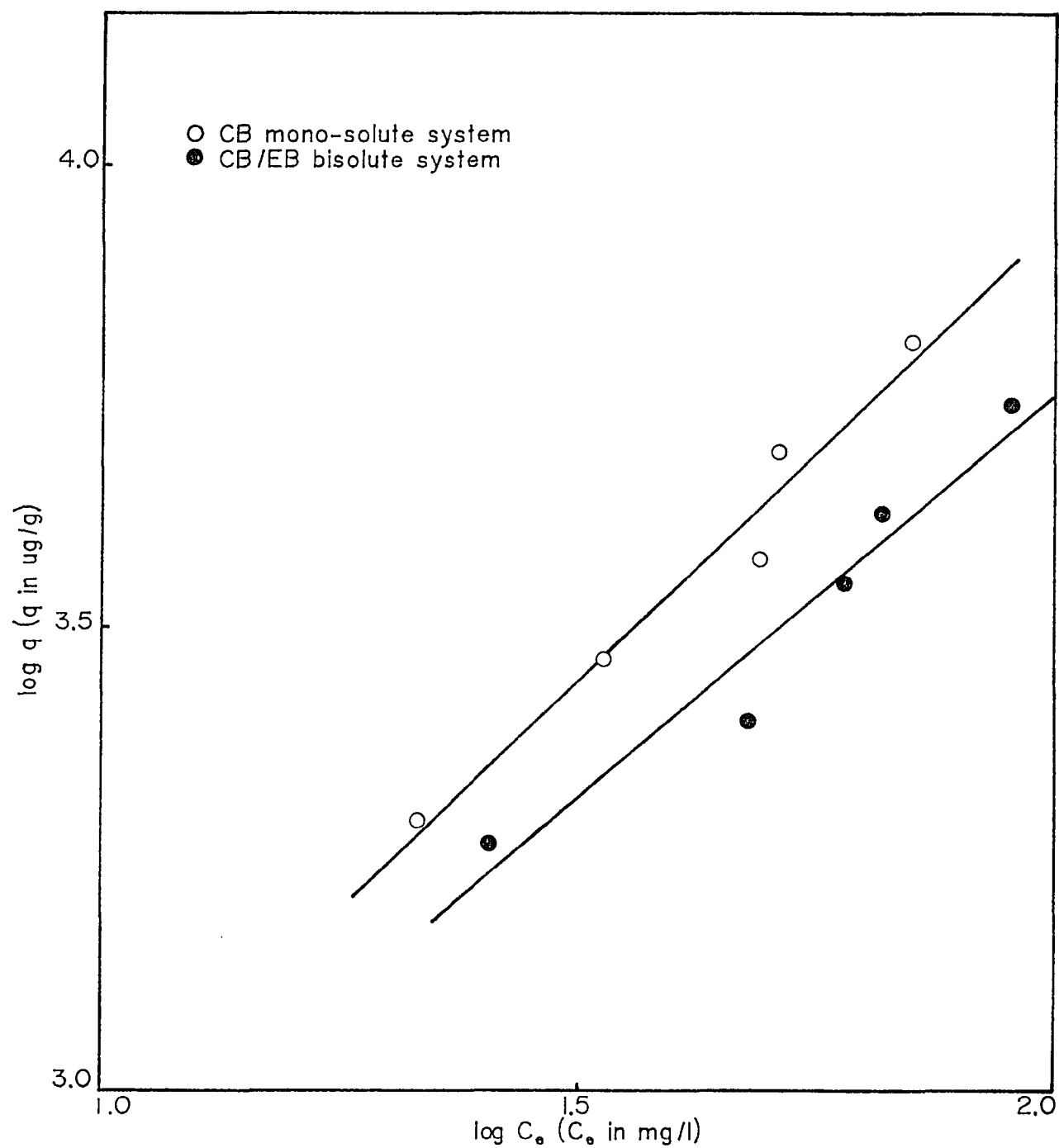


Figure 5.38: Adsorption Isotherms for Chlorobenzene on Activated Sludge Biomass.

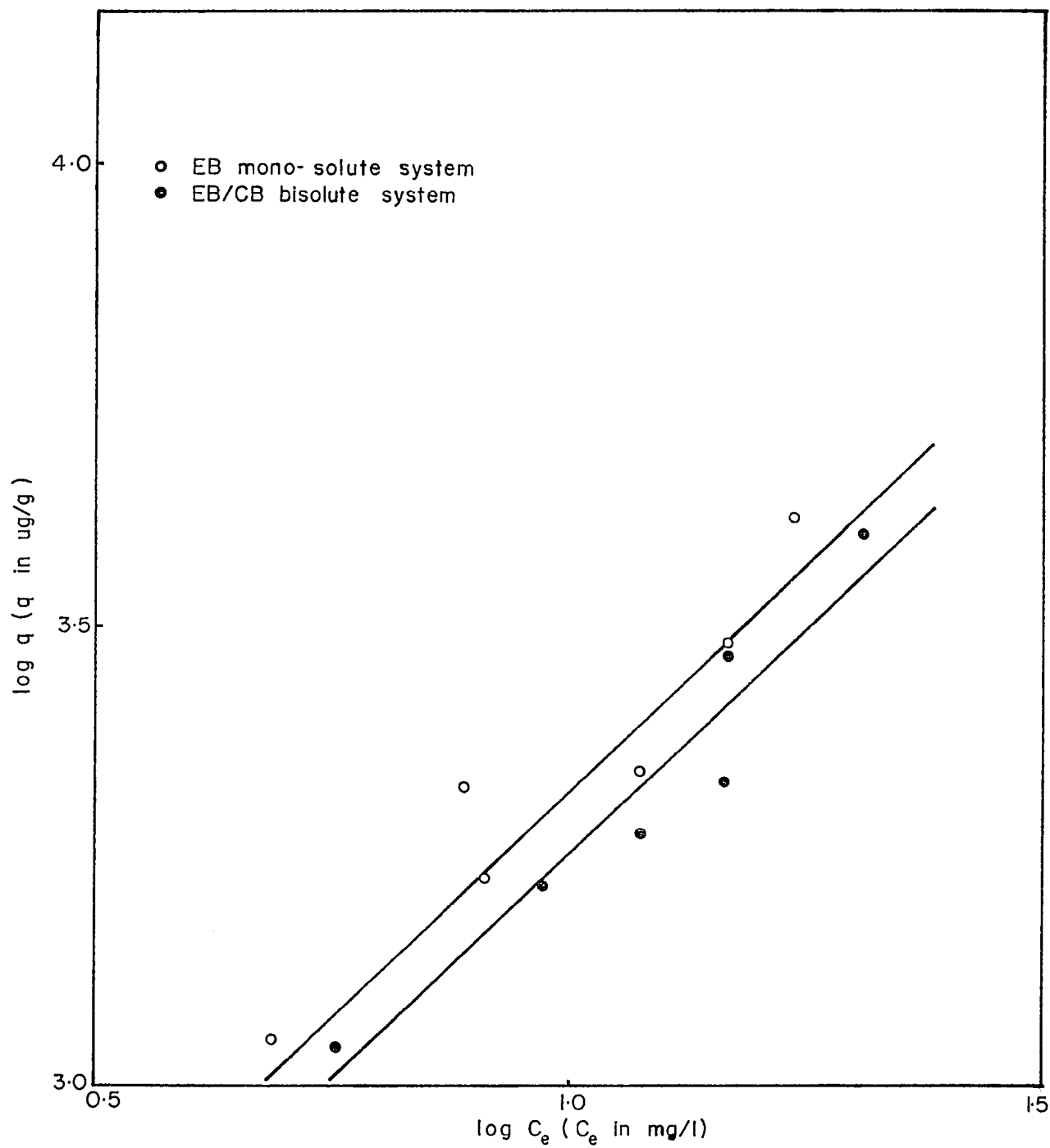


Figure 5.39: Adsorption Isotherms for Ethylbenzene on Activated Sludge Biomass.

bisolute solutions showed that the uptake of each solute is reduced in the presence of a second solute. The magnitude of the mutual interference may be indicated with an example: For a pure phenol solution, the activated sludge uptake capacity reached an equilibrium value of 407 ug/g at the equilibrium concentration of 100 ppm. Under the same conditions in a bisolute system containing both phenol and chlorophenol, the phenol uptake capacity was 267 ug/g, about 34% lower. Similarly for chlorophenol, uptake capacities of 1557 and 1419 ug/g were observed for the single and bisolute systems respectively, at an equilibrium concentration of 100 ppm, indicating 9% reduction in uptake capacity.

Although the amount of each solute adsorbed on the biomass was found to be reduced significantly relative to its value in the pure solution, the combined capacity is greater than that for either of the pure substances alone. It thus appears that total adsorptive capacity of biomass may be increased with mixed solutes. Because, in many instances, removal of organic compounds by microbial biomass will involve adsorption of pollutants rather than selective adsorption of one ingredient, the observed behavior may be an advantage rather than a drawback.

It is noteworthy that the less soluble compound was observed to be more favorably adsorbed in three of the four bisolute solutions studied. In the case of chlorophenol-nitrophenol bisolute solution, the less soluble nitrophenol was observed to be less favorably adsorbed than the more soluble chlorophenol.

But the octanol/water partition coefficient of chlorophenol and nitrophenol correctly predicts that chlorophenol should be more favorably adsorbed than nitrophenol. But in all four bisolute systems studied, the compound with high octanol/water partition coefficient was more favorably adsorbed. Thus the competitive adsorption is very well correlated with octanol/water partition coefficient than the aqueous solubility.

Experiments were also performed with activated carbon and the results are presented in Table 5.14.

**Table 5.14: Freundlich Constants and Adsorption Capacity at 100 ppm Equilibrium Concentration in Bisolute Systems for Activated Carbon**

Bisolute system	Compound	$K_d$	$1/n$	Adsorption Capacity at 100 ppm in ug/g
P - CP	Phenol	24717.24	0.137	46451.52
	2-Chlorophenol	42461.96	0.284	157036.29
P - NP	Phenol	13273.94	0.274	46881.32
	2-Nitrophenol	25118.86	0.504	255858.54
CP - NP	2-Chlorophenol	50466.13	0.195	123879.66
	2-Nitrophenol	64268.77	0.295	250034.53
CB - EB	Chlorobenzene	21457.05	0.646	420310.27
	Ethylbenzene	9840.00	0.973	868950.00

Comparison of Table 5.10 with Table 5.14 readily shows that the equilibrium capacity for each solute on the activated carbon was affected by the presence of other solute. In all four bisolute systems studied, the more hydrophobic compound was

observed to be more favorably adsorbed.

b. Initial Concentration of One Solute is Fixed and Other One is Varied

Experiments were performed to evaluate the effect of initial concentration on biosorption in bisolute systems. Combinations of phenol and chlorophenol; phenol and nitrophenol; chlorophenol and nitrophenol; chlorobenzene and ethylbenzene were selected for this study. The equilibrium data for adsorption for the compounds correlated well with Freundlich equation (with regression coefficients greater than 0.87) in the range of concentrations (50 - 200 mg/l) studied. Figures 5.40 through 5.47 show the competitive effect of each solute on the biosorption of other solute. The summary of the parameters of the Freundlich equation and the adsorption capacity at 100 ppm equilibrium concentration are presented in Table 5.15.

Comparison of Table 5.1 with Table 5.15 clearly shows that the equilibrium capacity for each solute on the activated sludge biomass is affected by the initial concentration of the other solute. The magnitude of the effect may be explained with an example: For a pure phenol solution, the activated sludge uptake capacity reached an equilibrium value of 407 ug/g at an equilibrium concentration of 100 ppm. Under the same conditions in a bisolute system containing both phenol and chlorophenol, the phenol uptake was 295 and 240 ug/g at the initial concentration of chlorophenol of 100 and 200 ppm respectively.

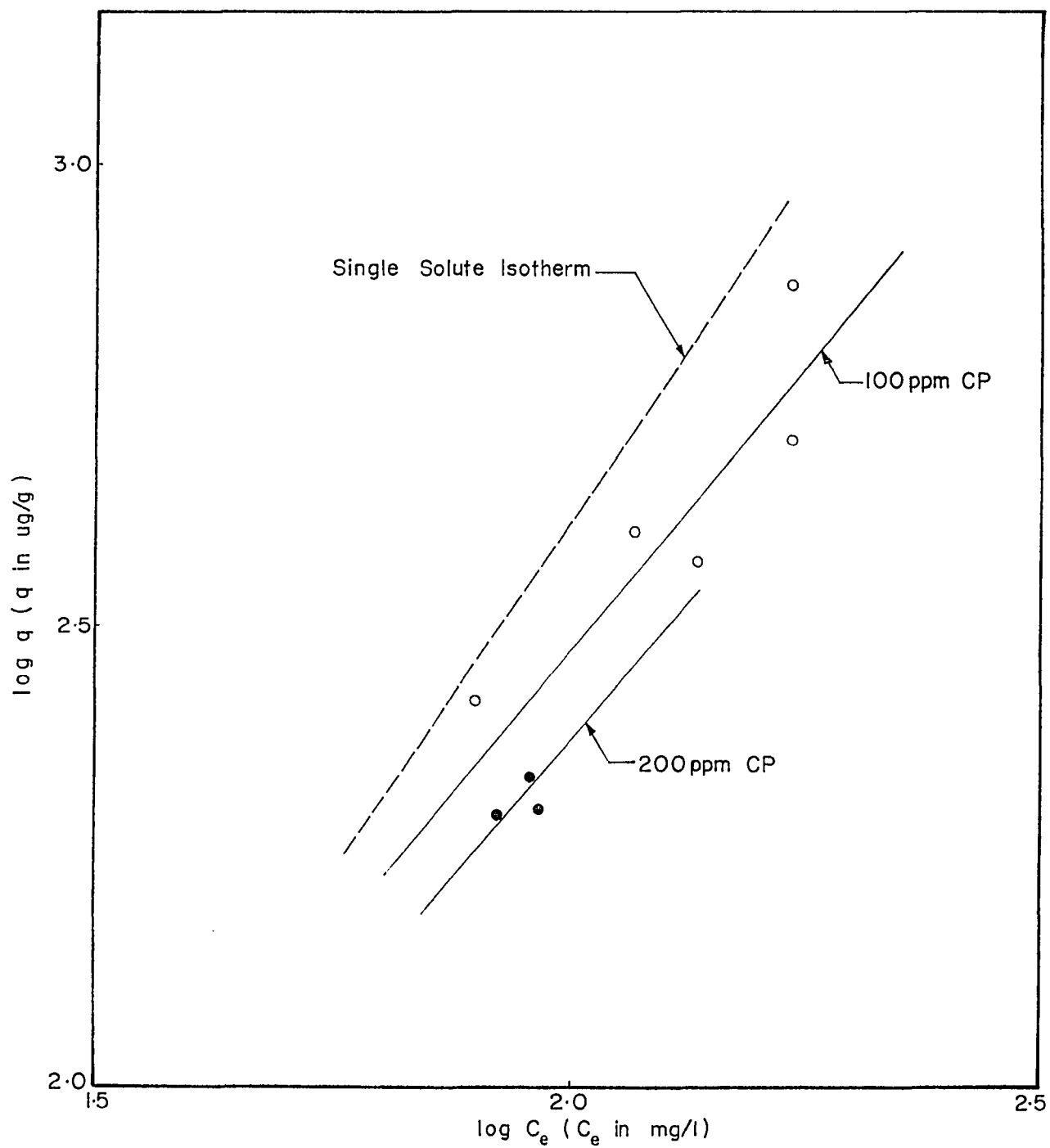


Figure 5.40: Adsorption Isotherms for Phenol in Competition with Chlorophenol.

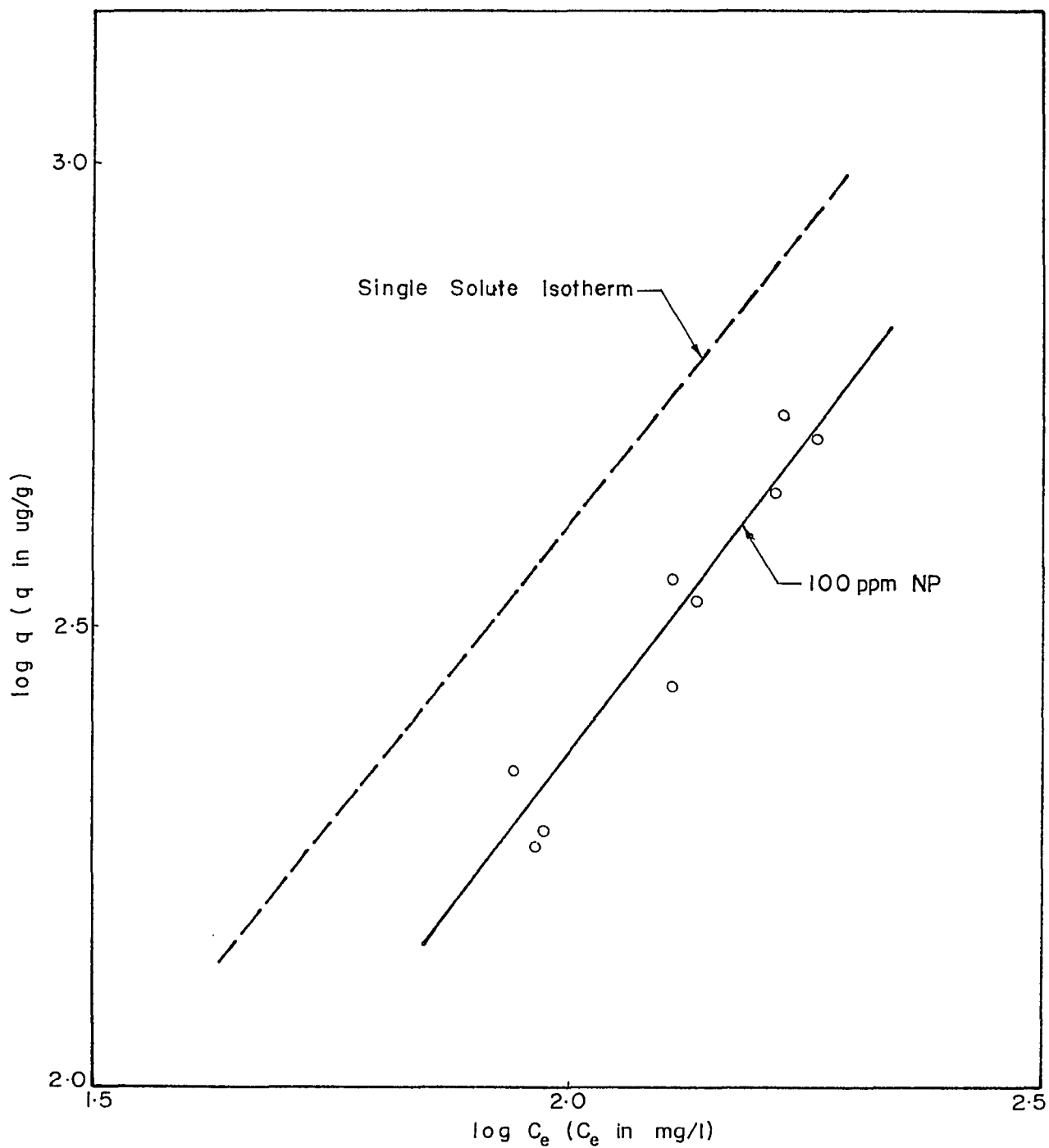


Figure 5.41: Adsorption Isotherms for Phenol in Competition with Nitrophenol.

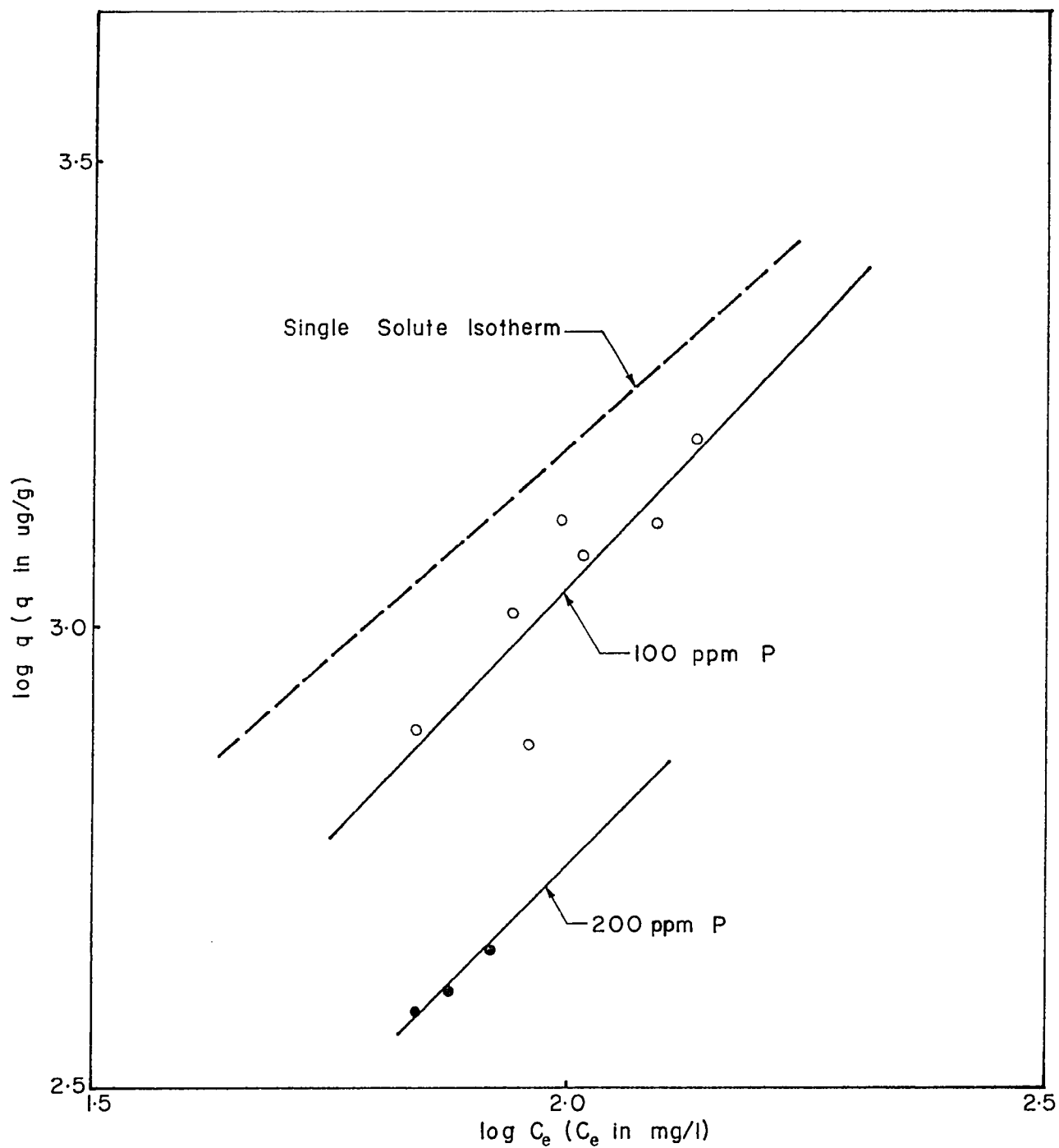


Figure 5.42: Adsorption Isotherms for Chlorophenol in Competition with Phenol.



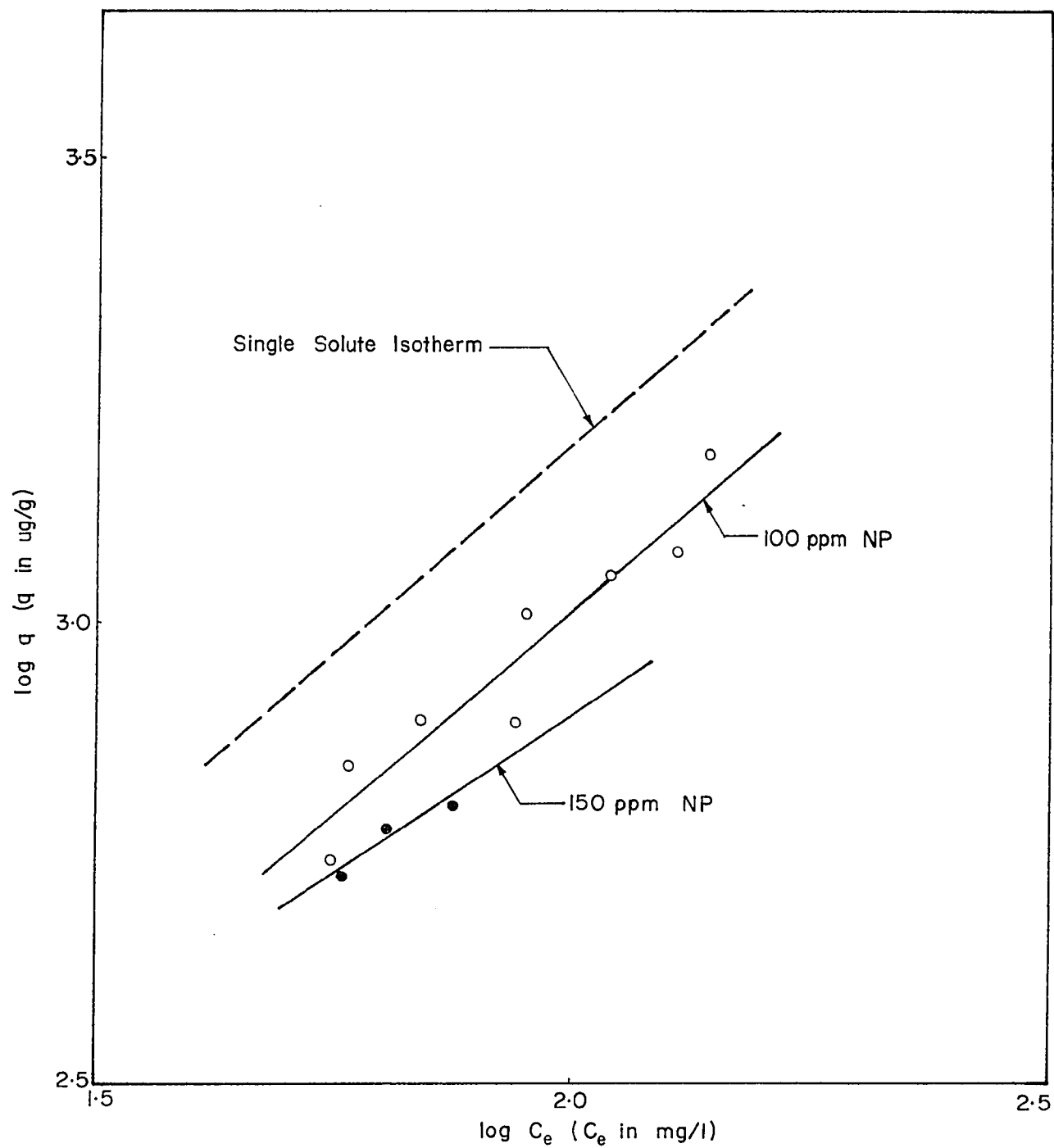


Figure 5.43: Adsorption Isotherms for Chlorophenol in Competition with Nitrophenol.

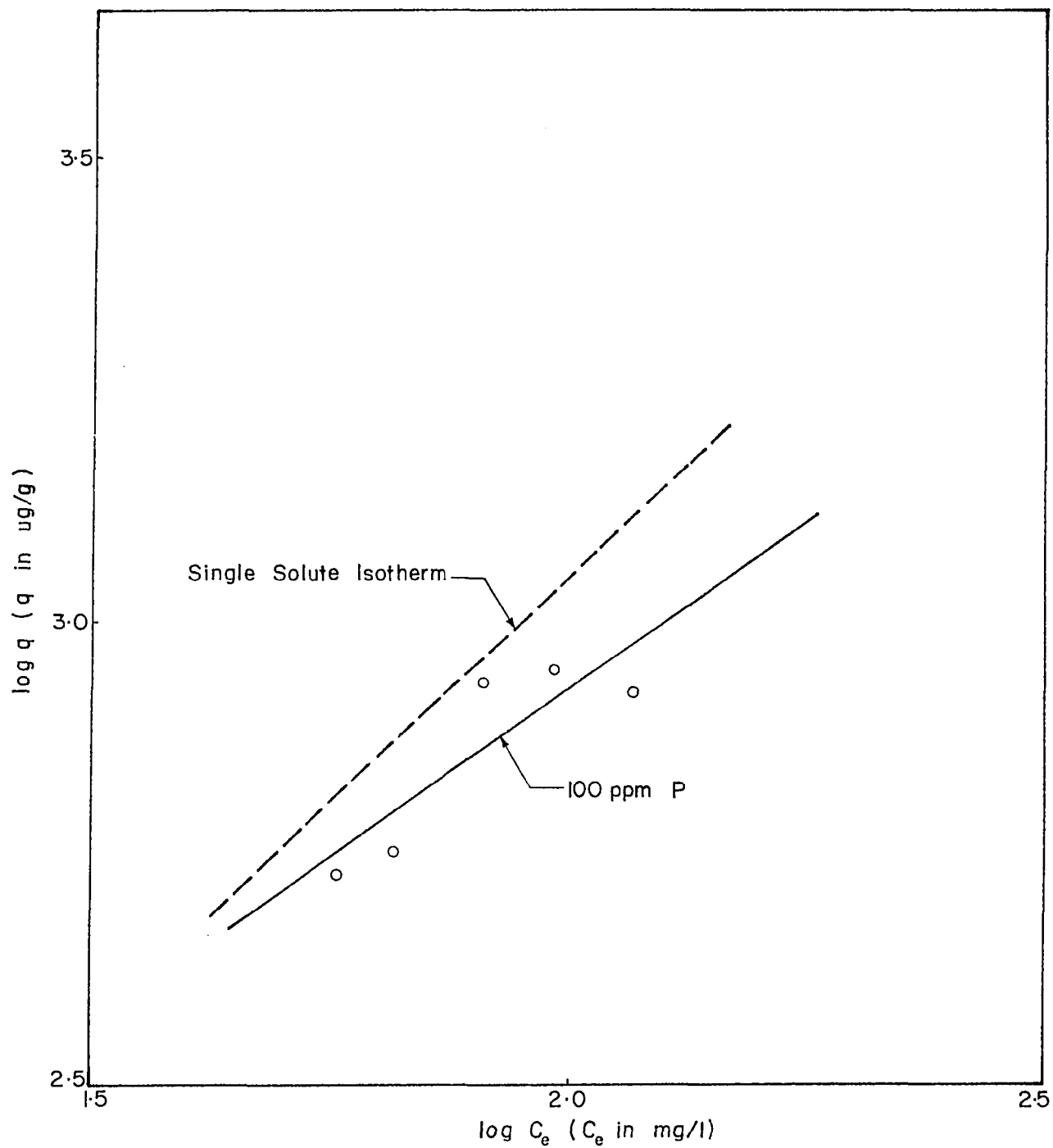


Figure 5.44: Adsorption Isotherms for Nitrophenol in Competition with Phenol.

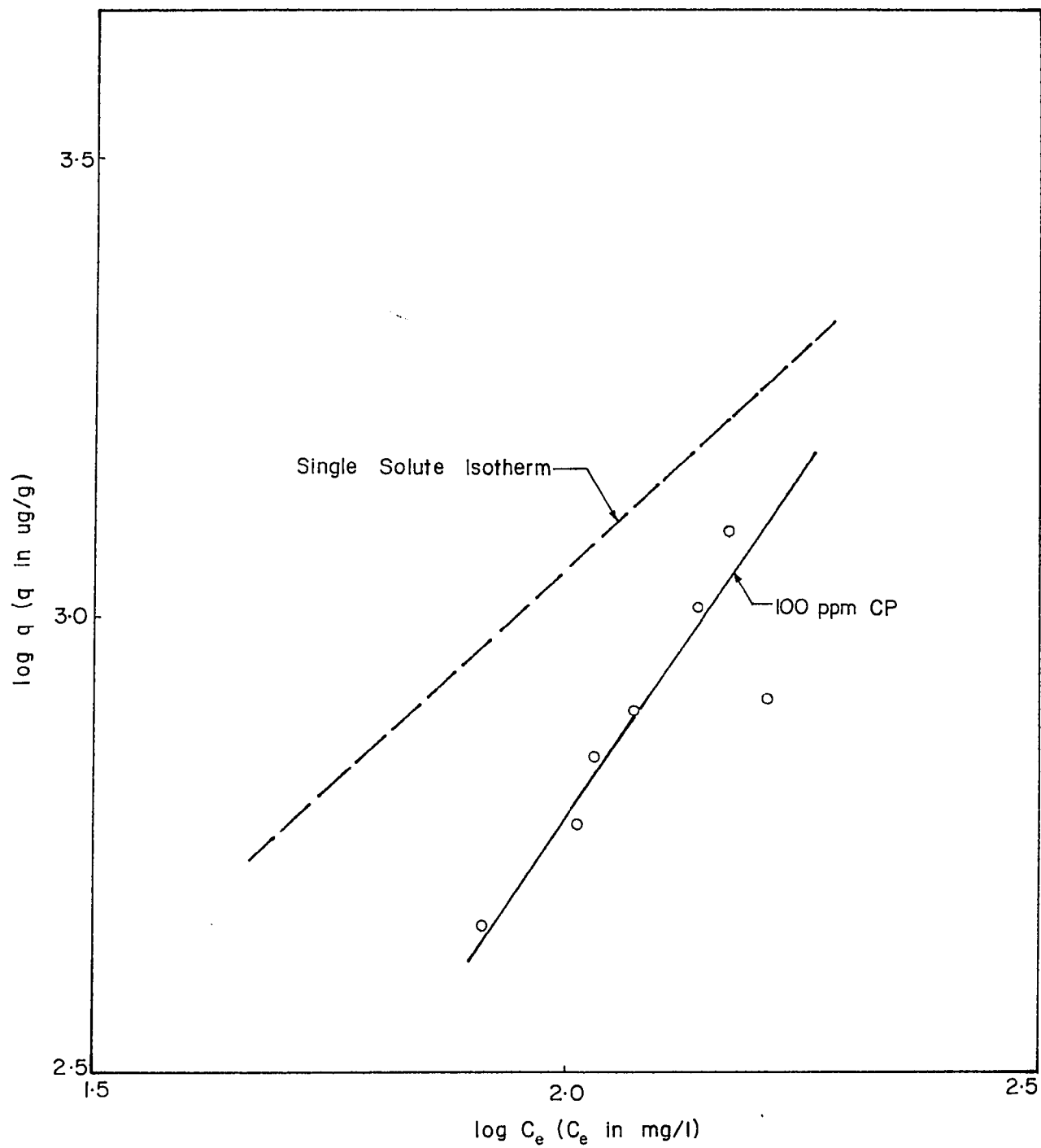


Figure 5.45: Adsorption Isotherms for Nitrophenol in Competition with Chlorophenol.

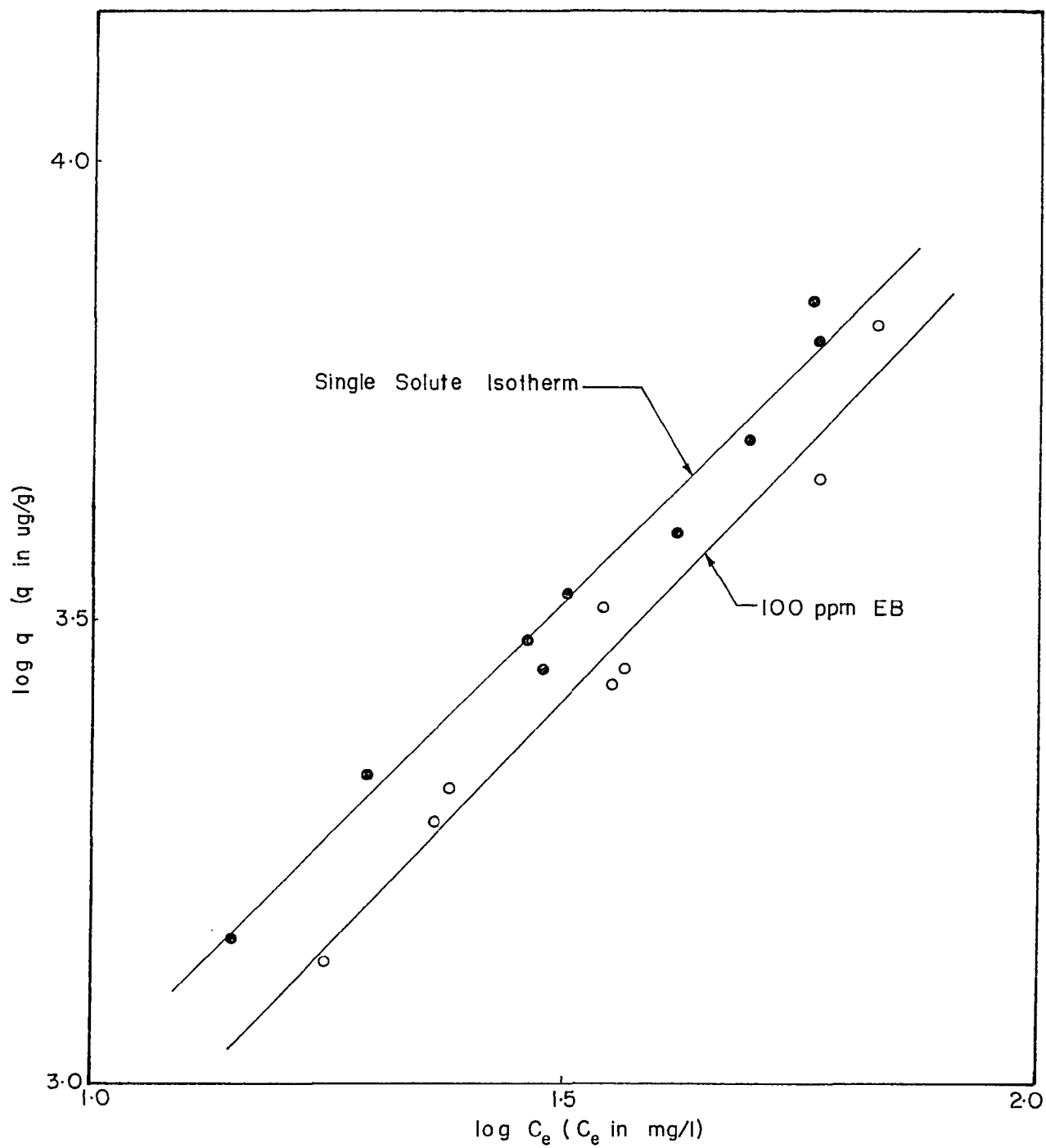


Figure 5.46: Adsorption Isotherms for Chlorobenzene in Competition with Ethylbenzene.

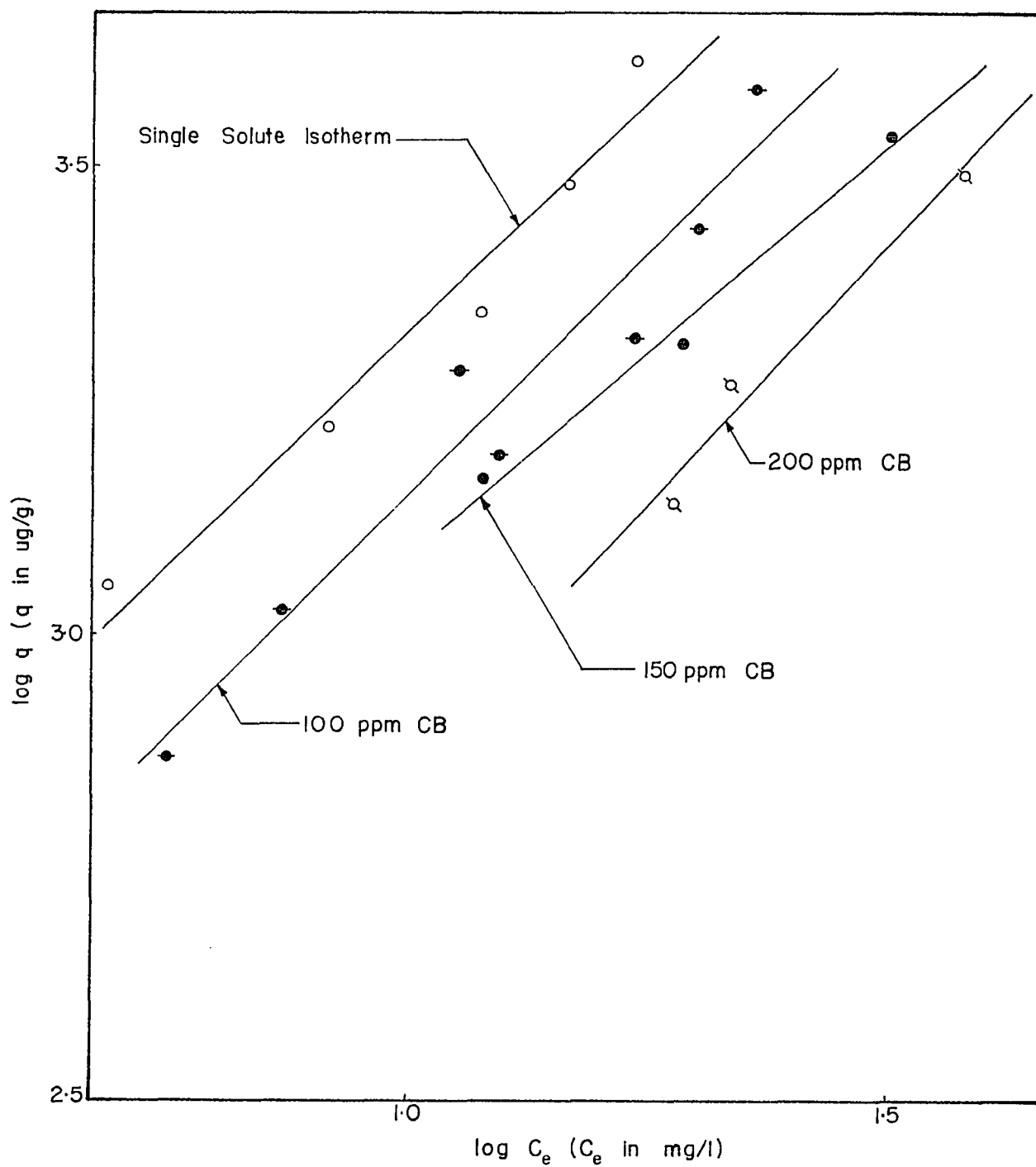


Figure 5.47: Adsorption Isotherms for Ethylbenzene in Competition with Chlorobenzene.

Table 5.15: Freundlich Constants and Adsorption Capacity at 100 ppm Equilibrium Concentration when the Initial Concentration of Other Solute is Constant

Bisolute System	$K_d$	$1/n$	Adsorption Capacity at 100 ppm in ug/g
Phenol/100 ppm CP	0.917	1.25	295.37
Phenol/200 ppm CP	0.954	1.20	239.63
Phenol/100 ppm NP	0.461	1.35	229.98
Chlorophenol/100 ppm P	7.925	1.07	1104.07
Chlorophenol/200 ppm P	4.810	1.03	549.72
Chlorophenol/100 ppm NP	15.453	0.91	1030.42
Chlorophenol/150 ppm NP	30.803	0.71	791.76
Nitrophenol/100 ppm P	27.925	0.74	839.45
Nitrophenol/100 ppm CP	0.479	1.55	594.75
Chlorobenzene/100 ppm EB	63.38	1.08	9119.10
Ethylbenzene/100 ppm CB	128.53	1.04	15452.70
Ethylbenzene/150 ppm CB	55.847	1.12	9616.12
Ethylbenzene/200 ppm CB	164.820	0.87	9015.92

## 2. Adsorption from Multi Solute Systems

The experimental results of competitive adsorption from bisolute systems have indicated that each solute affects adversely the equilibrium capacity for adsorption of the other compound present. Hence, it is interesting to study the competitive effect in multi solute systems. Three (phenol, chlorophenol and nitrophenol), four (phenol, chlorophenol, nitrophenol and chlorobenzene), and five (phenol, chlorophenol,

nitrophenol, chlorobenzene and ethylbenzene) solute systems were selected for the analysis. The equilibrium data for adsorption for the compounds correlated well with the Freundlich equation (with regression coefficients greater than 0.89) in the range of concentrations (50 - 200 mg/l) studied. The adsorption isotherms of each solute from the mixture are shown in Figures 5.48 to 5.52. The summary of the parameters of the Freundlich equation and the adsorption capacity at 100 ppm equilibrium concentration are presented in Table 5.16.

**Table 5.16: Freundlich Constants and Adsorption Capacity at 100 ppm Equilibrium Concentration in Multi Solute Systems**

Multi Solute System	Compound	$K_d$	$1/n$	Adsorption Capacity at 100 ppm
P-CP-NP	Phenol	4.73	0.88	278.52
	2-Chlorophenol	9.46	0.95	737.87
	2-Nitrophenol	7.91	1.01	839.48
P-CP-NP-CB	Phenol	0.26	1.51	264.38
	2-Chlorophenol	2.27	1.15	444.46
	2-Nitrophenol	3.27	1.19	779.86
	Chlorobenzene	101.86	0.80	4092.64
P-CP-NP-CB-EB	Phenol	0.98	1.13	180.81
	2-Chlorophenol	4.73	0.93	350.71
	2-Nitrophenol	2.38	1.21	641.12
	Chlorobenzene	101.60	0.75	3212.87
	Ethylbenzene	195.43	0.97	17337.69

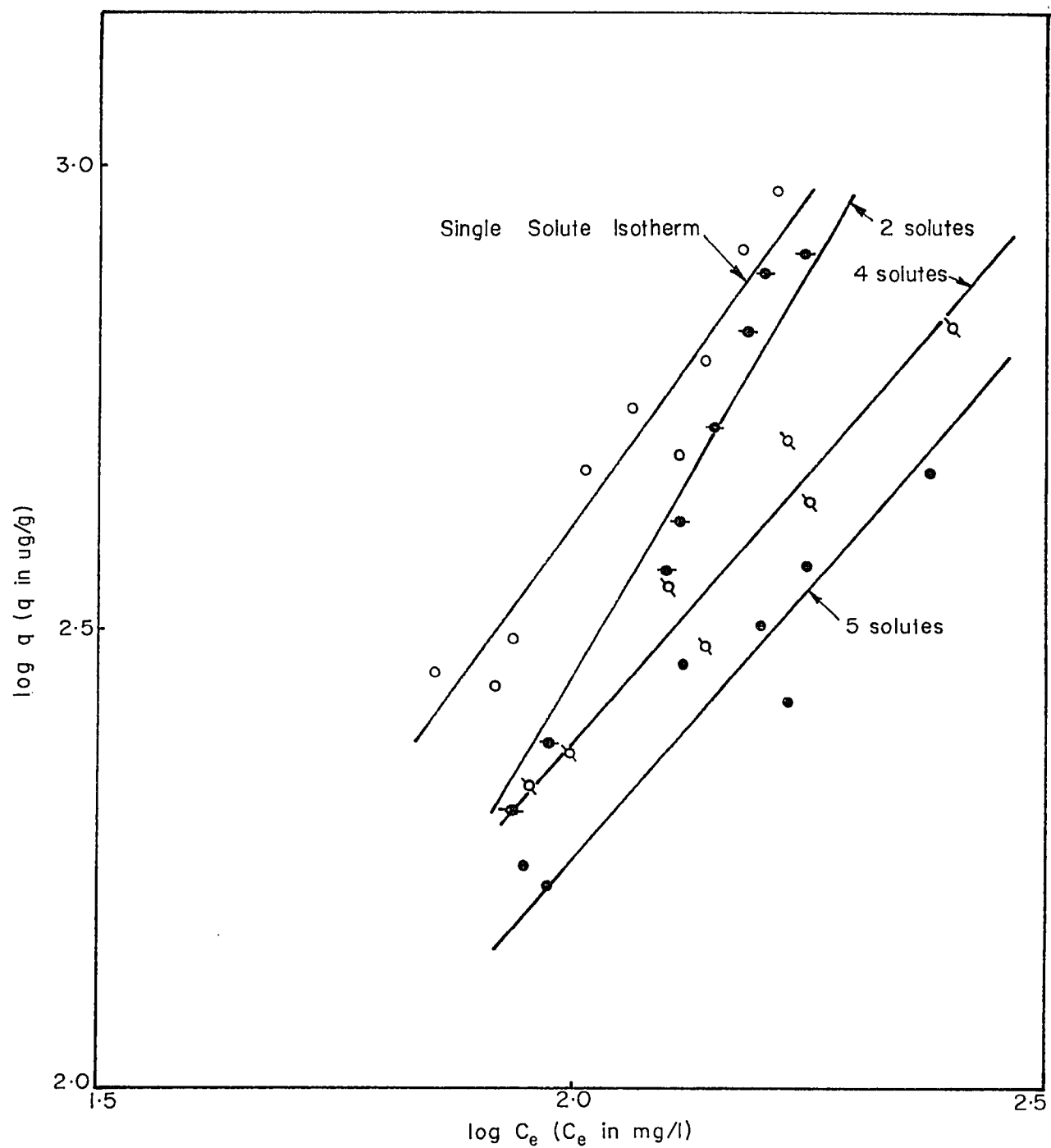


Figure 5.48: Adsorption Isotherms for Phenol in Multi-Solute Systems.



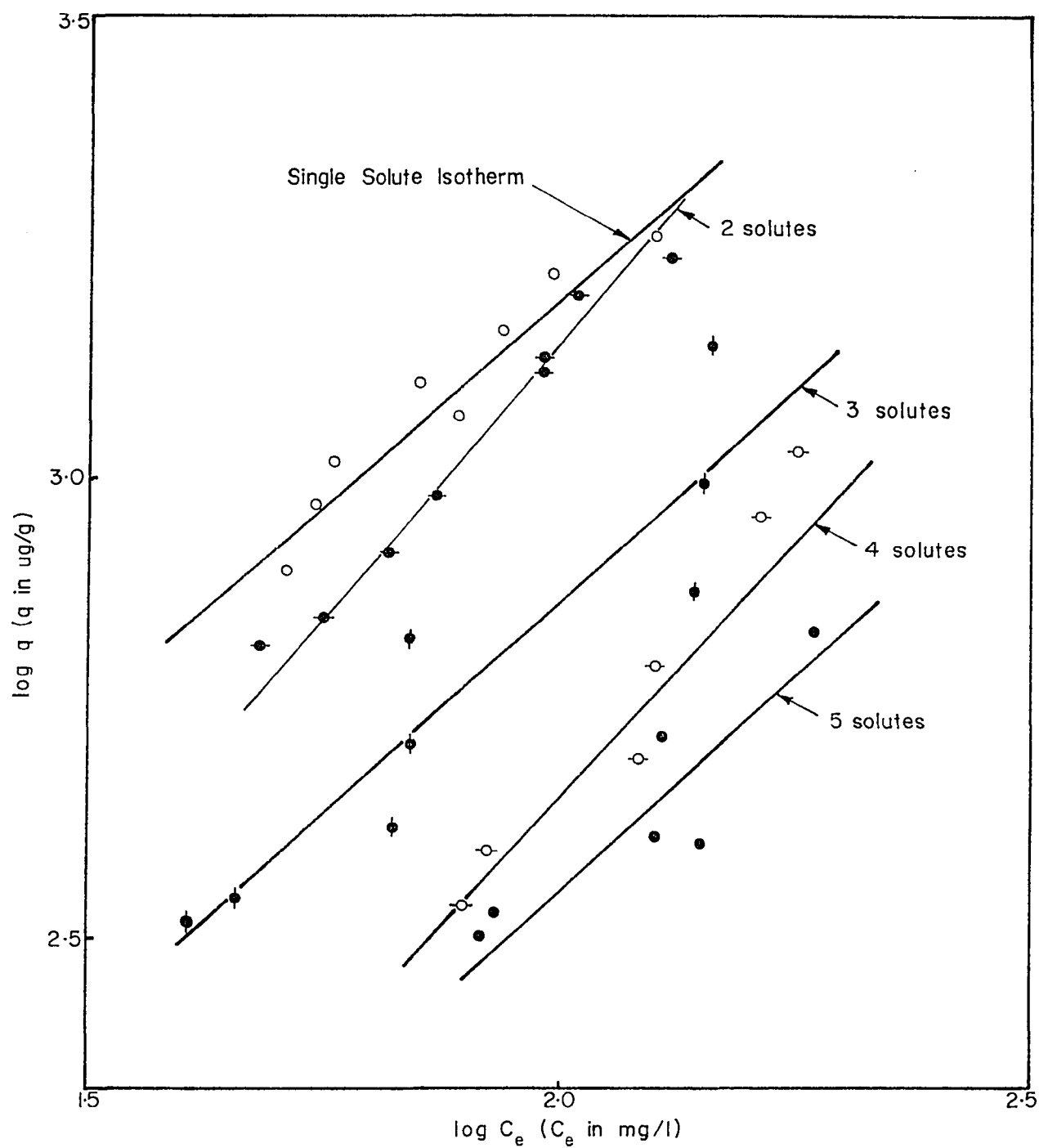
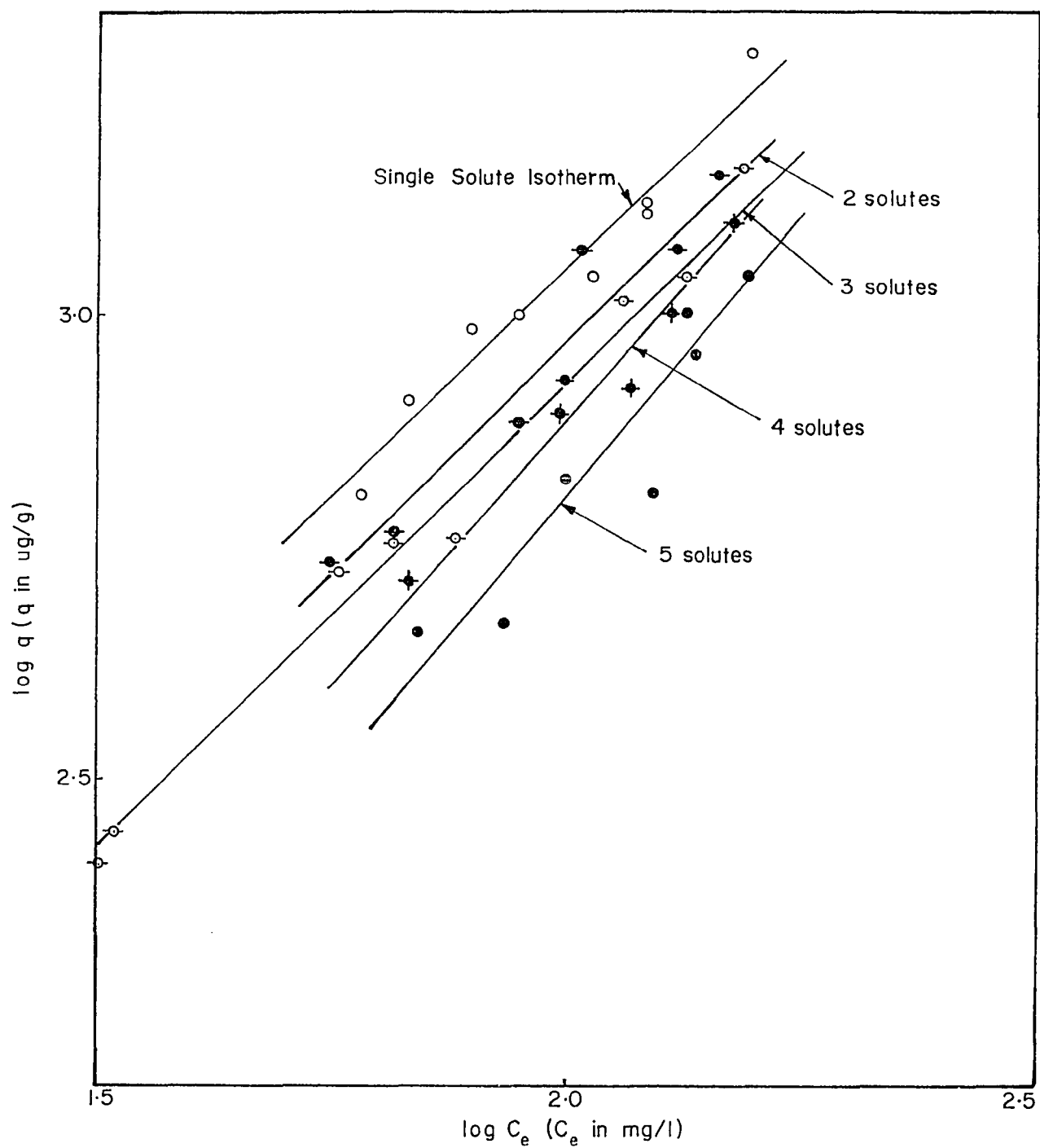


Figure 5.49: Adsorption Isotherms for Chlorophenol in Multi-Solute Systems.



**Figure 5.50: Adsorption Isotherms for Nitrophenol in Multi-Solute Systems.**

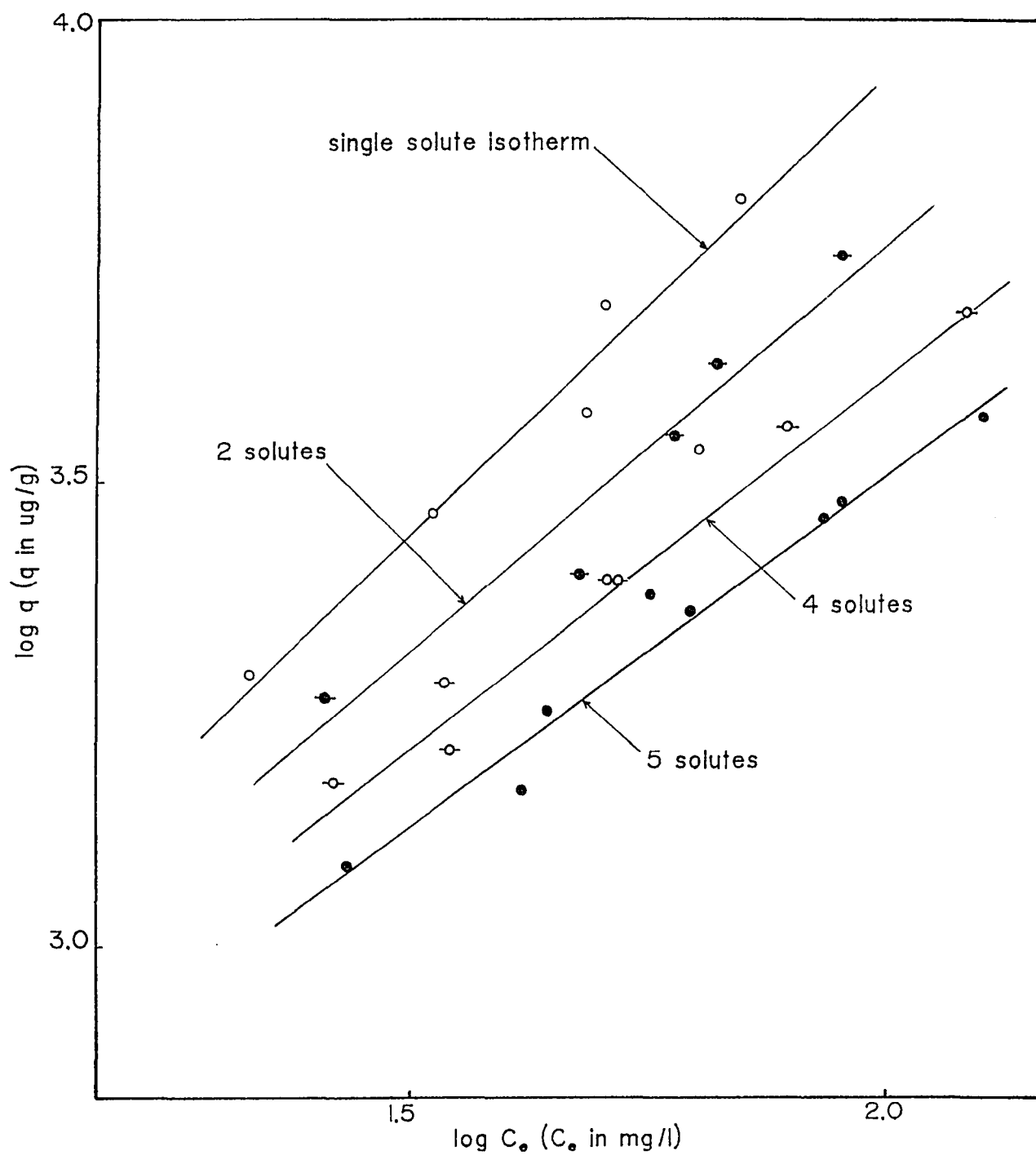
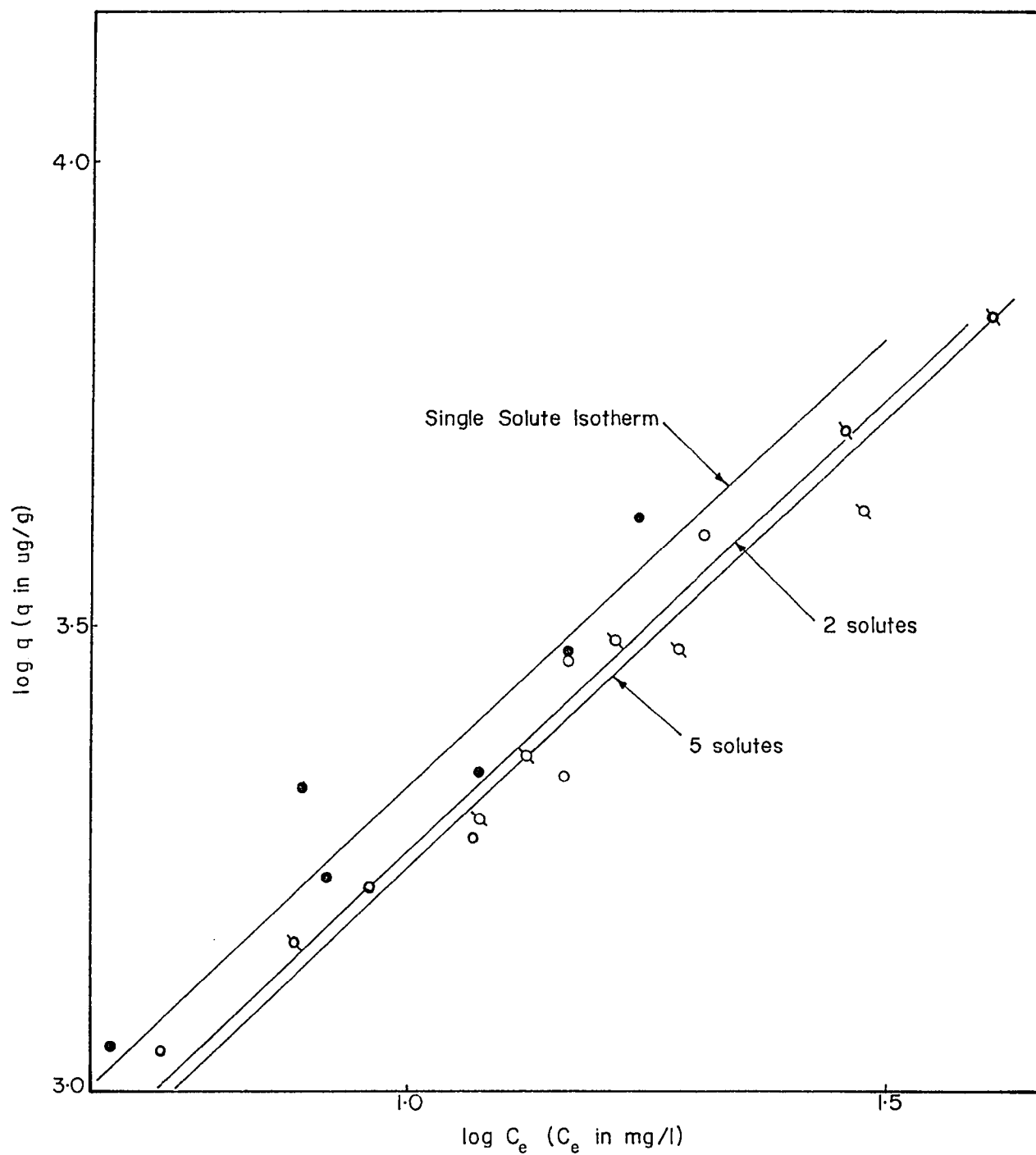


Figure 5.51: Adsorption Isotherms for Chlorobenzene in Multi-Solute Systems.



**Figure 5.52: Adsorption Isotherms for Ethylbenzene in Multi-Solute Systems.**

Comparison of Table 5.1 with Table 5.16 readily shows that the equilibrium capacity for each solute on the activated sludge biomass is affected by the presence of other solutes. The adsorption capacity for each compound from the mixed solution is about 20 - 80% of that when present alone in solution.

The cumulative adsorption capacity is higher than the individual adsorption capacities from their pure solutions except in the case of four solutes system. In the case of four solute system, the cumulative adsorption capacity is higher than the individual adsorption capacities of phenol, chlorophenol and nitrophenol from their pure solution, but it is less than the adsorption capacity for chlorobenzene from its pure solution. This can be explained in that the total surface area of activated sludge biomass available for the adsorption of the four solutes is not more than that available for the adsorption of chlorobenzene from pure solution. Since this area is shared with three other less effectively adsorbed compounds, less efficient use of the available area resulted. Chlorobenzene is the most effectively adsorbed compound of the four compounds used.

It can be seen from Table 5.16 that the effect of competitive adsorption become more pronounced with the increase in number of solutes in solution which emphasized the importance of this factor in the treatment plants when complex mixtures of organic pollutants are present in wastewater. The magnitude of the effect may be explained with an example: For a pure nitrophenol solution, the activated sludge uptake capacity reached an

equilibrium value of 1113 ug/g at the equilibrium concentration of 100 ppm. Under the same conditions in a two, three, four and five solute systems, the nitrophenol uptake capacity was 933, 839, 779, and 641 ug/g respectively.

It is noteworthy that less soluble compounds were observed to be more favorably adsorbed in all multi solute systems studied as opposed to bisolute systems. The results for adsorption from solutions containing three, four and five solutes indicate that the overall adsorption capacity is barely affected by the presence of more solutes in solution.

Experiments were also performed with activated carbon and the results are tabulated in Table 5.17.

Comparison of Table 5.10 with Table 5.17 readily shows that the equilibrium capacity for each solute on the activated carbon was affected by the presence of other solutes in solution. The adsorption capacity of each compound from the mixed solution was less than 50% of that when present alone in solution. The less soluble compound was more favorably adsorbed as in the case of biomass. Overall adsorption capacity was barely affected by the presence of more solutes in solution, which agree with the findings of Martin and Al-Bahrani(1977).

**Table 5.17: Freundlich Constants and Adsorption Capacity at 100 ppm Equilibrium Concentration in Multi Solute Systems for Activated Carbon**

Multi Solute System	Compound	$K_d$	1/n	Adsorption Capacity at 100 ppm
P-CP-NP-CB	Phenol	76.91	1.332	35465.00
	2-Chlorophenol	22855.99	0.285	84918.05
	2-Nitrophenol	24945.95	0.453	200909.30
	Chlorobenzene	7445.43	0.848	369734.52
P-CP-NP-CB-EB	Phenol	7.64	1.739	22960.41
	2-Chlorophenol	50466.13	0.088	75683.29
	2-Nitrophenol	47643.09	0.312	200447.16
	Chlorobenzene	19408.86	0.625	345143.76
	Ethylbenzene	15848.93	0.713	422668.56

F. Correlation of Sorptive Strength with Various Properties of the Sorbate

Biosorption has been modeled by a linear relationship between solid phase and liquid phase concentration (Voice and Weber, 1983). The model is of the form

$$q = K_p C_e \quad (5.7)$$

where,  $K_p$  is the linear partition coefficient. This linear model can be thought of as a special case of the Freundlich equation where the exponent parameter is equal to one. Review of the Freundlich parameters given in Tables 5.1 and 5.2 for activated

sludge biomass and nitrifying bacteria shows that many of the exponential parameters are equal to, or nearly equal to, one.

The summary of the values of the parameters of the linear adsorption isotherm for activated sludge and nitrifying bacteria are tabulated in Tables 5.18 and 5.19 respectively. Linear adsorption isotherms for all five compounds are given in Figures 5.53 and 5.54 for activated sludge and nitrifying bacteria respectively.

Table 3.1 presents a variety of properties of the sorbate compounds used in this research. Correlations were attempted between the  $K_p$  values for the biomass and the molecular properties. The resulting regression will have the form  $Y = A x + B$ , where  $Y$  is either  $K_p$  or  $\log K_p$  and  $x$  is the molecular properties. The following relationships have been found for activated sludge biomass.

**Table 5.18: Linear Adsorption Isotherm for Activated Sludge Biomass**

Compound	Equation	Regression Coefficient
Phenol	$q = 4.63 C_e$	0.98
2-Chlorophenol	$q = 15.73 C_e$	0.99
2-Nitrophenol	$q = 10.44 C_e$	0.98
Chlorobenzene	$q = 91.05 C_e$	0.99
Ethylbenzene	$q = 221.15 C_e$	0.99



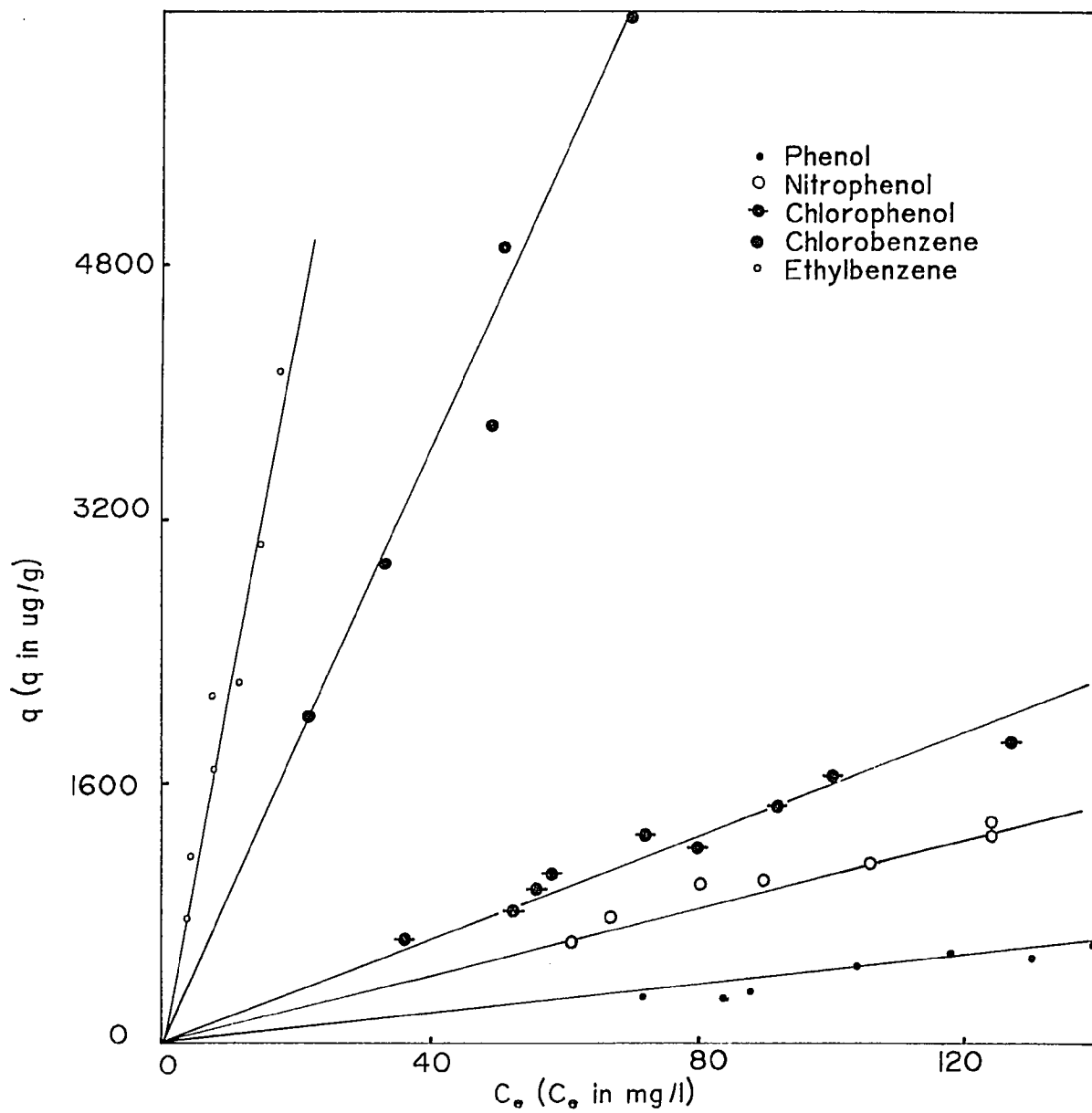


Figure 5.53: Linear Isotherms for All Compounds with Activated Sludge Biomass.

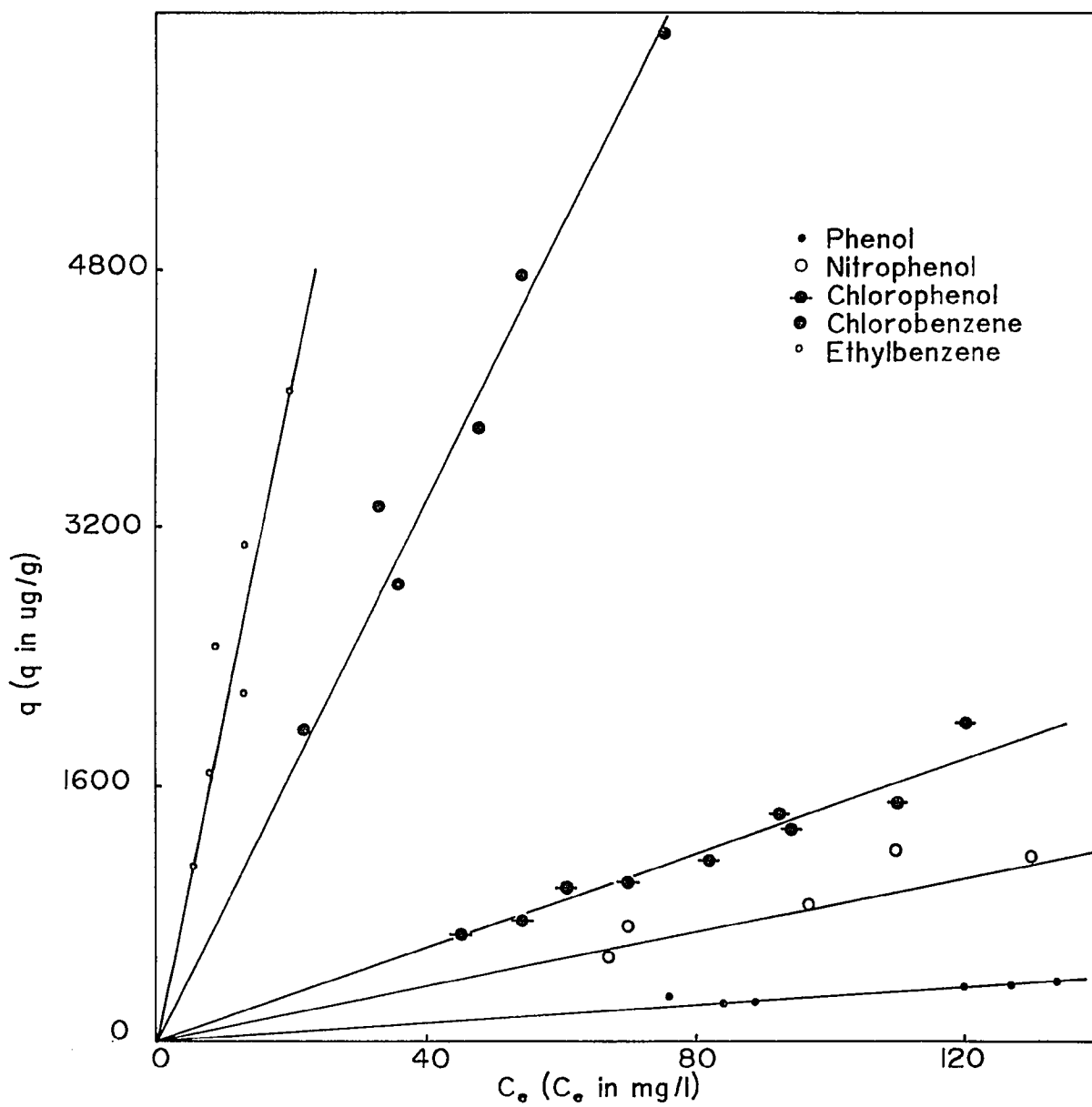


Figure 5.54: Linear Isotherms for All Compounds with Nitrifying Bacteria.

**Table 5.19: Linear Adsorption Isotherm for Nitrifying Bacteria**

Compound	Equation	Regression Coefficient
Phenol	$q = 3.043 C_e$	0.99
2-Chlorophenol	$q = 15.019 C_e$	0.99
2-Nitrophenol	$q = 8.658 C_e$	0.99
Chlorobenzene	$q = 84.837 C_e$	0.99
Ethylbenzene	$q = 203.963 C_e$	0.99

$$\log K_p = 0.967 \log K_{ow} - 0.76 \quad (r = 0.99) \quad (5.8)$$

$$\log K_p = -0.536 \log S + 3.321 \quad (r = -0.89) \quad (5.9)$$

$$\log K_p = 6.677 + 0.566 \quad (r = 0.69) \quad (5.10)$$

$$\log K_p = 0.022 P - 4.236 \quad (r = 0.79) \quad (5.11)$$

$$\log K_p = 0.048 V - 3.43 \quad (r = 0.91) \quad (5.12)$$

$$\log K_p = -0.005 M + 2.026 \quad (r = -0.13) \quad (5.13)$$

where  $K_{ow}$  = octanol/water partition coefficient

$S$  = aqueous solubility (mg/l)

= electronic polarizability ( $10^{-24} \text{ cm}^3$ )

$P$  = parachor ( $\text{cm}^3 \text{ dyne}^{1/4} \text{ mol cm}^{1/4}$ )

$V$  = molar volume ( $\text{cm}^3/\text{mol}$ )

$M$  = molecular weight (g/mol)

The relationships between  $K_p$  values and the molecular properties for nitrifying bacteria are given below:

$$\log K_p = 1.038 \log K_{ow} - 0.996 \quad (r = 0.99) \quad (5.14)$$

$$\log K_p = -0.571 \log S + 3.372 \quad (r = -0.89) \quad (5.15)$$

$$\log K_p = 7.56 + 0.38 \quad (r = 0.73) \quad (5.16)$$

$$\log K_p = 0.025 P - 4.859 \quad (r = 0.81) \quad (5.17)$$

$$\log K_p = 0.051 V - 3.843 \quad (r = 0.91) \quad (5.18)$$

$$\log K_p = -0.0032 M + 1.744 \quad (r = -0.007) \quad (5.19)$$

The above results clearly indicate that the sorption distribution coefficient is strongly correlated to aqueous solubility and octanol/water partition coefficient (with regression coefficient greater than 0.89) of the sorbate and to a lesser extent to both parachor and molar volume. But the sorption distribution coefficient is not correlated to the compound's molecular weight at all.

Linear partition coefficients,  $K_p$ , were also determined for each compound in competition with other sorbates and are given in Table 5.20. The linear model provides the advantage that the relative magnitude of the biosorptive uptake for different systems may be evaluated over the entire concentration range by comparing the linear partition coefficients,  $K_p$ .

From Table 5.20, it can be noted that in most cases, the linear partition coefficients for the competitive systems are almost same. The concentration ranges expected to occur in biological wastewater treatment plants are in ppb range and the adsorption capacities of biomass are much greater than the loadings achieved in biological WWTP. Hence, the effect of competition on biosorption of hazardous organic compounds in

biological WWTP may be very slight and insignificant. Therefore, it may be possible to model the behavior of individual compounds from single solute isotherm data without regard for competitive effects.

**Table 5.20: Linear Partition Coefficients for Competitive Adsorption**

Compound	Competing Compounds	K <sub>p</sub> (ml/g)
Phenol	None	4.63
Phenol	CP	3.84
Phenol	NP	3.80
Phenol	CP, NP	3.15
Phenol	CP, NP, CB	3.81
Phenol	CP, NP, CB, EB	1.94
2-Chlorophenol	None	15.73
2-Chlorophenol	P	14.29
2-Chlorophenol	NP	13.83
2-Chlorophenol	P, NP	9.01
2-Chlorophenol	P, NP, CB	5.32
2-Chlorophenol	P, NP, CB, EB	3.48
2-Nitrophenol	None	10.44
2-Nitrophenol	P	8.97
2-Nitrophenol	CP	5.91
2-Nitrophenol	P, CP	8.38
2-Nitrophenol	P, CP, CB	8.42
2-Nitrophenol	P, CP, CB, EB	7.69
Chlorobenzene	None	91.05
Chlorobenzene	EB	63.14
Chlorobenzene	P, CP, NP	48.99
Chlorobenzene	P, CP, NP, EB	32.82
Ethylbenzene	None	221.15
Ethylbenzene	CB	204.51
Ethylbenzene	P, CP, NP, CB	184.47

G. Determination of the Normalized Distribution Coefficient ( $K_{OC}$ ) and its Correlation to the Sorbate's Aqueous Solubility, and Octanol/Water Partition Coefficient

The literature pertaining to the sorption of nonionic, organic compounds with soils usually reports high correlation between the normalized sorption distribution coefficient,  $K_{OC}$ , and the sorbate's solubility(S) and octanol/water partition coefficient( $K_{OW}$ ). It is therefore of interest to know to what extent these variables are correlated for the data in this research. The normalized sorption distribution coefficient,  $K_{OC}$ , is defined as

$$K_{OC} = K_p / f_{OC} \quad (5.20)$$

where,  $f_{OC}$  is fraction of organic carbon.

Fraction of organic carbon ( $f_{OC}$ ) was determined by Galbraith Laboratories Inc., Knoxville, using an infrared absorption method. The  $f_{OC}$  of activated sludge and nitrifying bacteria was found to be 0.3673 and 0.3624 respectively. The calculated  $K_{OC}$  values are given in Table 5.21. From Table 5.21, it can be seen that except for phenol,  $K_{OC}$  values vary only in the range of 3 to 15% between activated sludge and nitrifying bacteria. This clearly indicates that the organic carbon content plays an important role in determining the sorption by the biomass.

Table 5.21: Calculated  $K_{OC}$  Values

Compound	$K_{OC}$	
	Activated Sludge	Nitrifying Bacteria
Phenol	12.61	8.40
2-Chlorophenol	42.83	41.44
2-Nitrophenol	28.42	23.89
Chlorobenzene	247.89	234.10
Ethylbenzene	602.10	562.81

Using the  $K_{OC}$  values in Table 5.21 and  $S$  and  $K_{OW}$  values from Table 3.1, a least square linear regression was performed to determine the relationship between  $\log K_{OC}$  and  $\log S$ , and  $\log K_{OC}$  and  $\log K_{OW}$  (which represents the regression relationships most commonly reported in the literature). The resulting regression equations are:

$$\log K_{OC} = - 0.554 \log S + 3.784 \quad (S \text{ in mg/l}) \quad (r = -0.89) \quad (5.21)$$

$$\log K_{OC} = 1.003 \log K_{OW} - 0.443 \quad (r = 0.99) \quad (5.22)$$

Equation (5.22) can be reduced to equation (5.23), which indicates the linear variation of  $K_{OC}$  and  $K_{OW}$ .

$$K_{OC} = 0.361 K_{OW} \quad (5.23)$$

According to the correlation coefficients, octanol/water partition coefficient is a better predictor than the aqueous solubility( $S$ ).  $\log K_{OC}$  is plotted against  $\log S$  and  $\log K_{OW}$  and

are shown in Figures 5.55 and 5.56 respectively.

Equations (5.21) and (5.22) seem to be in fairly good agreement with some of the regressions reported in the literature for these molecular properties. The following are the regression equations reported in various publications:

Authors	Equation	
La Poe	$\log K_{OC} = -0.468 \log S + 2.61$	S in mmol/l (r = -0.98)
	$\log K_{OC} = 0.93 \log K_{OW} + 0.0019$	(r = 0.786)
Karickhoff et al.	$\log K_{OC} = -0.54 \log S + 0.44$	(r = -0.97) S in mole fraction
	$\log K_{OC} = 1.00 \log K_{OW} - 0.21$	(r = 1.00)
Means et al.	$\log K_{OC} = -0.686 \log S + 4.273$	S in mg/l (r = -0.97)
	$\log K_{OC} = \log K_{OW} - 0.317$	(r = 0.99)

#### H. Adsorption and Desorption by Live Activated Sludge Biomass

Adsorption and desorption experiments were performed with live activated sludge biomass for all compounds. Freundlich adsorption isotherms for live activated sludge biomass with phenol, chlorophenol, nitrophenol, chlorobenzene and ethylbenzene are shown in Figures 5.57 through 5.61. Table 5.22 gives the Freundlich equation parameters and the adsorption capacity at 100 ppm equilibrium concentration.



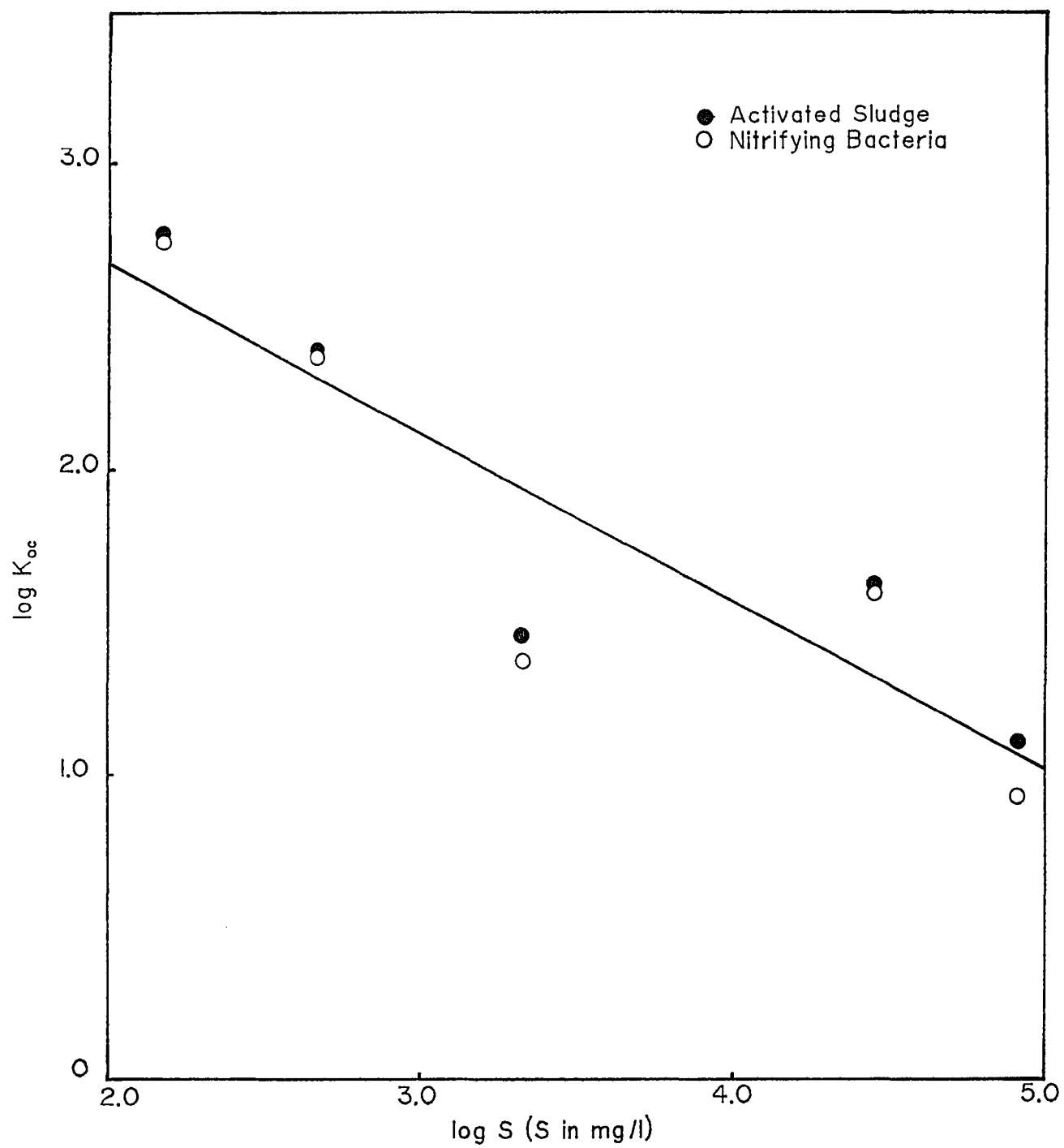


Figure 5.55: Plot of  $K_{oc}$  Versus Aqueous Solubility.

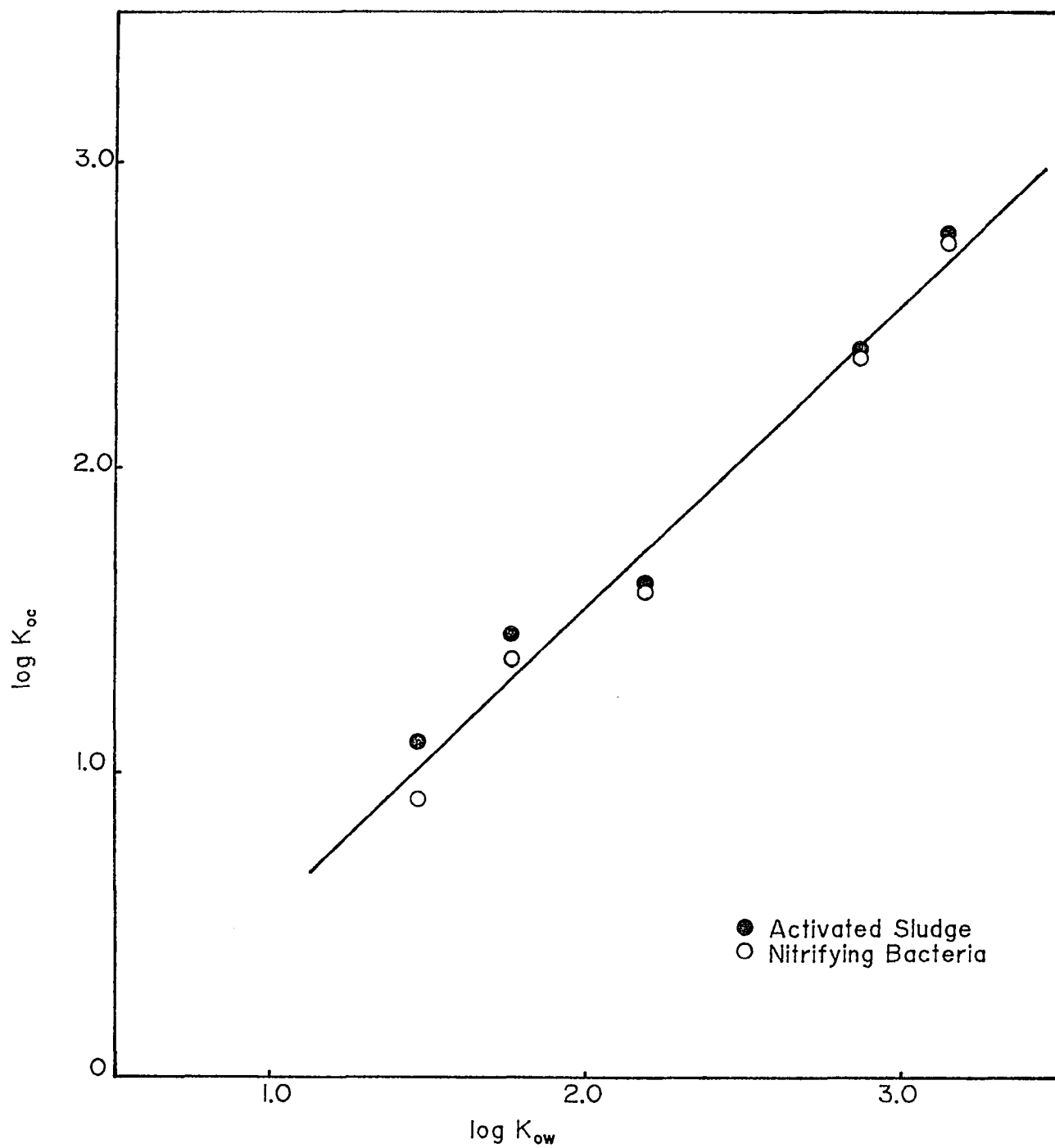


Figure 5.56: Plot of  $K_{OC}$  Versus  $K_{OW}$ .

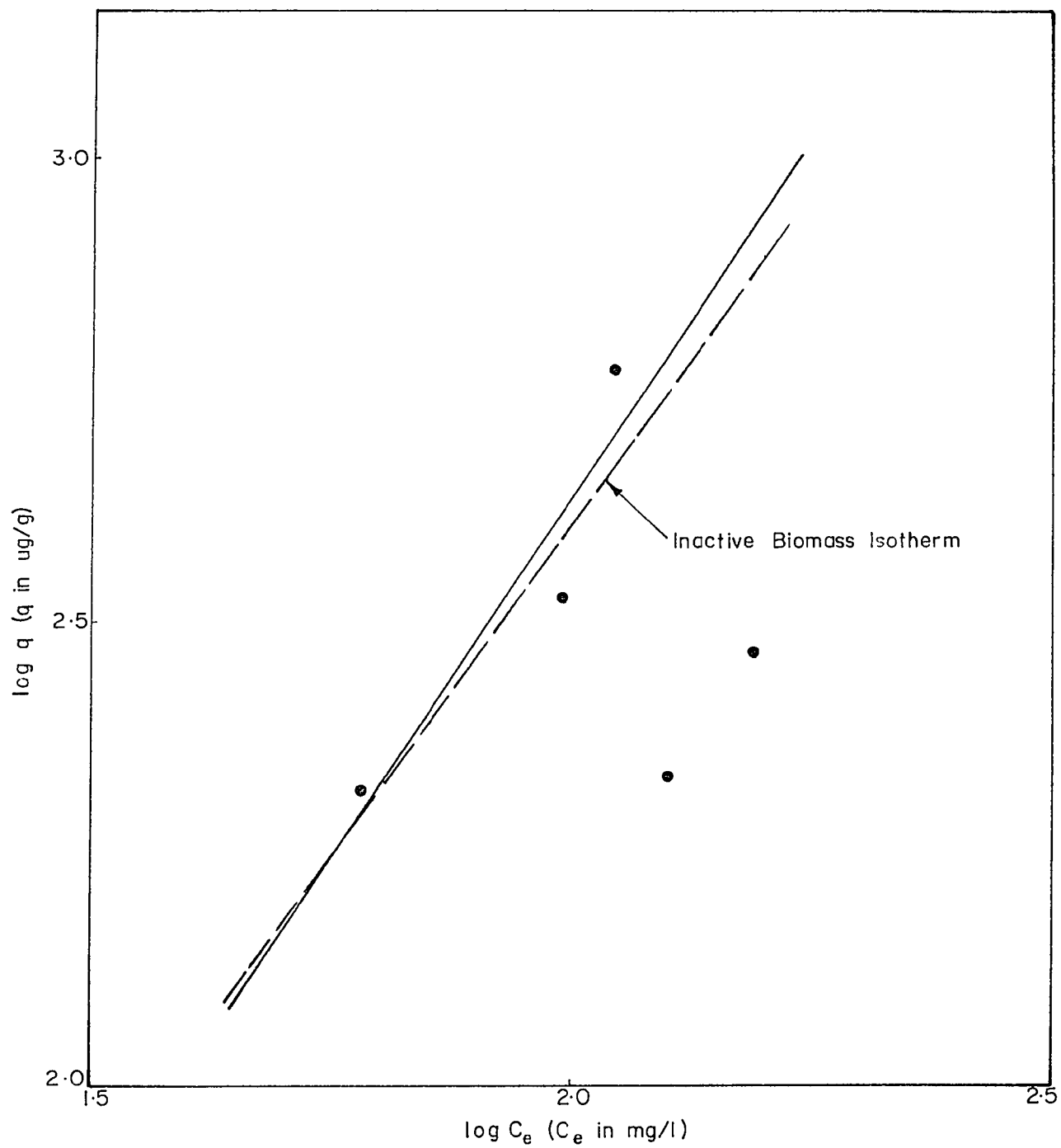


Figure 5.57: Freundlich Adsorption Isotherm for Phenol with Live Activated Sludge.

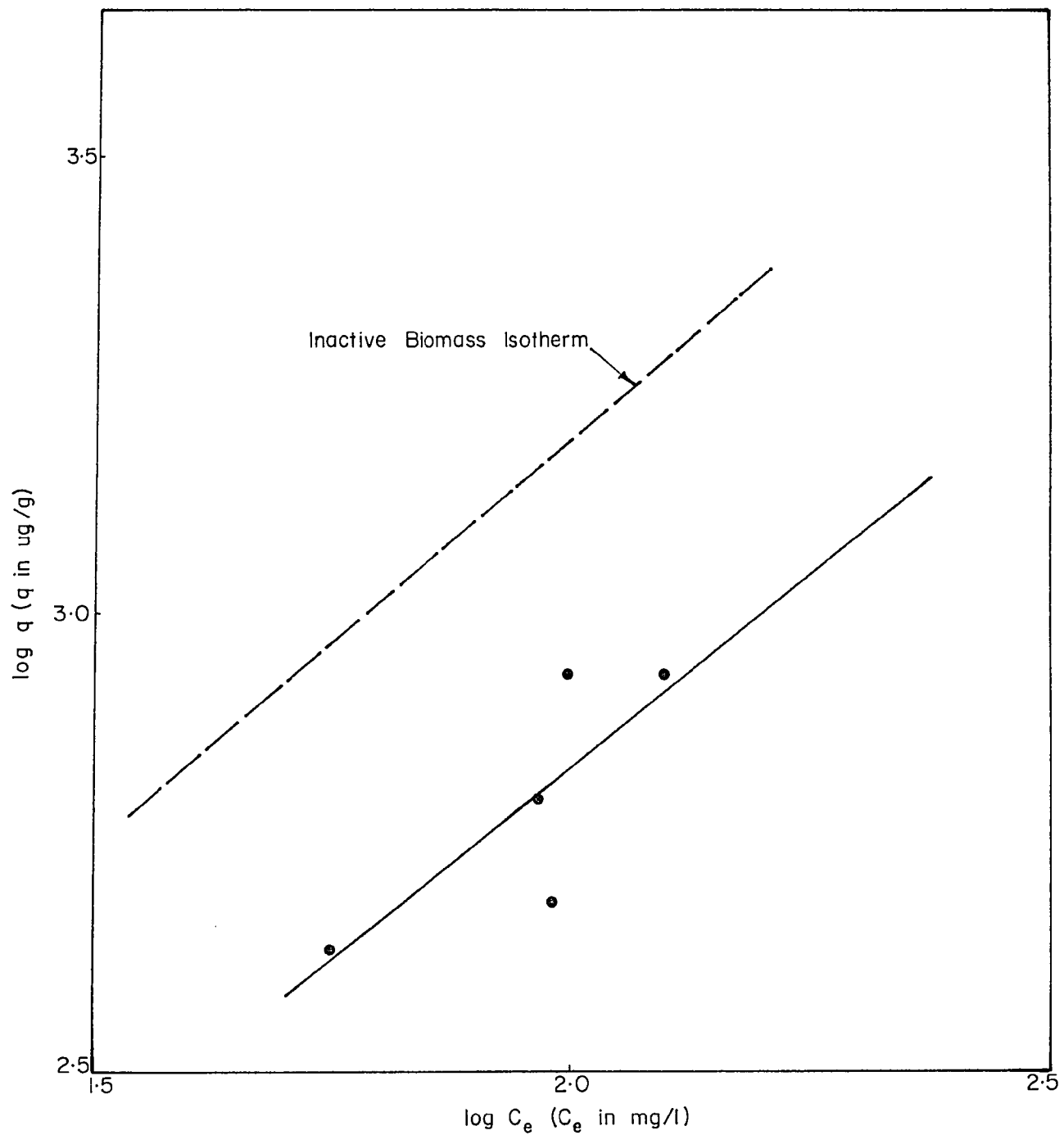


Figure 5.58: Freundlich Adsorption Isotherm for Chlorophenol with Live Activated Sludge.

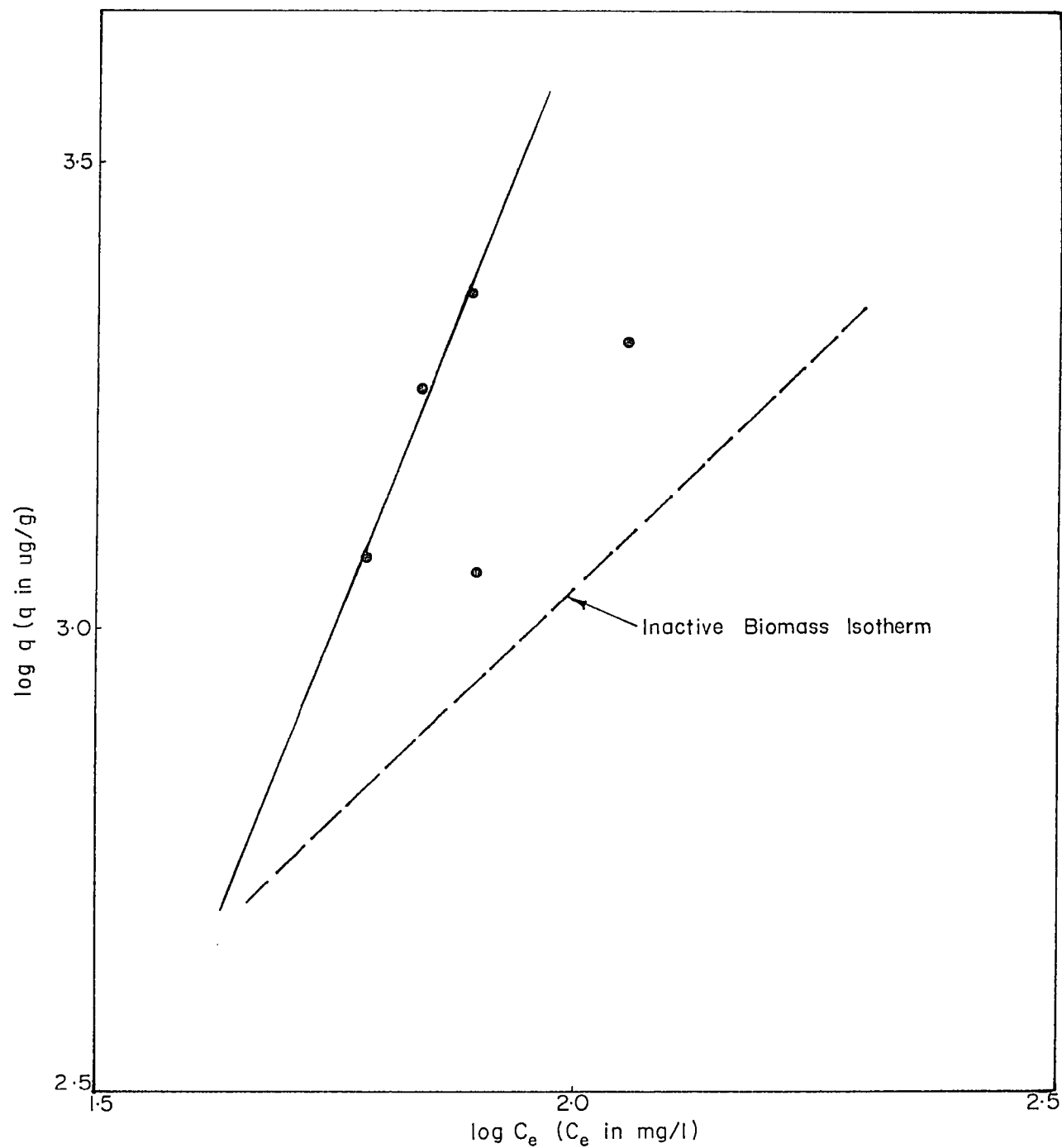


Figure 5.59: Freundlich Adsorption Isotherm for Nitrophenol with Live Activated Sludge.

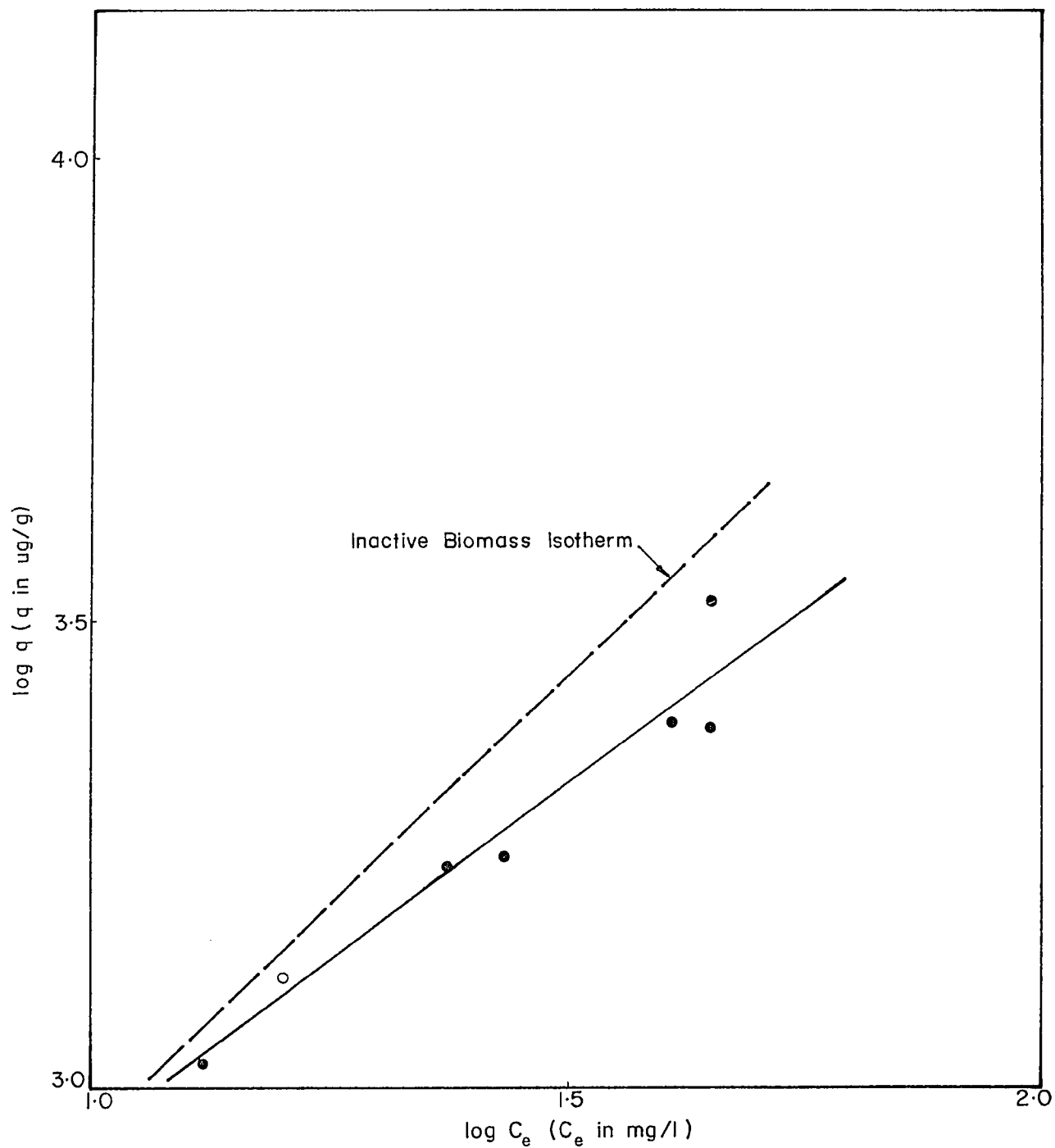


Figure 5.60: Freundlich Adsorption Isotherm for Chlorobenzene with Live Activated Sludge.

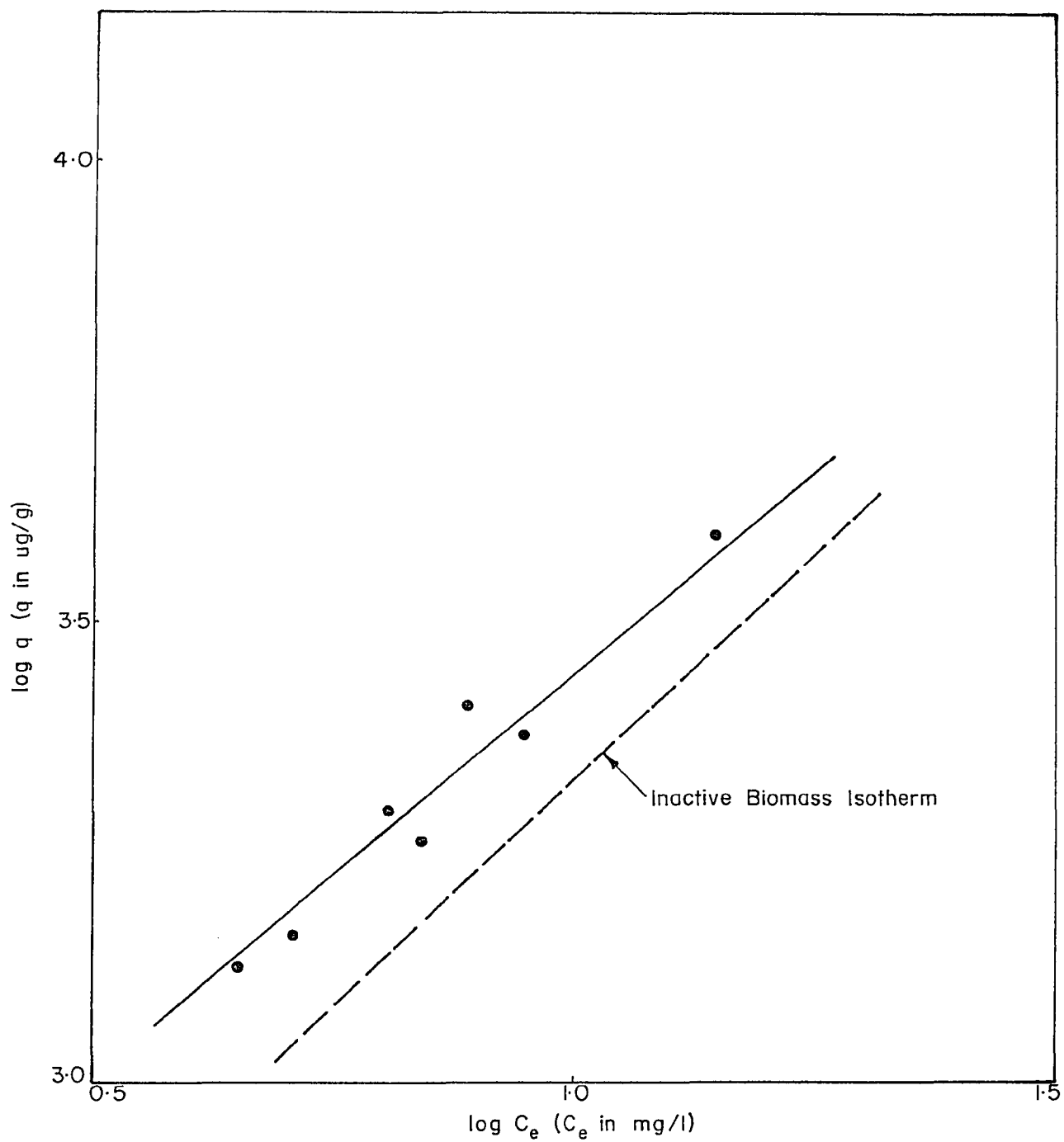


Figure 5.61: Freundlich Adsorption Isotherm for Ethylbenzene with Live Activated Sludge.

**Table 5.22:Freundlich adsorption Isotherm for Live Activated Sludge Biomass**

Compound	Equation	Adsorption Capacity at 100 ppm in ug/g
Phenol	$q = 0.346 C_e^{1.547}$	429.61
2-Chlorophenol	$q = 14.89 C_e^{0.829}$	677.48
2-Nitrophenol	$q = 0.031 C_e^{2.578}$	4439.78
Chlorobenzene	$q = 151.56 C_e^{0.764}$	5111.93
Ethylbenzene	$q = 391.74 C_e^{0.848}$	19453.51

Note that the order of sorptive strength is:

Ethylbenzene > Chlorobenzene > 2-Nitrophenol > 2-Chlorophenol > Phenol.

From the results, it can be seen that the uptake of nitrophenol and ethylbenzene by live biomass is greater than the uptake by inactive biomass (Figure 5.59 and 5.61). Phenol was found to be sorbed by live biomass to approximately the same level as by inactive biomass (Figure 5.57). But the uptake of chlorophenol and chlorobenzene by live biomass is less than the uptake by inactive biomass (Figure 5.58 and 5.60). Hence the results of this study suggest that a generalization cannot be made concerning the difference in biosorptive uptake by live and inactive biomass. The difference in uptake appears to depend on the specific sorbate.

Retained isotherms for all five compounds with live biomass



are shown in Figure 5.62 through 5.66. Table 5.23 gives the parameters of the Freundlich retained isotherm.

**Table 5.23: Freundlich retained Isotherm for Live Activated Sludge Biomass**

Compound	Equation	Regression Coefficient
Phenol	$q_{ret} = 0.139 C_e^{1.174}$	0.88
2-Chlorophenol	$q_{ret} = 27.79 C_e^{0.617}$	0.84
2-Nitrophenol	$q_{ret} = 0.026 C_e^{2.582}$	0.99
Chlorobenzene	$q_{ret} = 197.24 C_e^{0.626}$	0.93
Ethylbenzene	$q_{ret} = 381.94 C_e^{0.825}$	0.98

### I. Model Development

The amount of organic compound sorbed by the biomass can be given by combining equations (5.7), (5.20), and (5.23)

$$q = 0.361 * 10^{-6} f_{OC} K_{OW} C_e \quad (5.24)$$

Reasonable estimation of the sorption behavior of organic pollutants can be made from equation (5.24) from a knowledge of organic carbon content of the biomass and the octanol/water partition coefficient of the compound. These sorbate - sorbent properties are either known or can be easily measured in the laboratory.

It is of interest to examine the use of biosorption isotherms to predict the fate of hazardous organic compounds in biological

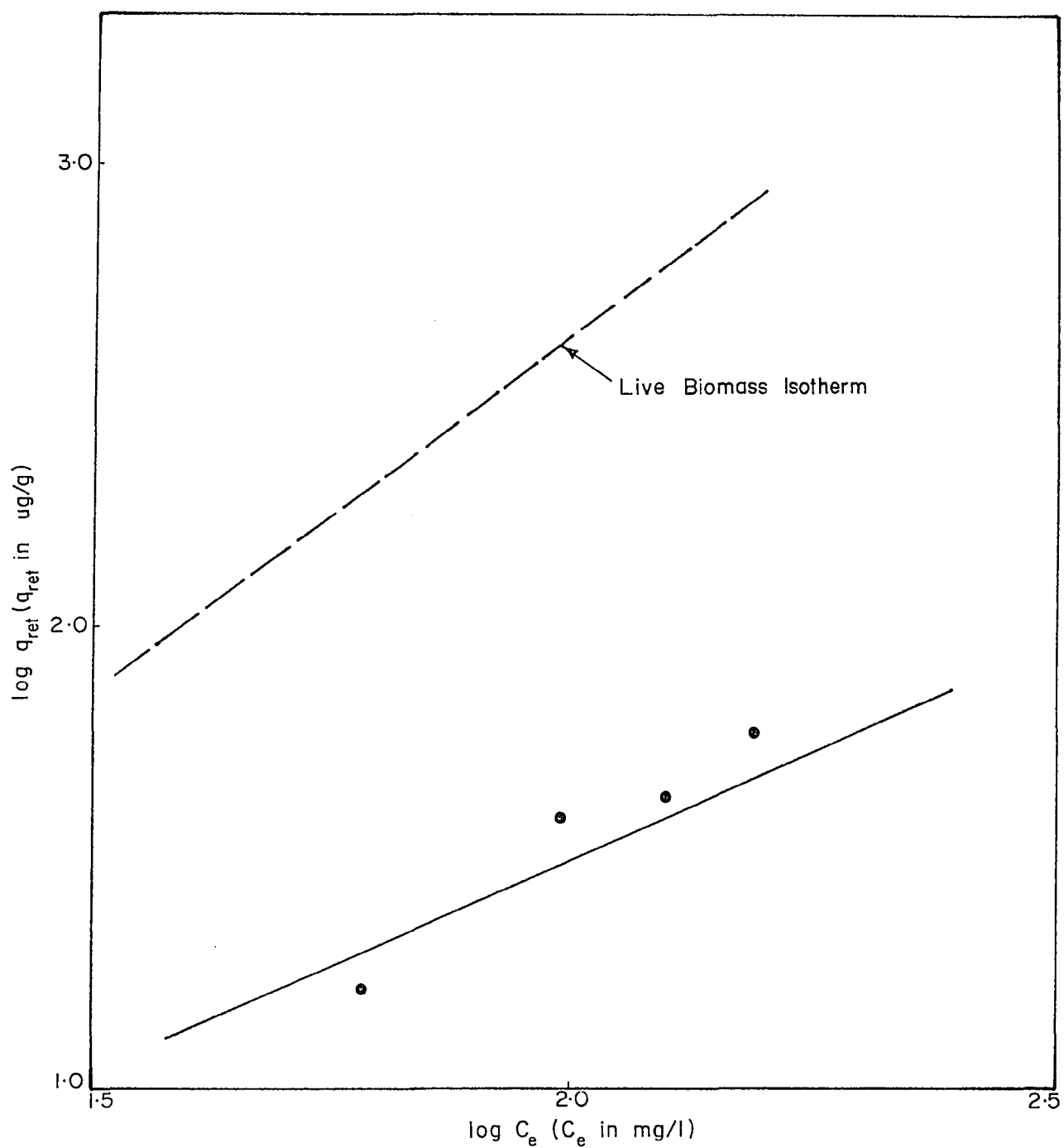


Figure 5.62: Freundlich Retained Isotherm for Phenol with Live Activated Sludge.

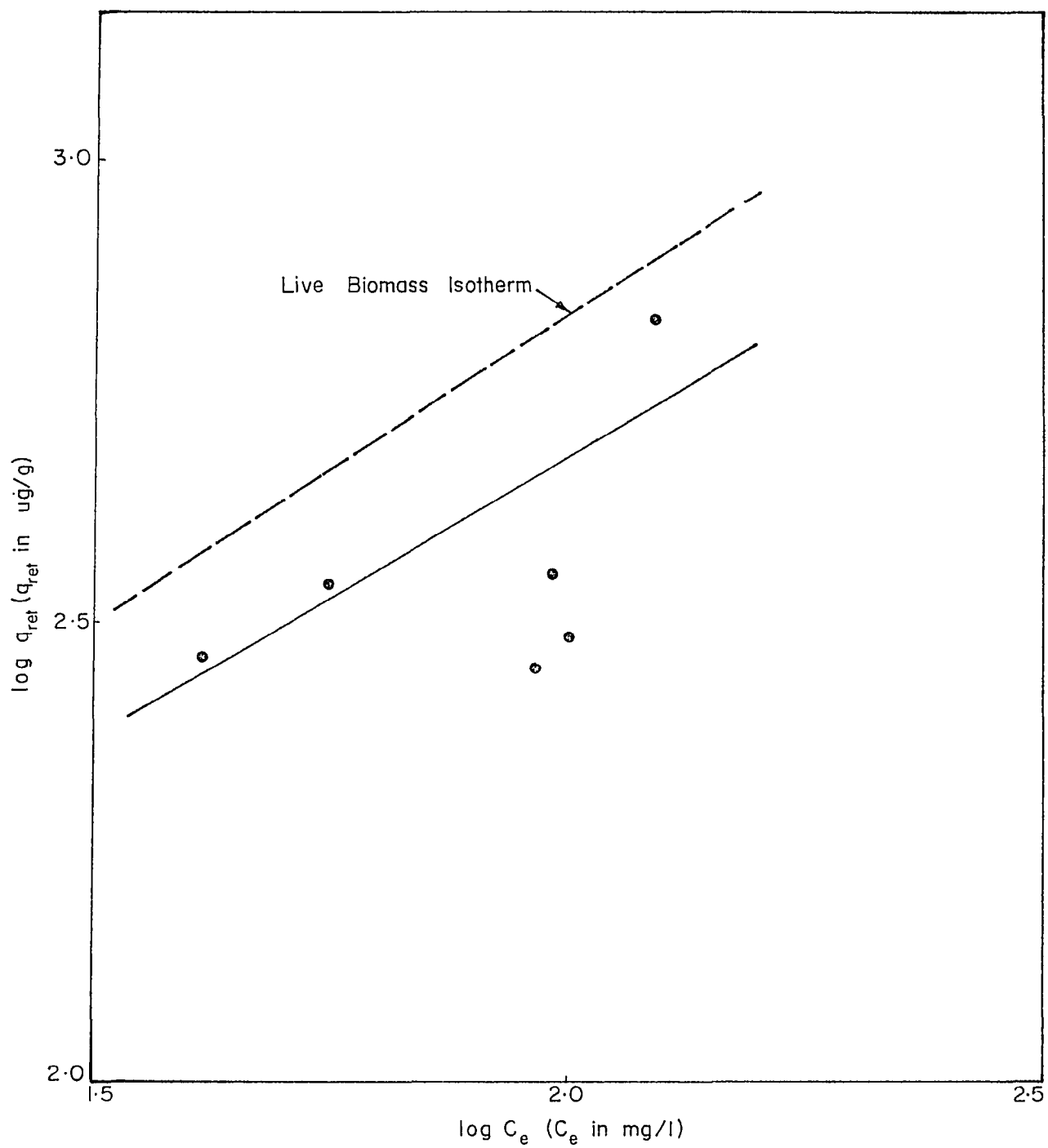


Figure 5.63: Freundlich Retained Isotherm for Chlorophenol with Live Activated Sludge.

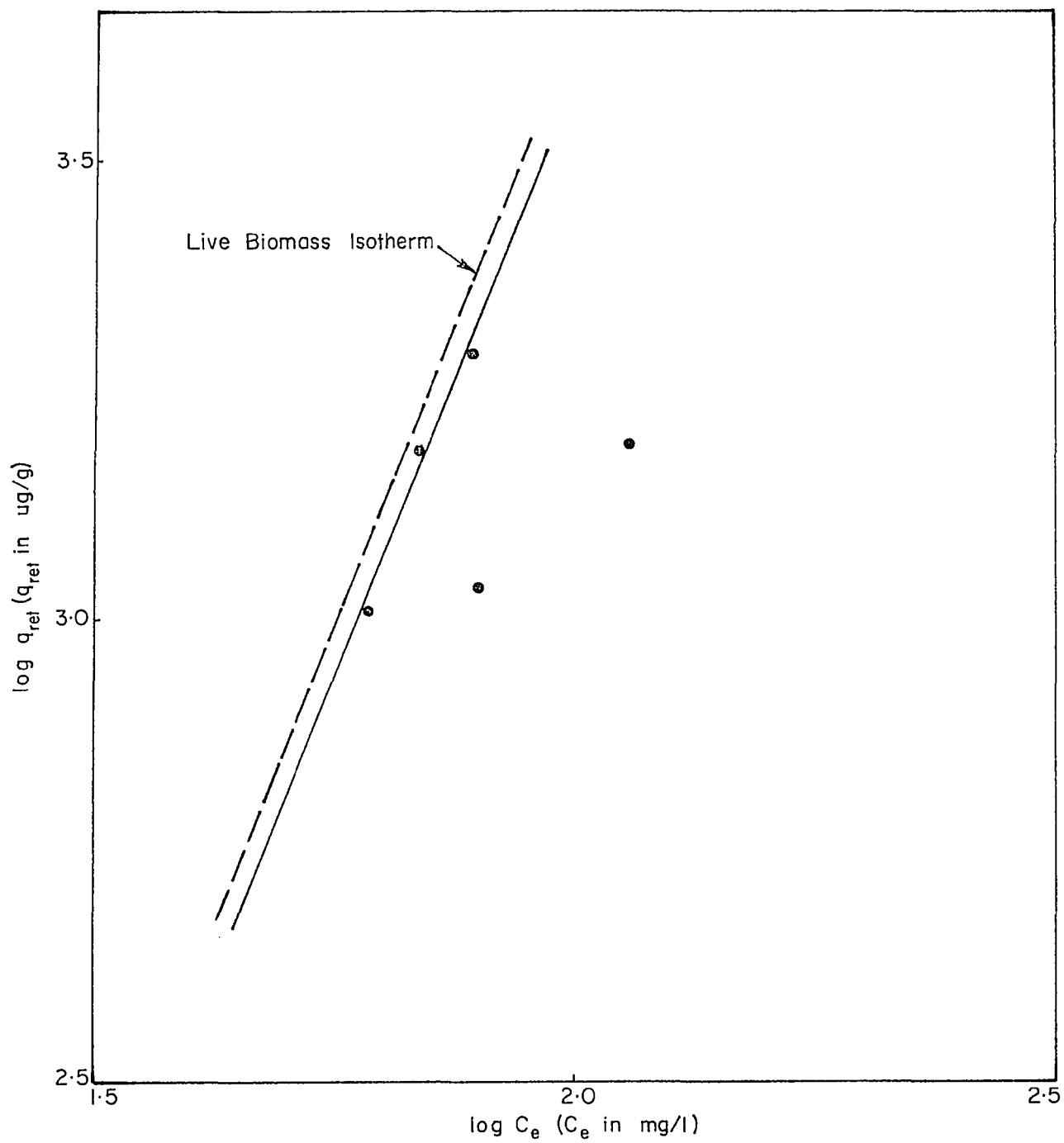
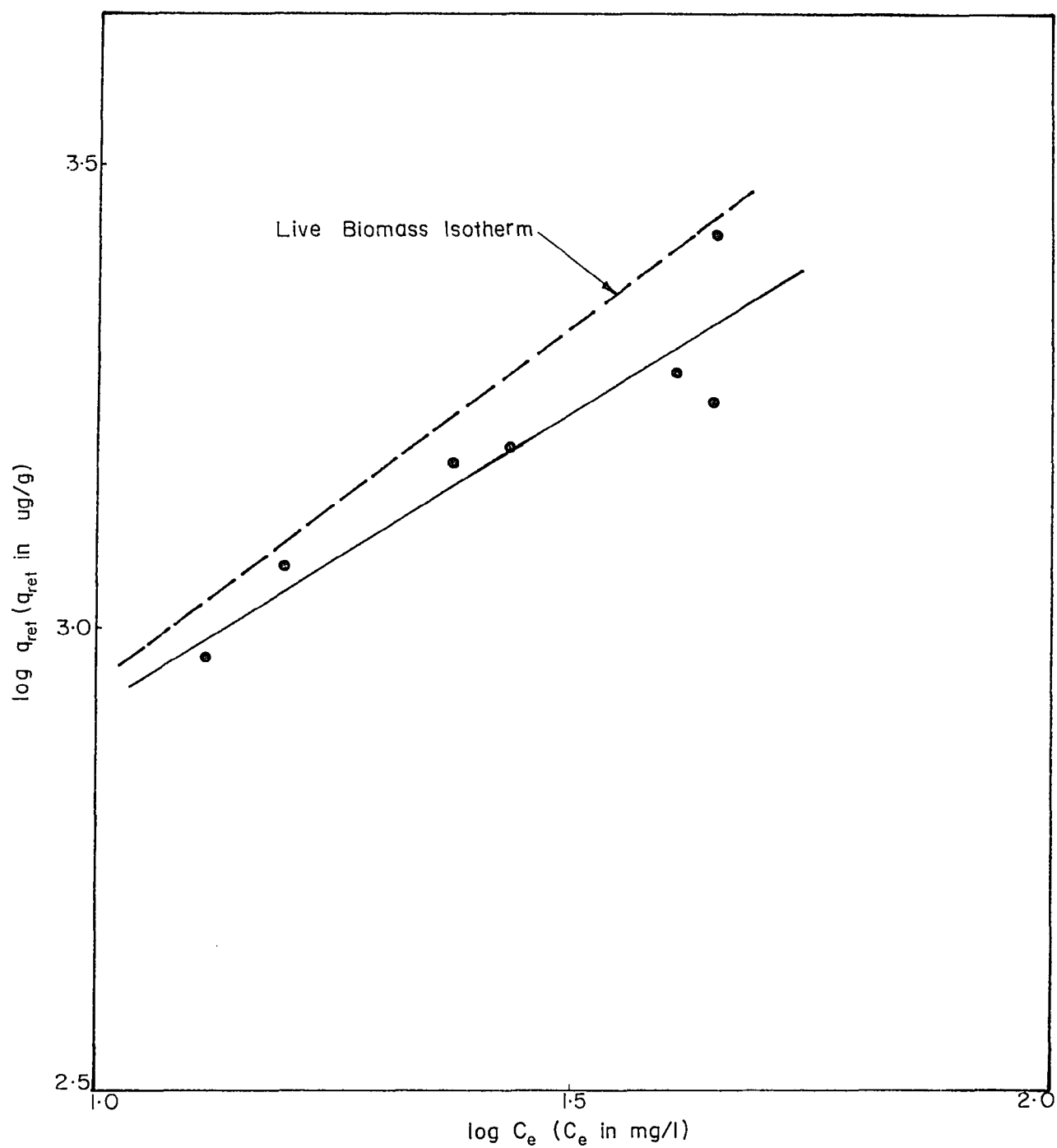


Figure 5.64: Freundlich Retained Isotherm for Nitrophenol with Live Activated Sludge.



**Figure 5.65: Freundlich Retained Isotherm for Chlorobenzene with Live Activated Sludge.**

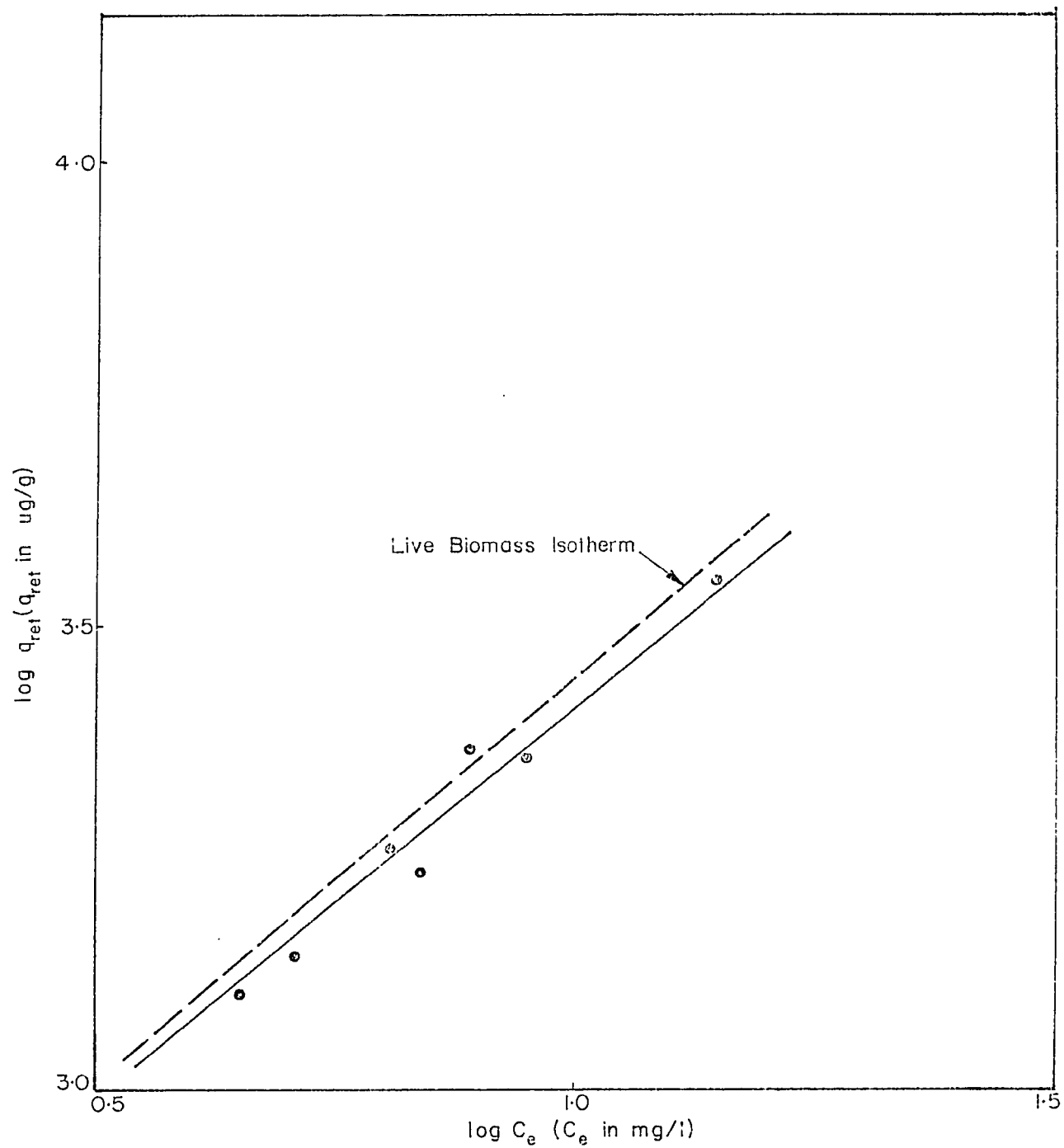


Figure 5.66: Freundlich Retained Isotherm for Ethylbenzene with Live Activated Sludge.

treatment systems. Petrasek et al. (1983) investigated the fate of a number of toxic organic compounds injected into the influent of an activated sludge pilot plant. They reported the following operating parameters (Table 5.24) for their pilot plant.

Table 5.24: Activated Sludge Pilot Plant Operating Parameters

Mean influent flow rate	0.088 l/s
Mixed liquor solids concentration	1900 mg/l
Waste sludge solids concentration	6400 mg/l
Solids retention time	7 days
Recycle ratio	0.42
Aeration basin volume	2549 liter

The waste sludge flow rate can be estimated from equation (5.25):

$$Q_w = \frac{V X}{\theta X_w} \quad (5.25)$$

where

$Q_w$  = waste sludge volumetric flow rate

$V$  = aeration basin volume

$X$  = mixed liquor biological solids concentration in aeration basin

$X_w$  = waste sludge biological solids concentration

$\theta$  = average biological solids retention time in aeration basin

A mass balance of an individual compound in a completely mixed aeration tank (Figure 5.67) is:

$$Q_o C_o = (Q_o - Q_w) C_e + Q_w X_w q + Q_w C_e \quad (5.26)$$

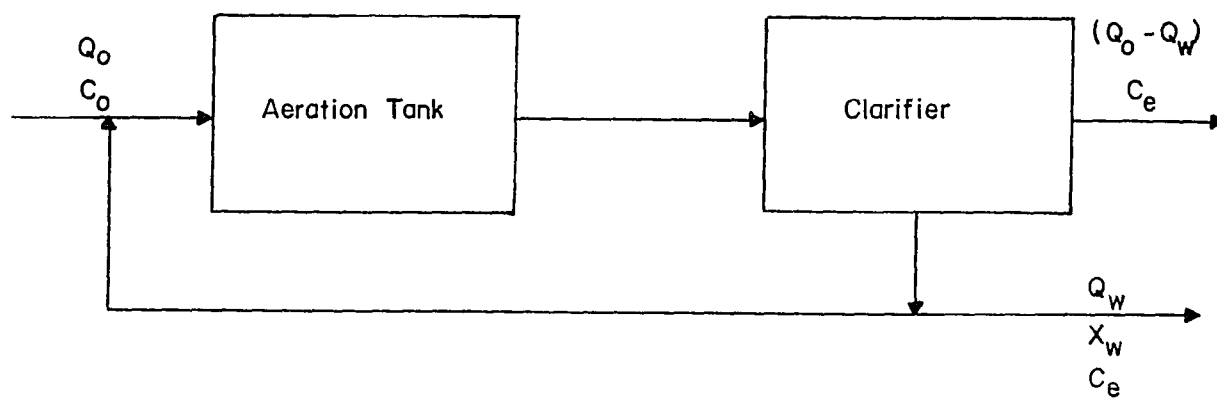


Figure 5.67: Schematic Diagram of Activated Sludge System.



where

$Q_o$  = influent flow rate (l/s)

$C_o$  = influent concentration of selected compound (ug/l)

$q$  = the amount of selected compound sorbed by the biomass (g/g)

The effluent concentration of the compound can be predicted by combining equations (5.24) and (5.26) and to solve for  $C_e$

$$C_e = \frac{Q_o C_o}{Q_o + 0.361 * 10^{-6} Q_w X_w f_{OC} K_{OW}} \quad (5.27)$$

The total concentration of the selected compound in the wasted flow,  $C_w$ , (including the portion sorbed into the sludge and the portion in solution) can be estimated by equation (5.28).

$$C_w = (0.361 * 10^{-6} X_w f_{OC} K_{OW} + 1) C_e \quad (5.28)$$

Using equations (5.25) - (5.28) and the data in Table 5.24, one can calculate the expected concentration of the hazardous organics in the pilot plant effluent and sludge, assuming biosorption is the only mechanism. Table 5.25 summarizes the calculated and the experimentally reported reactor performance data for phenol (easily biodegradable compound) and lindane (non-biodegradable compound).

**Table 5.25: Comparison of Observed and Calculated Reactor Performance**

Organic Compound	$C_o$ in ug/l	$C_e$ (ug/l)		$C_w$ (ug/l)	
		Observed	Calculated	Observed	Calculated
Phenol	196.2	13.5	196.13	92	201.93
Lindane	41.8	25.8	39.31	173	214.46

The lindane results on Table 5.25 show that when using the mechanism of biosorptive removal alone and a lindane influent concentration  $C_o = 41.8$  ug/l, the calculated pilot plant effluent is  $C_e = 39.31$  ug/l. The experimentally determined value has been reported as  $C_e = 25.8 \pm 6.4$  ug/l. For the biological sludge, the lindane concentration predicted by equation (5.28) is  $C_w = 214.46$  ug/l, while the experimental value has been reported as  $C_w = 173 \pm 41.6$  ug/l. This suggests that the pilot plant effluent and the biomass lindane concentrations that were calculated assuming biosorptive removal only, predicted reasonably well.

In the case of phenol, the agreement is poor for both the pilot plant effluent concentration and waste sludge phenol concentration. The biosorption based calculations overpredict the concentration in the effluent and waste sludge. This is likely due to the documented biodegradation of phenol by the microbial biomass, which results in a lower effluent concentration in the reactor (Petrasek et al., 1983).

The information presented above suggests that biosorption

based calculations can be used to provide an estimate of the level of hazardous organics, in the final effluent and the biological sludge of a biological WWTP, especially for biorefractory organics. Although the concentration of pollutants may be low in the influent and effluent of a biological WWTP, the concentration of the same pollutants in the sludge can be magnified significantly by the biosorptive phenomena, so that sludge disposal may present a significant environmental hazard.

## VI. CONCLUSIONS AND RECOMMENDATIONS

### A. Conclusions

The conclusions of this research are:

1. The adsorption process of liquid organic compounds by microbial biomass can be expressed by the Freundlich adsorption isotherm in the concentration range ( 50 - 200 mg/l) studied. The exponent  $1/n$  in the Freundlich equation is almost equal to one.

2. The general order of affinity of the sorbates tested in this research to the microbial biomass was:

Ethylbenzene > Chlorobenzene > 2-Chlorophenol > 2-Nitrophenol > Phenol.

3. The equilibrium adsorption uptake is independent of initial concentration of liquid organic compounds and biomass concentration because data obtained with different starting concentrations and biomass concentration fit the same isotherm.

4. The extent of biosorption by the microorganisms depends on the type of biomass. A comparison of the relative adsorptive capacities with the organic carbon contents showed a trend. Activated sludge biomass showed the higher uptake capacity and also had the larger organic carbon content.

5. Desorption studies show that there are considerable amount of desorption of phenol, chlorophenol and nitrophenol but not

chlorobenzene and ethylbenzene. The desorption is small for compounds with high adsorptive capacity.

6. Retained capacity of microbial biomass also can be expressed by the Freundlich isotherm and follows similar pattern as adsorption capacity.

7. Activated sludge biomass retained more than the nitrifying bacteria as one would expect according to their organic carbon contents.

8. Biosorption appears to be a physical rather than a chemical process.

9. The adsorptive capacity of biomass is much less compared to activated carbon. Uptake by activated carbon was about three orders of magnitude greater for phenol, chlorophenol, and nitrophenol and about two orders of magnitude greater for chlorobenzene and ethylbenzene at 100 ppm equilibrium concentration. However, the uptake per unit surface area is greater for the biomass than for activated carbon.

10. The following regression equations were determined between the normalized sorption distribution coefficient,  $K_{OC}$  and

a) the compound's octanol/water partition coefficient  $K_{OW}$

$$\log K_{OC} = 1.003 \log K_{OW} - 0.443 \quad (r = 0.99)$$

b) the compound's aqueous solubility  $S$  ( $S$  in mg/l)

$$\log K_{OC} = -0.554 \log S + 3.784 \quad (r = -0.89)$$

According to the correlation coefficients, octanol/water partition coefficient is a better predictor than the aqueous solubility.

11. The equilibrium adsorption capacity for each solute from a multi-solute solution on activated sludge biomass is affected by the presence of other solutes.

12. The uptake of each solute is reduced when the initial concentration of other solute is increased.

13. The octanol/water partition coefficient indicates the relative extent of adsorption in bisolute systems better than the aqueous solubility. But in multi-solute systems, less soluble compounds were more favorably adsorbed.

14. The effect of competitive adsorption become more pronounced with the increase in number of solutes in solution.

15. Live and inactive biomass do not exhibit the same biosorptive uptake, and the differences appear to depend on the specific sorbate.

16. Biosorption based calculations can be used to provide an estimate of the level of hazardous organics in the final effluent and the biological sludge of a biological wastewater treatment plants for biorefractory organics.

#### B. Recommendations for Future Research

The following are recommended for future reserch:

1. Investigation of biosorption of more non-biodegradable organic pollutants and additional types of biomass.
2. Study the effects of wastewater characteristics and treatment plant operating variables on the biosorption process.
3. Investigation of the fate of sorbed pollutants during sludge digestion and other sludge processing operations.
4. Examination of the behavior of sorbed pollutants after land disposal of waste sludges.

## APPENDIX A

### ADSORPTION FROM SINGLE SOLUTE SYSTEM

**Table A.1: Adsorption Isotherm for Phenol - Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	163.21	919.67
200	1.5	151.60	806.58
200	2.5	139.60	603.98
150	1.0	130.35	491.20
150	1.5	117.98	533.65
150	2.5	103.88	461.23
100	1.0	87.77	305.85
100	1.5	83.79	270.13
100	2.5	72.21	277.85

#### Freundlich Adsorption Isotherm

$$q = 0.53 C_e^{1.443} \quad (r = 0.96)$$

#### Linear Adsorption Isotherm

$$q = 4.628 C_e \quad (r = 0.98)$$

#### Langmuir Adsorption Isotherm

$$q = \frac{2.802 C_e}{1 - 0.00278 C_e} \quad (r = 0.96)$$



**Table A.2: Adsorption Isotherm for Chlorophenol - Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	126.95	1826.27
200	1.5	99.94	1667.63
200	2.5	72.21	1277.93
150	1.0	92.07	1448.17
150	1.5	79.35	1177.43
150	2.5	56.06	939.35
100	1.0	58.31	1042.20
100	1.5	52.25	795.88
100	2.5	36.40	635.98

Freundlich Adsorption Isotherm

$$q = 26.33 C_e^{0.886} \quad (r = 0.98)$$

Linear Adsorption Isotherm

$$q = 15.73 C_e \quad (r = 0.99)$$

Langmuir Adsorption Isotherm

$$q = \frac{18.321 C_e}{1 + 0.00174 C_e} \quad (r = 0.98)$$

Table A.3: Adsorption Isotherm for Nitrophenol - Activated  
Sludge Biomass System

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	161.08	1945.90
200	1.0	152.88	1177.87
200	1.5	123.11	1281.53
150	0.5	123.27	1336.40
150	1.0	105.96	1101.07
150	1.5	90.47	992.08
100	0.5	80.34	982.80
100	1.0	67.49	812.80
100	1.5	61.38	643.68

Freundlich Adsorption Isotherm

$$q = 11.49 C_e^{0.993} \quad (r = 0.98)$$

Linear Adsorption Isotherm

$$q = 10.44 C_e \quad (r = 0.98)$$

Langmuir Adsorption Isotherm

$$q = \frac{11.34 C_e}{1 + 0.000187 C_e} \quad (r = 0.97)$$

**Table A.4: Adsorption Isotherm for Chlorobenzene - Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	71.28	6435.85
200	1.0	48.78	3780.52
150	0.5	51.57	4921.70
150	1.0	33.36	2915.95
100	0.5	26.21	3689.50
100	1.0	21.74	1956.40

Freundlich Adsorption Isotherm

$$q = 88.51 C_e^{0.998} \quad (r = 0.98)$$

Linear Adsorption Isotherm

$$q = 91.05 C_e \quad (r = 0.99)$$

Langmuir Adsorption Isotherm

$$q = \frac{90.826 C_e}{1 + 0.00084 C_e} \quad (r = 0.99)$$

**Table A.5: Adsorption Isotherm for Ethylbenzene - Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.5	17.32	4133.90
100	1.0	11.97	2200.73
75	0.5	14.63	3018.70
75	1.0	8.26	1668.50
50	0.5	7.77	2111.30
50	1.0	4.87	1128.13

Freundlich Adsorption Isotherm

$$q = 223.10 C_e^{0.977} \quad (r = 0.98)$$

Linear Adsorption Isotherm

$$q = 221.15 C_e \quad (r = 0.99)$$

Langmuir Adsorption Isotherm

$$q = \frac{248.51 C_e}{1 + 0.0129 C_e} \quad (r = 0.96)$$

**Table A.6: Adsorption Isotherm for Phenol - Nitrifying Bacteria System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	179.80	505.05
200	1.5	168.52	524.73
200	2.0	158.94	513.31
150	1.0	133.97	400.67
150	1.5	126.95	384.22
150	2.0	120.30	371.27
100	1.0	89.19	270.35
100	1.5	84.43	259.48
100	2.0	76.00	299.95

Freundlich Adsorption Isotherm

$$q = 7.05 C_e^{0.831} \quad (r = 0.96)$$

Linear Adsorption Isotherm

$$q = 3.04 C_e \quad (r = 0.99)$$

Langmuir Adsorption Isotherm

$$q = \frac{3.953 C_e}{1 + 0.00215 C_e} \quad (r = 0.94)$$

**Table A.7: Adsorption Isotherm for Chlorophenol - Nitrifying Bacteria System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	119.78	2005.40
200	1.5	109.51	1508.13
200	2.0	93.77	1327.87
150	1.0	92.27	1443.20
150	1.5	81.88	1135.40
150	2.0	70.77	990.31
100	1.0	61.20	970.02
100	1.5	53.56	774.05
100	2.0	45.15	685.61

Freundlich Adsorption Isotherm

$$q = 13.97 C_e^{1.013} \quad (r = 0.98)$$

Linear Adsorption Isotherm

$$q = 15.02 C_e \quad (r = 0.99)$$

Langmuir Adsorption Isotherm

$$q = \frac{15.2 C_e}{1 + 0.000334 C_e} \quad (r = 0.98)$$

**Table A.8: Adsorption Isotherm for Nitrophenol - Nitrifying Bacteria System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	151.70	1207.45
200	1.5	130.82	1152.98
150	1.0	110.14	996.53
150	1.5	96.89	885.45
100	1.0	69.97	750.65
100	1.5	67.23	546.10

Freundlich Adsorption Isotherm

$$q = 17.39 C_e^{0.855} \quad (r = 0.95)$$

Linear Adsorption Isotherm

$$q = 8.66 C_e \quad (r = 0.99)$$

Langmuir Adsorption Isotherm

$$q = \frac{14.687 C_e}{1 + 0.0056 C_e} \quad (r = 0.99)$$

**Table A.9: Adsorption Isotherm for Chlorobenzene - Nitrifying Bacteria System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	74.59	6270.50
200	1.0	48.20	3794.92
150	0.5	54.12	4794.10
150	1.0	36.11	2847.30
100	0.5	33.44	3327.95
100	1.0	22.28	1943.07

Freundlich Adsorption Isotherm

$$q = 104.29 C_e^{0.948} \quad (r = 0.98)$$

Linear Adsorption Isotherm

$$q = 84.84 C_e \quad (r = 0.99)$$

Langmuir Adsorption Isotherm

$$q = \frac{90.711 C_e}{1 + 0.0013 C_e} \quad (r = 0.98)$$



Table A.10: Adsorption Isotherm for Ethylbenzene - Nitrifying Bacteria System

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.5	19.62	4019.05
100	1.0	13.09	2172.60
75	0.5	13.25	3087.35
75	1.0	8.47	1663.12
50	0.5	8.78	2060.95
50	1.0	6.04	1098.90

Freundlich Adsorption Isotherm

$$q = 183.06 C_e^{1.039} \quad (r = 0.95)$$

Linear Adsorption Isotherm

$$q = 203.96 C_e \quad (r = 0.99)$$

Langmuir Adsorption Isotherm

$$q = \frac{181.795 C_e}{1 - 0.00824 C_e} \quad (r = 0.96)$$

**Table A.11: Retained Isotherm for Phenol - Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
163.21	14.65	22.14	553.43
151.60	16.58	31.82	530.17
139.60	17.31	43.09	430.91
130.35	8.05	11.60	289.90
117.98	11.21	20.81	346.87
103.88	14.05	32.07	320.70
87.77	6.40	5.83	145.73
83.79	7.23	8.98	149.70
72.22	8.98	18.80	188.00

Freundlich Retained Isotherm

$$q_{\text{ret}} = 0.127 C_e^{1.539} \quad (r = 0.92)$$

**Table A.12: Retained Isotherm for Chlorophenol- Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
126.95	25.86	47.19	1179.85
99.94	30.12	69.94	1165.70
92.07	20.40	37.53	938.23
79.35	21.42	49.23	820.45
72.21	28.03	99.76	997.61
58.31	13.46	28.23	705.77
56.06	18.02	75.92	759.20
52.25	15.34	32.41	540.23
36.40	13.83	49.77	497.70

Freundlich Retained Isotherm

$$q_{\text{ret}} = 32.433 C_e^{0.757} \quad (r = 0.89)$$

**Table A.13: Retained Isotherm for Nitrophenol- Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
161.08	24.12	14.80	739.70
152.88	27.32	19.80	494.75
123.27	13.50	13.22	661.20
123.11	34.22	42.67	702.93
105.96	23.01	21.03	525.77
90.48	26.53	32.99	549.95
80.34	12.02	7.64	381.55
67.49	16.24	16.27	406.85
61.38	16.82	21.80	363.28

Freundlich Retained Isotherm

$$q_{\text{ret}} = 12.784 C_e^{0.811} \quad (r = 0.94)$$

**Table A.14: Retained Isotherm for Chlorobenzene - Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
71.28	29.76	98.96	4947.75
51.57	21.17	77.26	3863.40
48.78	21.40	129.82	3245.55
33.36	20.72	95.92	2397.97
26.21	13.37	60.42	3021.20
21.74	10.67	67.59	1689.55

Freundlich Retained Isotherm

$$q_{\text{ret}} = 100.46 C_e^{0.911} \quad (r = 0.99)$$

**Table A.15: Retained Isotherm for Ethylbenzene - Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
17.32	9.36	73.32	3666.00
14.63	8.66	51.71	2585.70
11.97	7.93	80.10	2002.45
8.26	6.24	60.50	1512.60
7.77	4.76	37.47	1873.20
4.87	3.52	41.61	1040.15

Freundlich Retained Isotherm

$$q_{\text{ret}} = 255.86 C_e^{0.886} \quad (r = 0.95)$$

**Table A.16: Retained Isotherm for Phenol- Nitrifying Bacteria System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
179.79	13.28	6.93	173.10
168.52	15.47	16.01	266.88
158.94	17.23	23.83	297.92
133.97	9.28	6.75	168.70
126.95	12.54	10.51	175.30
120.30	15.80	13.90	173.76
89.19	5.76	5.05	126.32
84.43	7.27	8.30	138.32
76.00	10.57	13.43	167.85

Freundlich Retained Isotherm

$$q_{\text{ret}} = 3.041 C_e^{0.867} \quad (r = 0.86)$$

**Table A.17: Retained Isotherm for Chlorophenol - Nitrifying Bacteria System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
119.78	34.91	45.31	1132.77
109.51	33.29	57.20	953.23
93.77	26.56	79.67	995.85
92.27	40.38	17.35	433.67
81.88	29.66	38.46	641.13
70.77	19.68	59.55	744.36
61.20	30.64	8.16	203.92
53.56	26.37	20.07	334.50
45.15	12.20	42.65	533.13

Freundlich Retained Isotherm

$$q_{\text{ret}} = 8.689 C_e^{1.011} \quad (r = 0.86)$$

**Table A.18: Retained Isotherm for Nitrophenol- Nitrifying Bacteria System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
151.70	20.17	28.13	703.30
130.82	24.69	43.86	730.98
110.14	16.30	23.56	584.53
96.89	18.14	34.97	583.08
69.97	12.35	17.68	441.77
67.23	10.44	22.33	372.12

Freundlich Retained Isotherm

$$q_{\text{ret}} = 16.144 C_e^{0.768} \quad (r = 0.96)$$

**Table A.19: Retained Isotherm for Chlorobenzene - Nitrifying Bacteria System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
74.59	39.06	86.35	4317.50
54.12	24.96	70.92	3545.85
48.20	33.51	118.29	2957.20
36.11	25.62	88.27	2206.70
33.44	16.54	50.02	2500.95
22.28	15.20	62.52	1563.05

Freundlich Retained Isotherm

$$q_{\text{ret}} = 118.98 C_e^{0.837} \quad (r = 0.98)$$

**Table A.20: Retained Isotherm for Ethylbenzene - Nitrifying Bacteria System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
19.62	14.72	65.66	3283.00
13.25	9.44	52.31	2615.25
13.10	10.68	76.22	1905.70
8.78	5.94	35.28	1764.10
8.47	6.87	59.66	1491.27
6.04	4.34	39.62	990.47

Freundlich Retained Isotherm

$$q_{\text{ret}} = 189.67 C_e^{0.964} \quad (r = 0.96)$$

## APPENDIX B

### ADSORPTION FROM BISOLUTE SYSTEMS

#### Phenol/Chlorophenol - Activated Sludge Biomass System

**Table A.21: Adsorption Isotherm for Phenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	164.45	813.75
200	1.5	160.93	651.17
200	2.0	153.26	584.21
150	1.0	129.96	500.87
150	1.5	129.84	336.00
150	2.0	125.65	304.41
100	1.5	89.01	183.08
100	2.0	80.59	242.64

#### Freundlich Adsorption Isotherm

$$q = 0.0747 C_e^{1.777} \quad (r = 0.91)$$

#### Phenol/Chlorophenol - Activated Sludge Biomass System

**Table A.22: Adsorption Isotherm for Chlorophenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	123.00	1925.10
200	1.5	102.78	1620.38
200	2.0	91.56	1355.47
150	1.0	95.76	1355.97
150	1.5	84.91	1084.88
150	2.0	75.37	932.93
100	1.0	68.91	777.17
100	1.5	60.40	659.92
100	2.0	45.91	676.15

#### Freundlich Adsorption Isotherm

$$q = 4.92 C_e^{1.23} \quad (r = 0.95)$$

# Phenol/Nitrophenol - Activated Sludge Biomass System

Table A.23: Adsorption Isotherm for Phenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	168.29	792.70
200	1.5	153.69	771.80
200	2.0	147.04	662.04
150	1.0	135.83	354.22
150	1.5	124.98	417.08
150	2.0	121.18	360.30
100	1.0	90.51	237.30
100	1.5	92.58	123.66
100	2.0	84.23	197.11

Freundlich Adsorption Isotherm

$$q = 0.0173 C_e^{2.103} \quad (r = 0.99)$$

# Phenol/Nitrophenol - Activated Sludge Biomass System

Table A.24: Adsorption Isotherm for Nitrophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	144.18	1395.52
200	1.5	130.76	1154.00
200	2.0	105.26	1184.23
150	1.0	116.06	848.47
150	1.5	99.35	844.17
150	2.0	89.20	759.97
100	1.0	77.77	555.63
100	1.5	65.07	582.15
100	2.0	55.94	550.74

Freundlich Adsorption Isotherm

$$q = 8.912 C_e^{1.01} \quad (r = 0.96)$$



Chlorophenol/Nitrophenol - Activated Sludge Biomass System

Table A.25: Adsorption Isotherm for Nitrophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	176.75	581.25
200	1.5	139.54	1007.66
200	2.0	132.31	846.17
150	1.0	119.94	751.50
150	1.5	110.70	655.02
150	2.0	104.55	568.15
100	1.0	88.17	295.75
100	1.5	83.20	279.98
100	2.0	76.88	289.01

Freundlich Adsorption Isotherm

$$q = 0.0106 C_e^{2.324} \quad (r = 0.98)$$

Chlorophenol/Nitrophenol - Activated Sludge Biomass System

Table A.26: Adsorption Isotherm for Chlorophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	131.60	1710.07
200	1.5	104.30	1595.00
200	2.0	96.49	1293.93
150	1.0	94.85	1378.83
150	1.5	79.83	1169.53
150	2.0	72.57	967.93
100	1.0	66.64	834.00
100	1.5	56.93	717.77
100	2.0	48.00	649.94

Freundlich Adsorption Isotherm

$$q = 9.556 C_e^{1.081} \quad (r = 0.98)$$

Chlorobenzene/Ethylbenzene - Activated Sludge Biomass System

Table A.27: Adsorption Isotherm for Chlorobenzene

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	88.81	5559.40
200	1.0	59.84	3504.00
150	0.5	65.99	4200.65
150	1.0	47.61	2559.77
100	0.5	31.83	3408.45
100	1.0	25.46	1863.57

Freundlich Adsorption Isotherm

$$q = 98.17 C_e^{0.884} \quad (r = 0.88)$$

Chlorobenzene/Ethylbenzene - Activated Sludge Biomass System

Table A.28: Adsorption Isotherm for Ethylbenzene

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	20.37	3981.07
200	1.0	14.55	2133.04
150	0.5	14.77	3013.06
150	1.0	9.39	1640.59
100	0.5	11.95	1901.08
100	1.0	5.68	1106.62

Freundlich Adsorption Isotherm

$$q = 187.72 C_e^{0.98} \quad (r = 0.96)$$

## APPENDIX C

### ADSORPTION FROM MULTI-SOLUTE SYSTEM

Phenol/Chlorophenol/Nitrophenol - Activated Sludge Biomass System

Table A.29: Adsorption Isotherm for Phenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	186.56	336.00
200	1.5	168.47	525.45
200	2.0	156.76	540.50
100	1.0	89.04	274.00
100	1.5	86.22	229.67
100	2.0	82.94	213.25
50	1.5	34.01	199.87

Freundlich Adsorption Isotherm

$$q = 4.73 C_e^{0.885} \quad (r = 0.83)$$

Phenol/Chlorophenol/Nitrophenol/Chlorobenzene - Activated Sludge Biomass System

Table A.30: Adsorption Isotherm for Phenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	168.01	800.00
150	1.5	125.08	415.33
100	1.0	91.51	212.25
100	1.5	86.98	217.00

Freundlich Adsorption Isotherm

$$q = 0.257 C_e^{1.507} \quad (r = 0.89)$$

Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-  
Activated Sludge Biomass System

Table A.31: Adsorption Isotherm for Phenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	187.36	316.00
200	1.5	177.81	373.17
150	1.5	131.08	315.33
100	1.0	94.61	134.87
100	1.5	89.44	176.00

Freundlich Adsorption Isotherm

$$q = 0.98 C_e^{1.133} \quad (r = 0.89)$$

Phenol/Chlorophenol/Nitrophenol - Activated Sludge Biomass System

Table A.32: Adsorption Isotherm for Chlorophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	144.76	1381.03
200	1.5	141.24	979.30
200	2.0	141.20	734.95
100	1.0	69.40	765.05
100	1.5	69.31	511.47
100	2.0	66.97	412.85
50	1.5	34.72	254.61
50	2.0	30.81	239.83

Freundlich Adsorption Isotherm

$$q = 9.462 C_e^{0.946} \quad (r = 0.93)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene - Activated Sludge Biomass System**

**Table A.33: Adsorption Isotherm for Chlorophenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	178.54	1072.90
200	1.0	163.79	905.07
200	1.5	166.33	561.15
150	0.5	125.02	1248.95
150	1.0	125.14	621.60
150	1.5	120.71	488.15
100	1.0	84.48	388.05
100	1.5	79.56	340.72

Freundlich Adsorption Isotherm

$$q = 2.27 C_e^{1.146} \quad (r = 0.98)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-Activated Sludge Biomass System**

**Table A.34: Adsorption Isotherm for Chlorophenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	186.35	682.65
150	0.5	142.10	395.15
150	1.0	128.99	527.27
150	1.5	125.78	403.60
100	1.0	86.72	331.93
100	1.5	83.05	282.57

Freundlich Adsorption Isotherm

$$q = 4.731 C_e^{0.935} \quad (r = 0.90)$$

Phenol/Chlorophenol/Nitrophenol - Activated Sludge Biomass System

Table A.35: Adsorption Isotherm for Nitrophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	152.00	1200.00
200	1.5	134.26	1095.68
200	2.0	113.93	1075.91
100	1.0	77.06	573.50
100	1.5	65.54	574.42
100	2.0	56.43	544.66
50	1.5	33.55	274.15
50	2.0	30.91	238.69

Freundlich Adsorption Isotherm

$$q = 7.907 C_e^{1.013} \quad (r = 0.99)$$

Phenol/Chlorophenol/Nitrophenol/Chlorobenzene - Activated Sludge Biomass System

Table A.36: Adsorption Isotherm for Nitrophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	149.75	1256.27
200	1.5	128.76	1187.27
150	0.5	136.32	684.00
150	1.0	116.72	832.05
150	1.5	97.97	867.12
100	1.0	81.73	456.85
100	1.5	66.22	563.00

Freundlich Adsorption Isotherm

$$q = 3.266 C_e^{1.189} \quad (r = 0.89)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-  
Activated Sludge Biomass System**

**Table A.37: Adsorption Isotherm for Nitrophenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	1.0	156.02	1099.37
200	1.5	133.65	1105.85
150	0.5	136.45	677.50
150	1.0	124.18	645.55
150	1.5	98.65	855.88
100	1.0	85.75	356.22
100	1.5	70.42	493.07

Freundlich Adsorption Isotherm

$$q = 2.382 C_e^{1.215} \quad (r = 0.80)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene - Activated Sludge  
Biomass System**

**Table A.38: Adsorption Isotherm for Chlorobenzene**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	120.27	3986.50
200	1.0	63.61	3409.80
200	1.5	51.43	2476.17
150	0.5	77.56	3622.00
150	1.0	52.18	2445.43
150	1.5	34.26	1929.07
100	1.0	34.99	1625.27
100	1.5	26.26	1228.92

Freundlich Adsorption Isotherm

$$q = 101.86 C_e^{0.802} \quad (r = 0.95)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-Activated Sludge Biomass System**

**Table A.39: Adsorption Isotherm for Chlorobenzene**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	126.30	3685.00
200	1.0	85.91	2852.37
200	1.5	62.13	2297.88
150	0.5	89.92	3004.15
150	1.0	55.83	2354.35
150	1.5	44.14	1764.27
100	1.0	41.21	1469.65
100	1.5	27.08	1215.26

Freundlich Adsorption Isotherm

$$q = 101.60 C_e^{0.75} \quad (r = 0.98)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-Activated Sludge Biomass System**

**Table A.40: Adsorption Isotherm for Ethylbenzene**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.5	40.89	2955.30
200	1.0	29.55	1761.27
200	1.5	19.13	1347.78
150	0.5	28.72	2313.80
150	1.0	16.38	1465.50
150	1.5	13.38	1026.90
100	1.0	12.01	949.80
100	1.5	7.81	703.12

Freundlich Adsorption Isotherm

$$q = 119.34 C_e^{0.85} \quad (r = 0.98)$$



## APPENDIX D

### ADSORPTION BY LIVE ACTIVATED SLUDGE

**Table A.41: Adsorption Isotherm for Phenol- Live Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
162.10	0.585	156.51	294.95
132.76	1.267	125.44	217.51
121.72	0.581	110.54	592.74
107.15	1.00	97.57	334.89
102.16	1.171	100.23	60.50
67.44	1.208	60.67	207.61

Freundlich Adsorption Isotherm

$$q = 0.139 C_e^{1.174} \quad (r = 0.88)$$

**Table A.42: Adsorption Isotherm for Chlorophenol- Live Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
66.91	0.974	55.85	424.34
143.19	0.781	124.19	849.46
107.02	0.791	96.23	477.92
62.75	1.169	41.07	738.92
96.71	1.085	86.22	375.06
125.24	1.176	100.05	855.07
62.09	1.203	41.48	689.86
87.95	1.389	64.57	717.64
114.72	1.464	93.19	640.84

Freundlich Adsorption Isotherm

$$q = 14.894 C_e^{0.829} \quad (r = 0.78)$$

**Table A.43: Adsorption Isotherm for Nitrophenol- Live  
Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
160.03	0.696	114.99	2022.11
135.29	1.332	69.45	1826.85
102.59	1.287	60.58	1193.21
111.57	0.959	79.01	1141.27
123.36	0.602	78.04	2288.59

Freundlich Adsorption Isotherm

$$q = 0.031 C_e^{2.578} \quad (r = 0.99)$$

**Table A.44: Adsorption Isotherm for Chlorobenzene - Live  
Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
67.52	1.890	13.00	1067.98
72.45	1.494	15.77	1309.17
119.61	0.998	40.66	2479.95
104.84	1.692	23.79	1713.40
146.29	1.442	44.45	2413.82
127.11	2.253	26.96	1748.53
157.01	1.055	44.88	3384.76

Freundlich Adsorption Isotherm

$$q = 151.56 C_e^{0.764} \quad (r = 0.96)$$

**Table A.45: Adsorption Isotherm for Ethylbenzene - Live Activated Sludge Biomass System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
83.06	0.531	14.13	3906.96
73.96	0.917	8.98	2395.29
67.68	1.244	7.00	1801.73
60.21	0.640	7.83	2548.66
51.91	1.159	5.15	1457.40
56.59	0.847	6.45	1961.28
38.04	0.819	4.50	1345.65
35.32	1.082	2.91	1060.17

Freundlich Adsorption Isotherm

$$q = 391.74 C_e^{0.848} \quad (r = 0.98)$$

**Table A.46: Retained Isotherm for Phenol - Live Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
156.51	4.46	1.13	59.53
125.44	6.33	0.99	29.31
97.57	8.46	1.11	39.02
60.67	6.23	0.54	16.48

Freundlich Retained Isotherm

$$q_{ret} = 0.139 C_e^{1.174} \quad (r = 0.88)$$

**Table A.47: Retained Isotherm for Chlorophenol- Live Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
55.85	2.14	8.93	342.35
124.19	4.08	14.92	666.99
96.23	2.83	7.96	352.52
100.05	16.23	8.95	303.91
41.47	11.95	8.66	289.77
93.19	12.03	9.50	282.74

Freundlich Retained Isotherm

$$q_{\text{ret}} = 27.797 C_e^{0.617} \quad (r = 0.84)$$

**Table A.48: Retained Isotherm for Nitrophenol- Live Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
114.98	10.38	34.66	1556.05
69.45	10.65	55.19	1531.27
60.58	5.87	36.14	1026.44
79.01	1.86	30.71	1076.18
78.04	6.29	39.02	1970.47

Freundlich Retained Isotherm

$$q_{\text{ret}} = 0.026 C_e^{2.582} \quad (r = 0.99)$$

**Table A.49: Retained Isotherm for Chlorobenzene - Live  
Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
13.00	7.33	47.18	924.39
15.77	5.78	50.90	1175.73
40.67	18.99	59.94	1883.18
23.79	10.73	70.32	1486.69
44.45	27.66	74.18	1758.24
26.96	10.59	89.55	1563.61
44.88	24.07	88.07	2658.24

Freundlich Retained Isotherm

$$q_{\text{ret}} = 197.24 C_e^{0.626} \quad (r = 0.93)$$

**Table A.50: Retained Isotherm for Ethylbenzene - Live  
Activated Sludge Biomass System**

Equilibrium Concentration in ppm	Desorbed Concentration in ppm	Retained Concentration in ppm	Retained Capacity in ug/g
14.13	6.63	62.29	3530.98
8.98	3.09	61.88	2281.09
7.00	3.24	57.44	1705.56
7.83	4.67	47.71	2321.39
5.15	2.51	44.24	1379.17
6.45	3.91	46.23	1808.37
4.50	2.05	31.48	1263.20
2.91	1.79	30.63	1001.69

Freundlich Retained Isotherm

$$q_{\text{ret}} = 381.94 C_e^{0.825} \quad (r = 0.98)$$

## APPENDIX E

### ADSORPTION FROM SINGLE SOLUTE SYSTEM

**Table A.51: Adsorption Isotherm for Phenol - Activated Carbon System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
300	0.5	160.11	139890
200	0.5	76.75	123253
150	0.5	38.97	111023
100	0.5	20.99	79001
75	0.5	9.89	65100

Freundlich Adsorption Isotherm

$$q = 34723.98 C_e^{0.286} \quad (r = 0.98)$$

**Table A.52: Adsorption Isotherm for Chlorophenol - Activated Carbon System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
300	0.5	73.04	226957
200	0.5	28.40	171603
150	0.5	15.05	134952
100	0.5	3.98	96017
75	0.5	1.79	73205

Freundlich Adsorption Isotherm

$$q = 61795.81 C_e^{0.301} \quad (r = 0.99)$$

**Table A.53: Adsorption Isotherm for Nitrophenol - Activated Carbon System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
300	0.5	32.97	267034
200	0.5	8.58	191416
150	0.5	4.14	145856
100	0.5	2.18	97817
75	0.5	1.22	73784

Freundlich Adsorption Isotherm

$$q = 74371.86 C_e^{0.393} \quad (r = 0.98)$$

**Table A.54: Adsorption Isotherm for Chlorobenzene - Activated Carbon System**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.2	22.69	443260
150	0.2	44.88	262810
100	0.2	16.40	208990
75	0.2	25.25	124370
50	0.2	9.95	100125

Freundlich Adsorption Isotherm

$$q = 16058.3 C_e^{0.779} \quad (r = 0.99)$$

Table A.55: Adsorption Isotherm for Ethylbenzene - Activated Carbon System

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	8.82	227940
80	0.2	9.60	176000
60	0.2	7.49	131270
50	0.2	3.99	115020
40	0.2	3.36	91590

Freundlich Adsorption Isotherm

$$q = 42648.13 C_e^{0.66} \quad (r = 0.88)$$

#### ADSORPTION FROM BISOLUTE SYSTEMS

Phenol/Chlorophenol - Activated Carbon System

Table A.56: Adsorption Isotherm for Chlorophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.2	132.46	168852
150	0.2	90.59	148527
100	0.2	47.55	131122
80	0.2	32.03	119912
50	0.2	14.88	87805

Freundlich Adsorption Isotherm

$$q = 42461.96 C_e^{0.284} \quad (r = 0.99)$$



# Phenol/Chlorophenol - Activated Carbon System

Table A.57: Adsorption Isotherm for Phenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.2	178.79	53006
150	0.2	131.96	39185
100	0.2	84.25	39375
80	0.2	62.14	44652
50	0.2	33.96	40105

## Freundlich Adsorption Isotherm

$$q = 24717.24 C_e^{0.137} \quad (r = 0.89)$$

# Phenol/Nitrophenol - Activated Carbon System

Table A.58: Adsorption Isotherm for Phenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.2	176.45	58867
100	0.2	83.99	40017
80	0.2	63.92	40207
50	0.2	34.08	37687

## Freundlich Adsorption Isotherm

$$q = 13273.94 C_e^{0.274} \quad (r = 0.90)$$

# Phenol/Nitrophenol - Activated Carbon System

Table A.59: Adsorption Isotherm for Nitrophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.2	99.35	271627
150	0.2	67.52	206192
100	0.2	35.98	160060
80	0.2	26.72	133197
50	0.2	13.57	91062

Freundlich Adsorption Isotherm

$$q = 25118.86 C_e^{0.504} \quad (r = 0.99)$$

# Chlorophenol/Nitrophenol - Activated Carbon System

Table A.60: Adsorption Isotherm for Nitrophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.2	107.91	230222
150	0.2	58.86	227860
100	0.2	26.93	182670
80	0.2	16.29	159277
50	0.2	7.83	105432

Freundlich Adsorption Isotherm

$$q = 64268.77 C_e^{0.295} \quad (r = 0.95)$$

# Chlorophenol/Nitrophenol - Activated Carbon System

Table A.61: Adsorption Isotherm for Chlorophenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
200	0.2	152.50	118745
150	0.2	102.43	118912
100	0.2	54.56	113587
80	0.2	36.89	107765
50	0.2	16.54	83655

## Freundlich Adsorption Isotherm

$$q = 50466.13 C_e^{0.195} \quad (r = 0.95)$$

# Chlorobenzene/Ethylbenzene - Activated Carbon System

Table A.62: Adsorption Isotherm for Chlorobenzene

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	19.02	202455
80	0.2	19.68	150797
60	0.2	12.78	118055
50	0.2	13.94	90155
40	0.2	8.01	79982

## Freundlich Adsorption Isotherm

$$q = 21457.05 C_e^{0.646} \quad (r = 0.92)$$

# Chlorobenzene/Ethylbenzene - Activated Carbon System

Table A.63: Adsorption Isotherm for Ethylbenzene

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	20.16	199595
80	0.2	18.49	153765
60	0.2	12.42	118950
50	0.2	11.29	96765
40	0.2	8.24	79397

Freundlich Adsorption Isotherm

$$q = 9840.0 C_e^{0.973} \quad (r = 0.98)$$

## ADSORPTION FROM MULTI-SOLUTE SYSTEM

# Phenol/Chlorophenol/Nitrophenol/Chlorobenzene - Activated Carbon System

Table A.64: Adsorption Isotherm for Phenol

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	88.59	28532
80	0.2	76.71	8212
60	0.2	53.03	17430
50	0.2	46.99	7535
40	0.2	36.56	8587

Freundlich Adsorption Isotherm

$$q = 76.91 C_e^{1.332} \quad (r = 0.98)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-  
Activated Carbon System**

**Table A.65: Adsorption Isotherm for Phenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	92.04	19902
80	0.2	74.49	13772
50	0.2	41.72	20707
40	0.2	31.41	21470

Freundlich Adsorption Isotherm

$$q = 7.638 C_e^{1.739} \quad (r = 0.99)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene - Activated Carbon  
System**

**Table A.66: Adsorption Isotherm for Chlorophenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	69.57	76082
80	0.2	55.25	61877
60	0.2	34.05	64867
50	0.2	27.18	57055
40	0.2	15.71	60730

Freundlich Adsorption Isotherm

$$q = 22855.99 C_e^{0.285} \quad (r = 0.97)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-  
Activated Carbon System**

**Table A.67: Adsorption Isotherm for Chlorophenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	70.59	73510
80	0.2	46.87	82830
60	0.2	32.54	68645
50	0.2	21.51	71230
40	0.2	14.47	63827

Freundlich Adsorption Isotherm

$$q = 50466.13 C_e^{0.088} \quad (r = 0.99)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene - Activated Carbon  
System**

**Table A.68: Adsorption Isotherm for Nitrophenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	43.15	142125
80	0.2	33.03	117437
60	0.2	19.95	100112
50	0.2	16.42	83950
40	0.2	10.35	74117

Freundlich Adsorption Isotherm

$$q = 24945.95 C_e^{0.453} \quad (r = 0.99)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-Activated Carbon System**

**Table A.69: Adsorption Isotherm for Nitrophenol**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	40.44	148907
80	0.2	24.18	139537
60	0.2	17.30	106757
50	0.2	10.36	99105
40	0.2	6.08	84810

Freundlich Adsorption Isotherm

$$q = 47643.09 C_e^{0.312} \quad (r = 0.97)$$

**Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-Activated Carbon System**

**Table A.70: Adsorption Isotherm for Chlorobenzene**

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	32.25	169367
80	0.2	21.61	145980
60	0.2	18.22	104450
50	0.2	11.92	95195
40	0.2	9.14	77147

Freundlich Adsorption Isotherm

$$q = 19408.86 C_e^{0.625} \quad (r = 0.96)$$

Phenol/Chlorophenol/Nitrophenol/Chlorobenzene - Activated Carbon System

Table A.71: Adsorption Isotherm for Chlorobenzene

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	33.01	165475
60	0.2	21.09	97275
50	0.2	19.82	75336
40	0.2	12.11	69663

Freundlich Adsorption Isotherm

$$q = 7445.43 C_e^{0.848} \quad (r = 0.91)$$

Phenol/Chlorophenol/Nitrophenol/Chlorobenzene/Ethylbenzene-Activated Carbon System

Table A.72: Adsorption Isotherm for Ethylbenzene

Initial Concentration in ppm	Weight of Biomass in g	Equilibrium Concentration in ppm	Adsorption Capacity in ug/g
100	0.2	27.78	180547
60	0.2	15.76	110592
50	0.2	13.65	90882
40	0.2	8.44	78890

Freundlich Adsorption Isotherm

$$q = 15848.93 C_e^{0.713} \quad (r = 0.97)$$



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