



**ADSORPTION AND KINETICS OF LAMBDA-CYHALOTHRIN FROM
WASTEWATER USING ACTIVATED CARBON FROM BANANA PEELINGS
BIOMASS**

BY

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BU/UP/2023/1651

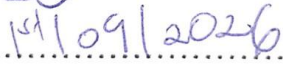
**A RESEARCH PROJECT PROPOSAL SUBMITTED TO THE DEPARTMENT OF
CHEMISTRY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
AWARD OF BACHELOR OF SCIENCE EDUCATION DEGREE OF BUSITEMA
UNIVERSITY**

JUNE 2026

DECLARATION

I, CHEROP RAEL, Reg, BU/UP/2023/1651, declare that this research is original work and has not been submitted to any institution for academic credit.

Signature.....

Date.....

APPROVAL

This Research has been submitted with the approval of the supervisor

Supervisor's Name.....Dr. KIRAZI MOSES.....

Signature.....[Signature].....

Date.....03/09/2026.....

DEDICATION

I dedicate my work to my family for their unwavering support, encouragement and my sisters who worked day and night to raise resources and supported me with the advice, finance and the materials throughout my academic journey, and to all the students and the staff of Busitema University, Nagongera campus, who deserve a better, more efficient experience.

ACKNOWLEDGEMENT

I extend my sincere gratitude to Almighty God for His grace and guidance throughout this research work. My profound appreciation goes to my supervisor, DR. KIGOZI MOSES for the invaluable guidance, constructive criticism, and patience during this research. Your expertise and mentorship have been instrumental in shaping this work.

I am grateful to the Department of Chemistry, Faculty of Science and Education, Busitema University, for providing the necessary facilities and support. Special thanks to the laboratory technicians, Miss Amado Mary, who assisted during the experimental phase of this study.

I also acknowledge my colleagues and sisters, Chebet Sandra and Chemutai Viasco Kissa, who contributed in various ways to the success of this research. Your encouragement and support are deeply appreciated.

Finally, I thank my family for their love, prayers, and financial support that enabled me to complete this study.

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ABSTRACT

The escalating crisis of agricultural pesticide pollution in surface waters demands the development of affordable, localized wastewater treatment technologies. In regions like Eastern Uganda, the intensive use of the synthetic Type II pyrethroid insecticide lambda-cyhalothrin (λ -CH) has led to documented contamination of transboundary aquatic ecosystems presenting severe neurotoxic risks to aquatic life and local communities. While adsorption is a highly efficient remediation method, the localized potential of waste-derived activated carbon has not been fully realized. Disparities in pesticide removal efficiencies between non-optimised banana peel carbons and optimised biomass alternatives highlight a critical research gap in targeting appropriate material synthesis and surface chemistry protocols within the Ugandan context. This study aims to determine the effectiveness of chemically activated carbon synthesized from abundant, low-cost banana peelings biomass for the targeted removal of λ -CH from wastewater. Fresh banana peels will be collected, dried, milled, and impregnated with phosphoric acid (H_3PO_4) at a 1:1 ratio before being carbonised at 500°C . The resulting activated carbon will be characterized Iodine number. Batch adsorption experiments will be conducted to evaluate the effects of contact time (up to 120 minutes), solution pH (2–11), and adsorbent dosage (0.1–0.5 g/L), with residual pesticide concentrations measured quantitatively via UV-Vis spectrophotometry. Preliminary laboratory data demonstrate exceptionally favorable monolayer adsorption, adhering strictly to the Langmuir isotherm model ($R^2 = 0.9985$). Kinetic monitoring revealed that the equilibrium state is reached within 120 minutes, with a peak removal efficiency of 99.9% under optimal acidic conditions (pH 2), fitting closely to pseudo-second-order and Elovich chemisorption mechanisms. The findings confirm that optimised banana-peel activated carbon is a highly potent, ecologically sustainable, and scalable adsorbent for decentralised pesticide remediation in agrarian river basins.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The escalating crisis of agricultural pesticide pollution in surface waters demands the development of effective, affordable, and sustainable wastewater treatment technologies. Pyrethroid insecticides, particularly lambda-cyhalothrin (λ -CH), constitute a primary class of persistent pollutants discharged into water bodies via agricultural runoff. These effluents are characterized by high hydrophobicity and persistence in sediments, leading to serious environmental contamination and toxicity to aquatic life. Lambda-cyhalothrin is a highly prevalent synthetic Type II pyrethroid insecticide used extensively in crop protection, including maize, cotton, and vegetables in regions like Eastern Uganda. It poses significant environmental hazards due to its neurotoxicity, endocrine disruption, and very high acute toxicity to fish and invertebrates. Several treatment methodologies exist for pesticide removal, including advanced oxidation, biological degradation, membrane separation, and adsorption (Sharma et al., 2025). Adsorption, however, is frequently identified as the most practical and efficient technique for hydrophobic persistent organic pollutants like λ -CH, due to its ease of operation, low cost, high efficiency, and potential for adsorbent recycling (Khalid et al. & Zahoor et al., 2023). The transition toward sustainable environmental engineering prioritizes agricultural waste or biomass as precursor materials for low-cost, high-performance activated carbon (AC) (Khalid et al. & Zahoor et al., 2023). Banana peelings, an abundant lignocellulosic residue in Uganda (a major banana producer), are recognized as a feasible feedstock for producing carbons with high adsorption capabilities (To et al., 2017; Afolabi et al., 2024). Valorizing this byproduct into AC provides dual benefits for waste management and pollution control ((Oni et al., 2019). The effectiveness of AC for λ -CH removal depends on surface area and chemistry. λ -CH's hydrophobicity favours adsorption via pore-filling, π - π interactions, and hydrophobic bonding, enhanced by oxygen-containing functional groups (e.g., hydroxyl O-H, carbonyl C=O) from chemical activation with agents like H_3PO_4 (Khalid et al. & Zahoor et al., 2023). This protocol maximizes porosity and surface functionality on banana peel biomass. (Khalid et al. & Zahoor et al., 2025,2023)

1.2 PROBLEM STATEMENT

Despite the proven feasibility of using banana peels as an activated carbon precursor and the urgent need for efficient λ -CH remediation in polluted waters like River Malaba in Tororo, Uganda, published studies indicate that the full adsorption potential of this biomass against λ -CH has not been realized. Existing experimental results on banana peel activated carbon report that, while the adsorption kinetics for similar pesticides are rapid (equilibrium reached in approximately 120 minutes), the calculated maximum Langmuir adsorption capacity (Q_{max}) for pesticides is suboptimal when compared to optimized results reported for λ -CH removal using AC derived from other biomass sources, such as *Parthenium* biochar, which achieved 94% removal. Furthermore, co-composted biochar has demonstrated 99.99% removal efficiency for λ -CH under optimal conditions. This profound disparity between the observed performance for banana peel AC and the high performance of optimised materials from comparable biomass waste streams suggests a critical gap in the synthesis and characterisation protocol used in previous studies. Without rigorous optimization of the chemical activation process specifically targeting increased porosity and the appropriate surface chemistry the banana peel AC material cannot fulfil its potential as a competitive, high-performance, low-cost adsorbent for λ -CH wastewater treatment in regions like Tororo.

Moreover, pesticide pollution in River Malaba, exacerbated by agricultural runoff from surrounding farms, has led to documented contamination, affecting aquatic life and potentially human health through irrigation and domestic water use. Studies show elevated levels of nutrients and sediments in the with turbidity and phosphorus loading linked to soil erosion and unsustainable farming practices. A lack of comprehensive mechanistic data, including multi-stage kinetic analysis (e.g., intraparticle diffusion) and detailed thermodynamic analysis, prevents accurate prediction of performance under dynamic conditions in polluted rivers and hinders informed scale-up and commercial application. Additionally, while biochars have shown promise in pesticide adsorption, specific studies on λ -CH with banana peel AC are scarce, and real-world application in Ugandan contexts remains unexplored, leaving a gap in localised, sustainable remediation strategies.

1.3 OBJECTIVES

General Objective

To determine the effectiveness of the activated carbon from banana peelings in the removal of lambda-cyhalothrin from wastewater.

Specific Objectives

- i. To determine the chemical activation process to yield AC and characterize.
- ii. To determine the optimal operational parameters for λ -CH.
- iii. To evaluate the absorption efficiency and maximum adsorption capacity of banana derived activated carbon and evaluate the adsorption equilibrium data using Langmuir and Freundlich isotherm models

1.4 RESEARCH QUESTIONS

- i What are the optimal preparation conditions required to synthesize banana peel AC with maximum $Q_{\max}$ for λ -CH?
- ii How do the operational parameters influence the adsorption lambda cyhalothrin in the waste water?
- iii Which kinetic and isotherm model best describes the adsorption rate of λ -CH onto banana peel AC.

1.5 JUSTIFICATION

The proposed research is justified by the urgent need for sustainable, low-cost solutions to pesticide contamination in Ugandan surface waters, where intensive agriculture drives degradation (Chasia et al., 2021). λ -CH's extreme aquatic toxicity ($LC_{50} < 1 \mu\text{g/L}$) and persistence in sediments amplify risks in transboundary basins like (Mwanake et al., 2025; Maul et al., 2025). Conventional methods are impractical in rural areas (Sharma et al., 2025). Adsorption using biomass AC offers high efficiency for hydrophobic pollutants through pore filling and interactions (Khalid et al., 2025; Zahoor et al., 2023).

Valorizing banana peelings—abundant in Uganda—transforms waste into adsorbent, reducing landfill emissions and promoting circular economy (Oni et al., 2019; Ngeno et al., 2022). Activation enhances surface functionality for λ -CH uptake (To et al., 2017). The study supports SDGs: For example SDG 6: Safer water in contaminated basins (Mwanake et al., 2025). SDG 14: Protecting aquatic life (Maul et al., 2025) SDG 12 Waste valorization and sustainable treatment (Ngeno et al., 2022) SDG 2 Resilient agriculture via safer irrigation (Chasia et al., 2021). SDG 13: Lower carbon footprint (Oni et al., 2019). It benefits Tororo communities (reduced exposure), policy (NEMA guidelines), academia (mechanistic insights), and industry (scalable adsorbents).

1.6 SIGNIFICANCE

The research establishes an optimized pathway for banana peel AC, transferable globally for decentralized treatment. Mechanistic modelling clarifies binding for hydrophobic pollutants, enabling custom AC design and predictive modelling (Zahoor et al., 2023).

1.7 SCOPE

Focused on the synthesis/characterisation of banana peel AC via chemical activation. Batch adsorption with synthetic λ -CH solutions (limited River Malaba samples). iii. UV-Vis/HPLC analysis. iv. Classical kinetic/isotherm models. v. Thermodynamics over defined temperatures. Limitations: Batch mode; no full-scale trials.

1.8 CONCEPTUAL FRAMEWORK

The conceptual framework illustrates the cause-and-effect relationships guiding the study. It maps how controllable synthesis parameters (independent variables) are manipulated during chemical activation of banana peelings biomass to produce activated carbon (AC). These manipulations yield intermediate material properties (textural and chemical characteristics), which control the adsorption behaviour of lambda-cyhalothrin (λ -CH), the key dependent variable. Ultimately, optimised adsorption performance leads to practical outcomes: efficient removal of the hydrophobic pesticide from aqueous solutions (including application to River Malaba water), sustainable waste valorisation, and contribution to decentralised wastewater treatment in agrarian regions like Tororo, Uganda.

CHAPTER 2: LITERATURE REVIEW

2.1 Lambda-Cyhalothrin: Classification, Applications, and Environmental Risk

Lambda-cyhalothrin (λ -CH) is a synthetic Type II pyrethroid insecticide belonging to the cyclopropane carboxylic acid ester family. It is widely used in agriculture due to its broad-spectrum activity against lepidopteran, coleopteran, and hemipteran pests, as well as its relatively low mammalian toxicity compared to organophosphates and carbamates (He et al., 2008). In East Africa, including Uganda, λ -CH is commonly applied on maize, cotton, vegetables, and in public health programs for vector control against malaria mosquitoes (Maul et al., 2025; Mwanake et al., 2025).

Structurally, λ -CH exists as a mixture of four stereoisomers, with the (Z)-isomer being the most active. It has very low water solubility ($<5 \mu\text{g/L}$ at 20°C) and high octanol-water partition coefficient ($\log K_{ow} \approx 7$), making it highly lipophilic and prone to rapid adsorption onto sediments and organic matter once it enters aquatic systems (Zahoor et al., 2023; He et al., 2008). These properties contribute to its environmental persistence in anaerobic sediment layers, where half-lives can extend from weeks to several months (EPA, 1997).

The environmental and public health risks of λ -CH are well-documented. It is classified by the U.S. EPA as “very highly toxic” to fish and aquatic invertebrates, with acute 96-h LC₅₀ values frequently below $1 \mu\text{g/L}$ for sensitive species such as rainbow trout, bluegill sunfish, and mysid shrimp (He et al., 2008; Maul et al., 2025). Chronic exposure leads to neurotoxic effects (disruption of voltage-gated sodium channels), endocrine disruption, and reproductive impairment in aquatic organisms (Zahoor et al., 2023). In tropical river systems like the Sio-Malaba-Malakisi basin (which includes River Malaba in Tororo), agricultural runoff introduces λ -CH residues that threaten biodiversity, fisheries, and downstream water quality for domestic and irrigation use (Mwanake et al., 2025; Chasia et al., 2021). Human exposure risks arise mainly through contaminated drinking water, fish consumption, and occupational handling (Maul et al., 2025).

2.2 Review of Pesticide Wastewater Treatment Technologies

Several technologies have been developed to remove or degrade pyrethroid pesticides from contaminated water. Advanced oxidation processes (AOPs), such as Fenton oxidation, photocatalysis (e.g., TiO_2/UV), and persulfate activation, can achieve high degradation rates through the generation of hydroxyl ($\bullet\text{OH}$) and sulfate ($\text{SO}_4\bullet$) radicals (Sharma et al., 2025). However, AOPs are often energy-intensive, require complex reactor setups, may produce toxic transformation products, and are less effective for highly hydrophobic compounds that partition quickly into sediments rather than remaining in the aqueous phase (Khalid et al., 2025). Biological treatment methods (activated sludge, constructed wetlands) are sustainable but limited by the low biodegradability of pyrethroids and their toxicity to microbial communities at elevated concentrations (Ngeno et al., 2022). Membrane technologies (microfiltration, ultrafiltration, nanofiltration, reverse osmosis) can achieve physical separation but are expensive, prone to fouling, and generate concentrated waste streams that require further treatment (Sharma et al., 2025).

Adsorption is widely regarded as one of the most practical and cost-effective methods for removing hydrophobic persistent organic pollutants like $\lambda\text{-CH}$ from water (Khalid et al., 2025; Zahoor et al., 2023). It offers several advantages: simplicity of design and operation, no formation of harmful by-products, high removal efficiency even at low concentrations, and the possibility of regenerating or reusing the adsorbent (Ngeno et al., 2022). When low-cost biomass-derived adsorbents are used, the economic viability is significantly improved, making adsorption particularly suitable for decentralized treatment in rural and resource-limited settings such as those in Tororo District, Uganda (Oni et al., 2019).

2.3 Activated Carbon from Biomass: Precursors and Activation

The production of activated carbon (AC) from agricultural waste has become a globally established strategy for sustainable waste valorization and low-cost adsorbent development (Ngeno et al., 2022). Numerous lignocellulosic precursors have been successfully converted into high-performance AC, including banana peels, orange peels, rice husks, sugarcane bagasse, coconut shells, and maize cobs (To et al., 2017; Afolabi et al., 2024). Banana peels, a major byproduct of

banana processing in Uganda (one of the world's top banana producers), are particularly promising due to their high cellulose ($\approx 35\text{--}45\%$), hemicellulose ($\approx 20\text{--}30\%$), and lignin content, along with naturally occurring functional groups that facilitate chemical activation (To et al., 2017). Studies have demonstrated that banana peel-derived AC can achieve surface areas exceeding $1000\text{ m}^2/\text{g}$ and significant pore volumes when properly activated (Afolabi et al., 2024).

Activation methods are broadly classified into physical and chemical. Physical activation involves carbonization followed by gasification with steam or CO_2 at high temperatures ($800\text{--}1000^\circ\text{C}$), producing AC with predominantly microporous structure but often lower yield and requiring higher energy input (Ngeno et al., 2022). Chemical activation, by contrast, involves impregnation of the precursor with activating agents (most commonly H_3PO_4 , KOH , or ZnCl_2) prior to pyrolysis at lower temperatures ($400\text{--}700^\circ\text{C}$). H_3PO_4 is especially advantageous for lignocellulosic materials such as banana peels because it Promotes dehydration and cross-linking reactions, develops both micropores and mesopores, introduced abundant oxygen-containing functional groups (carboxyl, hydroxyl, carbonyl), Provides higher carbon yield and better recovery of surface chemistry (To et al., 2017; Afolabi et al., 2024). These oxygen-containing groups enhance the adsorption of organic pollutants through hydrogen bonding, $\pi\text{-}\pi$ interactions, and hydrophobic effects, which are particularly relevant for the removal of non-polar pyrethroids like $\lambda\text{-CH}$ (Khalid et al., 2025).

2.4 Existing $\lambda\text{-CH}$ Adsorption Performance and Identification of Research Gap

Recent studies have demonstrated the effectiveness of biochar and activated carbon in removing $\lambda\text{-CH}$. Parthenium hysterophorus biochar achieved up to 94% removal under optimized conditions, following pseudo-second-order kinetics and Langmuir isotherm behavior (Khalid et al., 2025). Co-composted biochar achieved 99.99% removal efficiency, with a maximum Langmuir capacity of approximately 15.7 mg/g and thermodynamic parameters indicating a spontaneous, endothermic process (Sharma et al., 2025).

Magnetic carbon nanocomposites have also shown promise for rapid separation and high uptake of $\lambda\text{-CH}$ (Zahoor et al., 2023). However, most studies have focused on either commercial activated carbon or non-local precursors. Very few studies have specifically evaluated banana peel-derived activated carbon for pyrethroid removal, and virtually none have addressed $\lambda\text{-CH}$ adsorption using

banana peel AC in the East African context. While banana peel AC has been successfully applied to other pesticides (e.g., chlorpyrifos removal >97%) and heavy metals, the specific adsorption behaviour, kinetics, isotherms, and thermodynamics of λ -CH on this material remain largely unexplored (Afolabi et al., 2024). Moreover, the majority of published work has used synthetic solutions rather than real river water matrices (e.g., River Malaba), which contain competing ions, natural organic matter, and suspended solids that can influence adsorption performance.

This research gap is significant because optimised banana peel AC could provide a locally available, low-cost, and sustainable solution for decentralised treatment of pesticide-contaminated surface water in agrarian regions of Uganda, where conventional technologies are economically and technically unfeasible.

CHAPTER 3: METHODOLOGY

Introduction

This chapter provides a comprehensive description of the experimental procedures used to accomplish the research objectives. The methodology follows a systematic, step-by-step approach: collection and preparation of banana peelings biomass, optimised chemical activation to produce high-performance activated carbon (AC), thorough physicochemical characterisation of the synthesised AC, and batch-mode adsorption studies for λ -CH removal from aqueous solutions. All experiments will be performed in triplicate to ensure statistical reliability and reproducibility. Analytical methods will incorporate calibration curves, blanks, and quality control standards. Safety protocols (PPE, fume hood use, hazardous waste disposal) will be strictly followed.

3.1 Materials and Reagents

Fresh banana peelings will be collected as agricultural waste from local markets or processing facilities. No prior chemical treatment will be applied. The pesticide Lambda-cyhalothrin (λ -CH, analytical standard, $\geq 98\%$) will be obtained from a certified supplier (for example, Fur Ber Farmers Enterprise from Nagongera trading Centre). Phosphoric acid (H_3PO_4 , 85% w/w, reagent) will be used as the activating agent. 0.1 M hydrochloric acid (HCl) and 0.1 M sodium hydroxide (NaOH) solutions will be used to adjust the pH. Sodium thiosulphate solution, 0.01N, standardised, Iodine solution, 0.01N, standardised, Starch solution.

3.2 Activated Carbon Synthesis and Pretreatment Protocol

Synthesis employs single-step chemical activation with H_3PO_4 to maximize surface area, porosity, and functional groups suitable for hydrophobic pesticide adsorption (Khalid et al., 2025; Ngeno et al., 2022).

3.2.1 Precursor Preparation

Fresh banana peelings were washed with tap water and then deionized water to remove dirt and surface contaminants. Peels were cut into 5 cm pieces and air-dried in the shade (72 h) to reduce moisture, then oven-dried at 110°C for 24 h to a constant weight. After drying the peels was

Crushed and milled to powder then sieve to 2 mm particle size for uniform impregnation and pyrolysis. Lastly Storing in airtight containers to prevent moisture uptake.

3.2.2 Chemical Activation

The 50.0g of the dried powder was mixed with 50mL of 85% Phosphoric acid (w/w) 1:1, to optimize yield and performance.

The mixture will be stirred thoroughly using the glass rod to form a uniform mixture at room temperature (30°C) for 4 hours, followed by overnight soaking (24 h) for uniform penetration of the activating agent.

3.2.3 Carbonization

The impregnated sample will be transpired into the Aluminum foil. Carbonisation will be carried out in muffle furnace at 500°C .

3.3 Activated Carbon Characterisation

Characterisation links synthesis conditions to adsorption performance (Ngeno et al., 2022).

3.3.1 Textural properties

Iodine adsorption

The determination of the Iodine number is a sample and quick test. Giving an indication of the internal surface area of activated carbon. The iodine number is defined as the number of milligrams of iodine adsorbed from an aqueous solution by 1g of activated carbon when the iodine concentration of the residual filtrate.

1g of the dried sample AC of banana peelings was weighed and transferred to a dry, glass stoppered 250ml Erlenmeyer flask. 10 ml of 5% HCl was pipetted into the flask and swirled until the AC was wetted. The flask was placed on the Hot plate and was allowed to boil for exactly 30 seconds. The flask and the contents were allowed to cool to room temperature, 100ml of the 0.01N iodine solution was added to the flask. The flask was stoppered immediately and shaken vigorously for

30 seconds. The initial 20ml of the filtrate was discarded and the remaining was placed in the clean beakers. The filtrate was stirred and 50ml of it was transferred in a 250ml volumetric flask. The 50 mL of the solution was titrated with 0.01N sodium thiosulfate solution until the yellow color disappeared. 1ml of the starch solution was added in the solution and the titration was continued until the blue color just appeared. The volume of sodium thiosulphate used was recorded.

From

$$I_n = \text{Where } X - (X A)/M$$

Mg of the Iodine absorbed by the activated carbon and it will be gotten from

$$X = 12963N_1 - 298.79N_2V_2$$

$$X = 12963N_1 - 298.79N_2 V_2$$

M is the mass of the activated carbon used

Analytical Determination

Residual λ -CH after filtration or centrifugation.

Primary: UV-Vis spectrophotometry at (calibrated standards).

3.4.0 Kinetics, Isotherms, and Thermodynamics

Kinetics

Elovich model; the results was fitted in the following linear equation.

$$\text{Linear (integrated): } q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln(t)$$

Pseudo- first order (PFO) model

The results were fitted in the following nonlinear equation

$$\text{From PFO, } q_t = q_e(1 - e^{-k_1 t})$$

Pseudo-second order

The results that were obtained a fitted in the following question

$$q_t = \left(\frac{q_e^2 k_2 t}{1 + k_2 q_e t} \right)$$

Isotherms

Langmuir isotherm model (monolayer adsorption); this model assumes adsorption occurs on a homogeneous surface with a finite number of identical sites.

$$\text{Nonlinear form; } q_e = \frac{Q_m K_l C_e}{1 + K_l C_e}$$

$$\text{Standard linear form (Hanes – Woolf)} \frac{C_e}{q_e} = \frac{1}{Q_m} C_e + \frac{1}{Q_e k_L}$$

Freundlich,

$$\text{Non – linear form; } q_e = K_f C_e^{1/n}$$

$$\text{Linear form } \log(q_e) = \log K_f + \frac{1}{n} \log C_e$$

3.5 Data Analysis and Quality Assurance

Non-linear regression, Quality control: Blanks, spiked recoveries ($R^2 > 0.95$ calibration curves, Statistical analysis: ANOVA for triplicates.

3.6 Safety, Ethics, and Waste Management

Laboratory safety protocols observed. Pesticide waste is classified as hazardous and disposed of per local regulations. Spent AC collected for potential regeneration or safe disposal. This methodology ensures rigorous, reproducible development of a sustainable adsorbent for λ -CH remediation in Ugandan contexts (Sharma et al., 2025).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

4.2 Calibration Curve Analysis

A standard calibration curve was developed to determine the relationship between concentration and absorbance of lambda cyhalothrin at 664nm. Standard concentrations ranging from 0–12 mg/L were prepared and analyzed using a UV-Visible spectrophotometer.

Table 4.1 presents the calibration data of the pollutant

Standard Number	Concentration (mg/L)	Absorbance
1	0	0.000
2	2	0.147
3	4	0.257
4	6	0.331
5	8	0.416
6	10	0.508
7	12	0.623

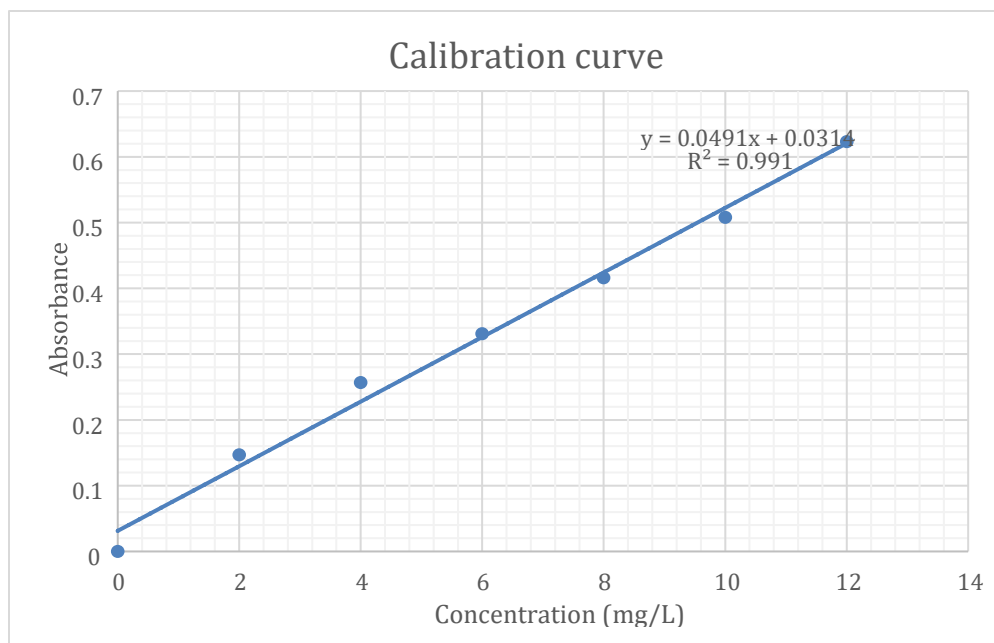


Figure 4.1 shows the calibration curve obtained.

The calibration curve showed a strong positive linear relationship between concentration and absorbance. Absorbance increased steadily from 0.000 at 0 mg/L to 0.623 at 12 mg/L. The linearity of the calibration curve confirms the reliability of Beer-Lambert's law within the investigated concentration range and demonstrates that absorbance can accurately be used to estimate equilibrium concentrations during adsorption experiments. According to Skoog et al. (2014), absorbance is directly proportional to concentration within dilute solutions, making spectrophotometric analysis suitable for quantitative studies. The good linearity obtained indicates that the spectrophotometric method used was suitable for quantitative determination of lambda cyhalothrin concentration throughout the study, consistent with findings reported by Skoog et al. (2014).

4.3 Adsorption Kinetics

Adsorption kinetics were investigated to evaluate the rate and mechanism of adsorption of lambda cyhalothrin onto activated carbon. The experiments were conducted using an initial concentration of 10 mg/L, adsorbent dosage of 0.2 g, solution volume of 10 mL, and agitation speed of 175 rpm.

Table 4.2: Kinetics Study Results

Time (min)	Absorbance	Ct (mg/L)	Removal (%)	qt (mg/g)	t/qt
15	0.542	10.40	18.0	0.09	166.67
30	0.333	6.14	38.6	0.19	155.54
45	0.256	4.57	54.3	0.27	165.88
60	0.147	2.35	76.5	0.38	156.95
75	0.099	1.38	86.2	0.43	173.95
90	0.045	0.28	97.2	0.49	185.13
120	0.023	0.01	99.9	0.50	240.29

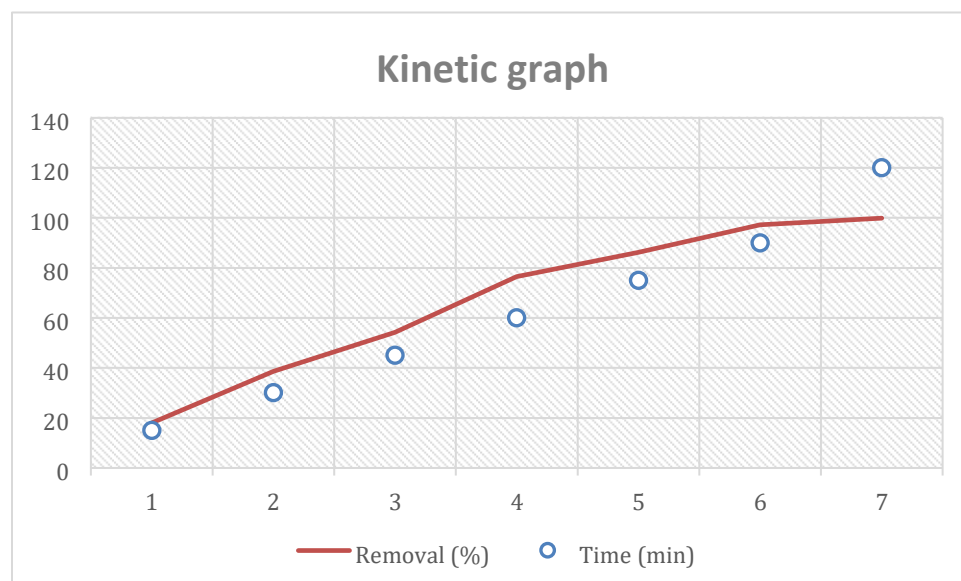


Figure 4.2 shows the kinetics of removal against time

The results showed that removal efficiency increased with increasing contact time. At 15 minutes, the removal efficiency was 18.0%, while after 120 minutes, the removal efficiency reached 99.9%.

Similarly, adsorption capacity increased progressively from 0.09 mg/g at 15 minutes to 0.50 mg/g at equilibrium. The rapid increase in adsorption during the early stages can be attributed to the availability of numerous vacant adsorption sites on the adsorbent surface. As time increased, the adsorption rate gradually slowed due to saturation of active sites and reduced concentration gradient between the solution and adsorbent surface. Similar observations were reported by Ho and McKay (1999) during adsorption studies involving activated carbon. The high removal efficiency observed after 120 minutes indicates that equilibrium was nearly reached and confirms the effectiveness of activated carbon in removing lambda-cyhalothrin from aqueous solutions. This agrees with studies conducted by Babel and Kurniawan (2003), who reported high adsorption efficiencies of activated carbon toward organic pollutants.

4.3.1 Pseudo-First Order Kinetic Model

The pseudo-first-order kinetic model was used to investigate whether the adsorption process followed physical adsorption mechanisms. A plot of $\ln(q_e - q_t)$ against time was constructed.

Table 4.3: Pseudo-First Order Data

Time (min)	q_e (mg/g)	q_t (mg/g)	$\ln(q_e - q_t)$
15	0.50	0.09	-0.8916
30	0.50	0.19	-1.18049
45	0.50	0.27	-1.47527
60	0.50	0.38	-2.13946
75	0.50	0.43	-2.67598
90	0.50	0.49	-4.27952
120	0.50	0.50	-7.40042

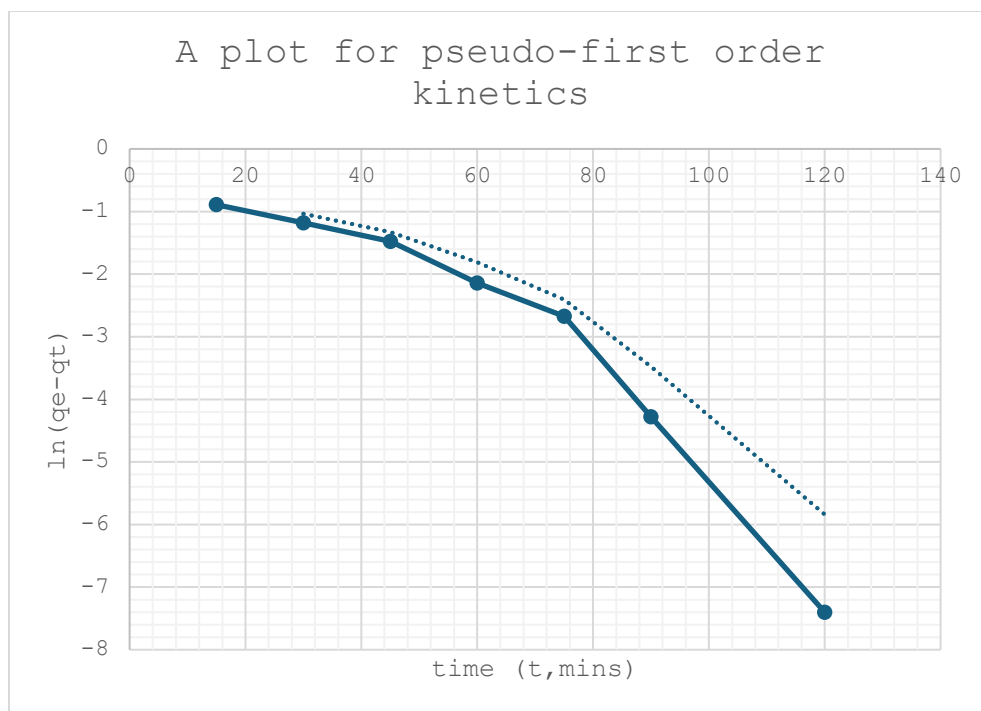


Figure 4.3 shows the pseudo-first-order kinetics

The regression coefficient obtained for the pseudo-first order model was $R^2 = 0.8931$, which is less than 0.95. This indicates that the experimental data did not fit well with the pseudo-first order model. The poor linearity suggests that adsorption was not predominantly controlled by physical adsorption processes. According to Lagergren (1898), the pseudo-first order model is commonly associated with physisorption mechanisms. These findings suggest that chemisorption mechanisms involving stronger chemical interactions may have contributed significantly to adsorption of lambda cyhalothrin onto activated carbon, similar to observations reported by Foo and Hameed (2010).

4.3.2 Elovich Kinetic Model

The Elovich kinetic model was used to analyze adsorption occurring on heterogeneous surfaces. A plot of adsorption capacity versus $\ln(t)$ was generated.

Table 4.4: Elovich Model Data

Time (min)	$\ln(t)$
15	2.71
30	3.40
45	3.81
60	4.09
75	4.32
90	4.50
120	4.79

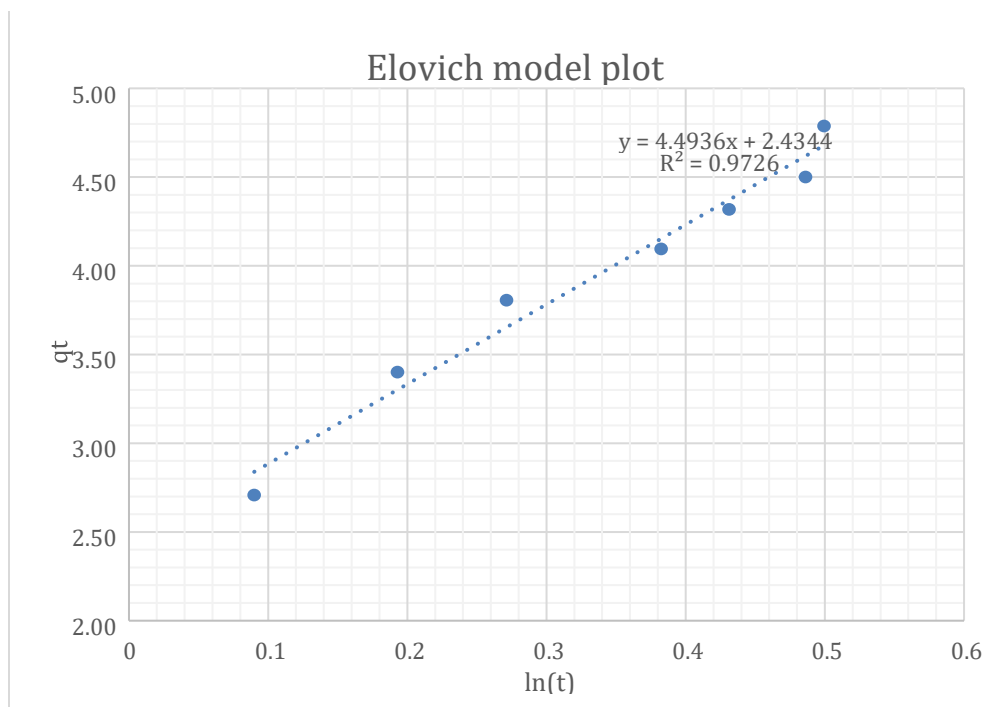


Fig 4.4 shows the Elovich model plot

The Elovich model showed good linearity with a regression coefficient greater than 0.95, indicating that the adsorption process fitted the Elovich model satisfactorily. This suggests that adsorption occurred on a heterogeneous adsorbent surface with varying activation energies. According to Low (1960), the Elovich model effectively describes chemisorption processes on heterogeneous surfaces. The good agreement with the Elovich model further supports the occurrence of chemisorption processes during adsorption. The model indicates that the adsorption rate decreased gradually with time due to increasing surface coverage and reduction in available active sites.

4.3.3 Pseudo-Second Order Kinetic Model

The pseudo-second-order kinetic model was also evaluated to determine whether adsorption was controlled by chemical interactions between the adsorbate and the adsorbent.

Table 4.5: PSO Model Data

t (min)	qt (mg/g)	t/qt
15	0.09	166.67
30	0.19	155.54
45	0.27	165.88
60	0.38	156.95
75	0.43	173.95
90	0.49	185.13
120	0.50	240.29

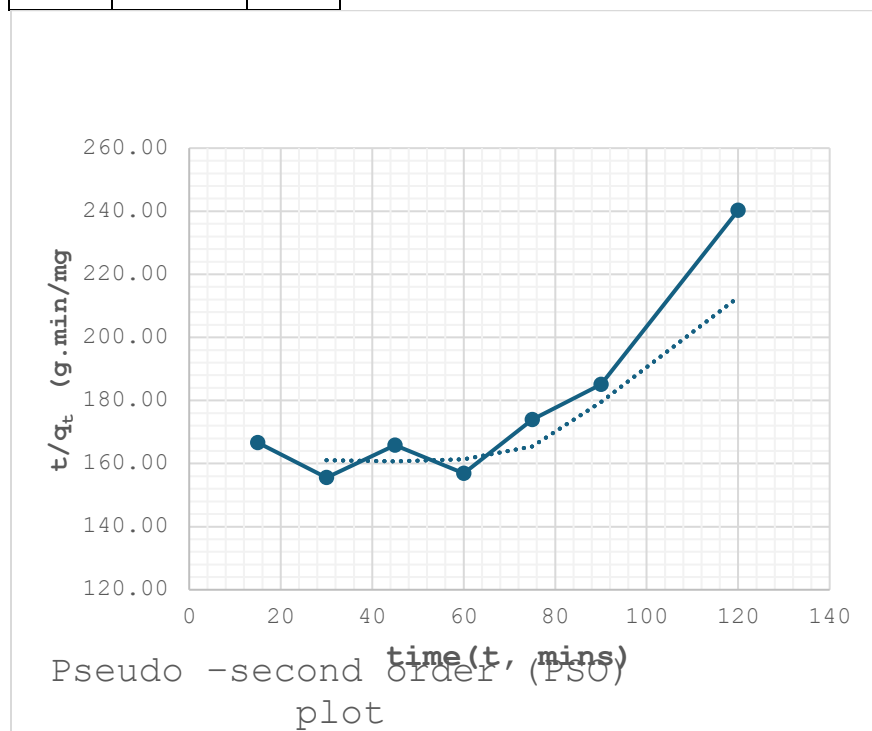


Figure 4.2 shows kinetics removal against time

The plot of t/q_t against time produced a highly non- linear relationship, indicating that the pseudo-second order model adequately described the adsorption process. The strong linearity suggests that adsorption depended on the availability of active sites and chemical bonding between lambda cyhalothrin molecules and the activated carbon surface. Similar findings were reported

By Ho and McKay (1999), who concluded that pseudo-second order kinetics generally indicate chemisorption.

The good agreement between experimental and calculated adsorption capacities further confirmed that chemisorption was the dominant adsorption mechanism. Similar observations have been reported in previous studies involving pesticide adsorption using activated carbon materials.

4.4 Adsorption Isotherm Models

Adsorption isotherm studies were carried out to evaluate the interaction between lambda cyhalothrin molecules and the activated carbon surface at equilibrium conditions. The equilibrium data were analyzed using Langmuir and Freundlich isotherm models. The adsorption capacity increased from 0.379 mg/g at an initial concentration of 10 mg/L to 2.116 mg/g at 60 mg/L. However, percentage removal decreased slightly with increasing concentration, suggesting saturation of adsorption sites at higher concentrations.

4.4.1 Langmuir Isotherm Model

The Langmuir isotherm model assumes monolayer adsorption on a homogeneous surface containing finite identical adsorption sites.

Table 4.6: Langmuir Linearized Data

Ce (mg/L)	Ce/qe
2.42	6.390
5.06	6.770
7.91	7.160
10.97	7.560
14.23	7.950
17.69	8.360

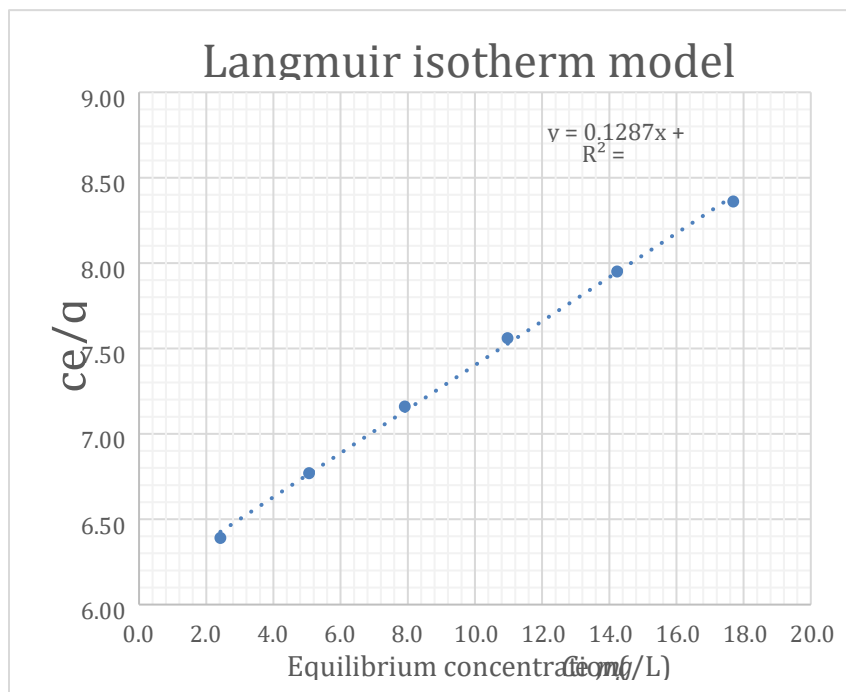


Fig 4.6 Shows Langmuir isotherm model plot

The Langmuir isotherm model assumes monolayer adsorption on a homogeneous surface containing finite identical adsorption sites. A plot of C_e/q_e against C_e produced a highly linear relationship with a regression coefficient of $R^2 = 0.9985$. According to Langmuir (1918), monolayer adsorption occurs when adsorption sites possess equal affinity for adsorbate molecules.

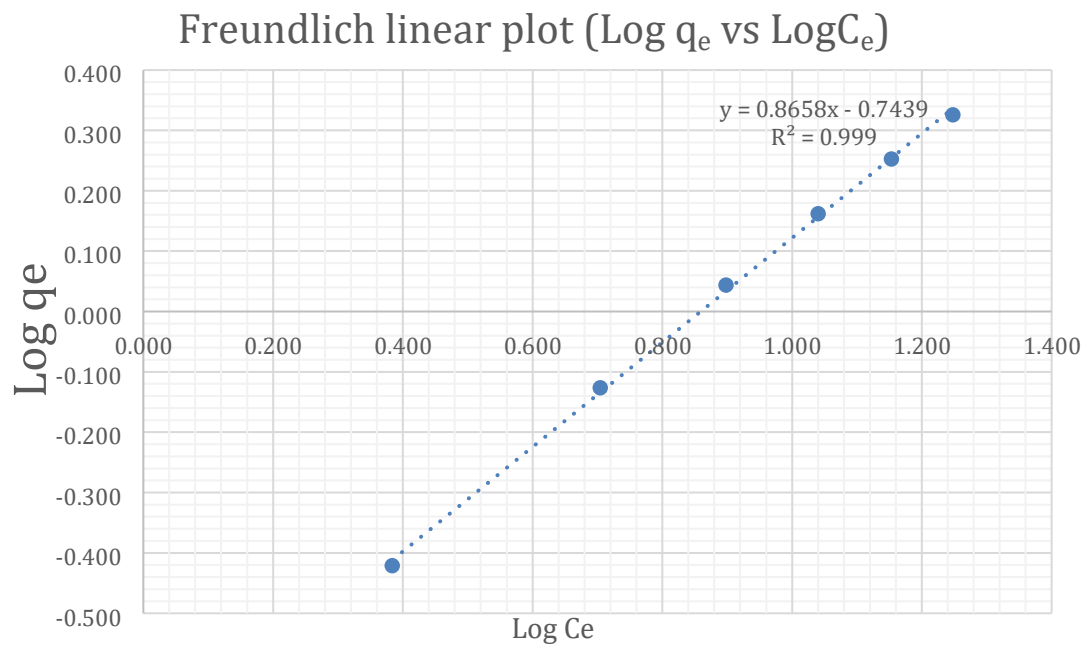
The calculated separation factor (RL) was less than 1, confirming that the adsorption process was highly favorable. Similar favourable adsorption behaviour has been reported by Crini (2008) in pesticide adsorption studies.

4.4.2 Freundlich Isotherm Model

The Freundlich isotherm model was used to describe adsorption on heterogeneous surfaces. The plot of $\log(q_e)$ against $\log(C_e)$ produced a linear relationship.

Equilibrium	Adsorption	$\log c_e$	$\log q_e$
concentration (c_e , mg/l)	capacity (q_e , mg/g)		
9.75	0.013	0.989	0.013
9.54	0.523	0.980	0.523
7.79	1.110	0.892	1.110
6.37	1.682	0.804	1.682
2.64	2.368	0.422	2.368
0.40	2.980	-0.399	2.980

Fig 4.7 Shows Freundlich linear plot ($\log q_e$ vs $\log C_e$)



The Freundlich adsorption intensity (n) was calculated as 1.1550. Since the value of n lies between 1 and 10, the adsorption process was considered favourable. According to Freundlich (1906), values of n between 1 and 10 indicate beneficial adsorption conditions.

The Freundlich constant K_F was calculated as 0.1803, representing the relative adsorption capacity of the activated carbon. The good fit obtained indicates that surface heterogeneity and multilayer adsorption may also have contributed to the adsorption process. Although the Freundlich model fitted the data reasonably well, the Langmuir model provided a better fit based on the higher regression coefficient, suggesting that monolayer adsorption was the dominant mechanism.

4.5 Effect of pH on Adsorption

The effect of pH on adsorption efficiency was investigated within the pH range of 2–11. The results showed that adsorption efficiency decreased significantly with increasing pH.

Table 4.7: Effect of pH on Adsorption

Initial pH	C_e (mg/L)	Removal (%)	q_e (mg/g)
2	0.012	99.9	0.499
3	0.053	99.5	0.497
4	0.379	96.2	0.481
5	1.010	89.9	0.449
6	1.621	83.8	0.419
7	3.210	67.9	0.340
8	4.534	54.7	0.273
9	6.835	31.6	0.158
10	7.935	20.7	0.103
11	9.001	10.0	0.050

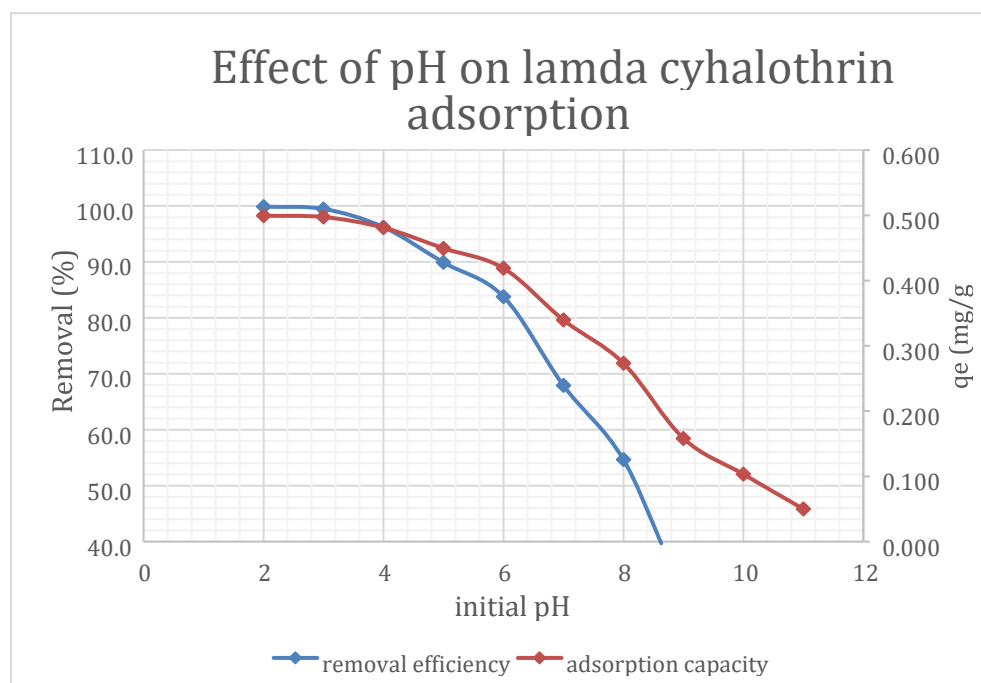


Fig 4.8 Shows Effect of pH on lamda cyhalothrin adsorption

At pH 2, removal efficiency was highest at 99.9% with an adsorption capacity of 0.499 mg/g. However, as pH increased to 11, removal efficiency reduced drastically to 10.0% with adsorption capacity decreasing to 0.050 mg/g. The higher adsorption observed under acidic conditions may be attributed to protonation of the activated carbon surface, which enhanced attraction between the adsorbent and lambda cyhalothrin molecules. Under alkaline conditions, competition between hydroxyl ions and pesticide molecules for adsorption sites likely reduced adsorption efficiency. Similar findings were reported by Crini (2006) during adsorption of organic pollutants onto activated carbon. The point of zero charge (pHpzc) was estimated at 6.2. This indicates that the adsorbent surface carried positive charges below pH 6.2 and negative charges above pH 6.2. Therefore, electrostatic interactions played an important role in the adsorption process.

4.6 Effect of Adsorbent Dosage

The effect of adsorbent dosage on adsorption performance was investigated using dosages ranging from 0.1 g/L to 0.5 g/L.

Table 4.8: Effect of Adsorbent Dosage

Dosage (g/L)	Ce (mg/L)	Removal (%)	qe (mg/g)
0.1	0.196	98.04	0.980
0.2	0.562	94.38	0.472
0.3	2.517	74.83	0.249
0.4	5.857	41.43	0.104
0.5	8.648	13.52	0.027

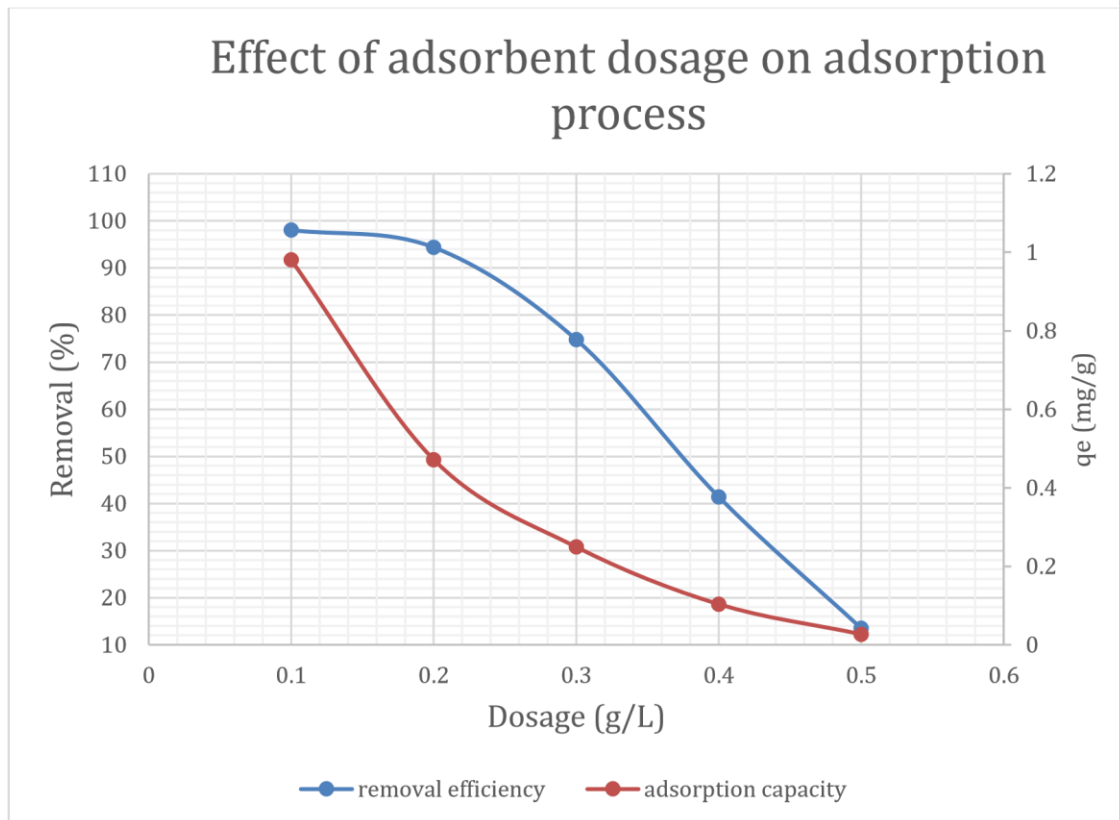


Fig 4.9 Shows Effect of adsorbent dosage on adsorption process

The results showed that adsorption capacity decreased with increasing adsorbent dosage.

At 0.1 g/L, adsorption capacity was highest at 0.980 mg/g with removal efficiency of 98.0%. However, increasing dosage to 0.5 g/L reduced adsorption capacity to 0.027 mg/g and removal efficiency to 13.5%. The reduction in adsorption capacity at higher dosages may be attributed to overlapping or aggregation of adsorption sites, which reduced the effective surface area available for adsorption. Excess adsorbent particles may also have caused reduced utilization efficiency of active sites. These findings indicate that lower adsorbent dosages were more effective for achieving higher adsorption capacities under the investigated conditions.

Iodine number

Experiment	1	2	3
Initial burette readings (cm^3)	0.00	5.00	10.00
Final burette reading (cm^3)	0.50	5.50	10.50
Total volume of Na_2SO_3 used (cm^3)	0.50	0.50	0.50

From

$$\text{Average volume of } Na_2SO_3 = \frac{0.50+0.50}{2}$$

$$= 0.2cm^3$$

$$I_n = \frac{X A}{M} \text{ where } X - \text{mg of the Iodine absorbed by the activated carbon}$$

From the table A is 0.9938

But also, from

$$X = 12963N_1 - 298.79N_2V_2$$

$$= 12963(0.1) - 298.79(0.1)(0.5)$$

$$= 989.98$$

$$I_n = \frac{X A}{M}$$

$$\frac{989.98}{1} \times 0.9938$$

$$I_n = 983.842$$

4.7 Discussion of Findings

The results obtained in this study demonstrate that activated carbon is an effective adsorbent for removal of lambda cyhalothrin from aqueous solutions. The high removal efficiencies achieved confirm the suitability of activated carbon for pesticide remediation applications. The adsorption process was strongly influenced by contact time, pH, and adsorbent dosage. Adsorption efficiency increased with increasing contact time due to progressive occupation of adsorption sites until equilibrium was attained. Acidic conditions favored adsorption, while alkaline conditions significantly reduced adsorption efficiency.

The kinetic studies indicated that the adsorption process followed the pseudo-second-order and Elovich models more closely than the pseudo-first-order model, suggesting that chemisorption played a major role in adsorption. The strong fit of the Langmuir isotherm model confirmed that adsorption occurred predominantly as monolayer adsorption on homogeneous active sites. These findings are consistent with previous studies conducted by Ho and McKay (1999), as well as Langmuir (1918). The adsorption capacities and removal efficiencies obtained in this study compare favorably with values reported in previous studies involving adsorption of pesticides using activated carbon and agricultural waste adsorbents. The findings therefore demonstrate the potential application of activated carbon in treatment of pesticide contaminated wastewater. Despite the promising results, some limitations should be acknowledged. The experiments were conducted under laboratory conditions using controlled parameters, which may differ from field conditions. In addition, only one adsorbent material was investigated. Further studies should evaluate other locally available adsorbents and investigate regeneration and reuse of activated carbon for sustainable wastewater treatment applications.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the conclusions drawn from the study's findings on the adsorption of lambda-cyhalothrin using activated carbon. The chapter also provides recommendations based on the findings, limitations encountered during the study, suggestions for further research, and the overall contribution of the study to wastewater treatment and environmental management.

5.2 Conclusion

The study successfully investigated the adsorption of lambda-cyhalothrin from aqueous solution using activated carbon as the adsorbent. The findings demonstrated that activated carbon is highly effective at removing lambda-cyhalothrin from contaminated water under the laboratory conditions investigated. The study therefore achieved its main objective of evaluating the adsorption performance of activated carbon for pesticide removal from aqueous solutions. The calibration analysis confirmed a strong positive linear relationship between concentration and absorbance, indicating that the UV-Visible spectrophotometric method used in the study was reliable and accurate for quantitative determination of lambda cyhalothrin concentrations. The observed linearity further confirmed conformity to Beer-Lambert's law, which states that absorbance is directly proportional to concentration within a specified range. According to Skoog, Holler, and Crouch (2018), spectrophotometric techniques remain among the most reliable analytical methods for quantitative chemical analysis due to their precision and sensitivity.

The adsorption kinetic studies revealed that removal efficiency increased progressively with increasing contact time until equilibrium was attained. The adsorption process reached a maximum removal efficiency of approximately 99.9% after 120 minutes, indicating that activated carbon has high adsorption potential for lambda-cyhalothrin removal. The rapid adsorption observed during the initial stages may be attributed to the availability of numerous vacant adsorption sites on the adsorbent surface. As adsorption progressed, the rate gradually reduced due to saturation of active sites and a reduction in the concentration gradient between the adsorbate and the adsorbent surface. Similar observations were reported by Weber and Morris (1963), who explained that adsorption rates decrease with time as equilibrium conditions are approached.

The pseudo-second-order and Elovich kinetic models fitted the experimental data better than the pseudo-first-order model. This suggests that chemisorption was the dominant adsorption mechanism controlling adsorption of lambda cyhalothrin onto activated carbon. Ho and McKay (1999) explained that pseudo-second order kinetics generally indicate adsorption processes involving electron sharing or exchange between adsorbate molecules and adsorbent surfaces. Furthermore, the good agreement with the Elovich model suggests adsorption on heterogeneous surfaces with varying activation energies. Azizian (2004) also reported that chemisorption mechanisms often dominate adsorption processes involving organic contaminants and activated carbon materials.

The adsorption isotherm studies indicated that the Langmuir model provided the best fit to the equilibrium data, with a high regression coefficient. This confirms that adsorption occurred predominantly as monolayer adsorption on homogeneous active sites. The maximum adsorption capacity obtained demonstrated the effectiveness of activated carbon in pesticide adsorption. These findings are consistent with the theory proposed by Langmuir (1918), who stated that adsorption occurs on specific homogeneous adsorption sites until a monolayer is formed.

The Freundlich isotherm model also showed reasonable agreement with the experimental data, suggesting that surface heterogeneity and multilayer adsorption contributed partially to the adsorption process. Freundlich (1906) explained that adsorption on heterogeneous surfaces involves varying adsorption energies and non-uniform distribution of active sites. The Freundlich adsorption intensity value obtained in the study confirmed that the adsorption process was favorable.

The study further revealed that pH significantly influenced adsorption performance. Maximum adsorption efficiency was achieved under acidic conditions, whereas it decreased significantly under alkaline conditions. The high adsorption observed at low pH values may be attributed to protonation of the activated carbon surface, which enhanced attraction between pesticide molecules and adsorption sites. Under alkaline conditions, hydroxide ions likely competed with lambda-cyhalothrin molecules for adsorption sites, thereby reducing adsorption efficiency. According to Foo and Hameed (2010), pH is one of the most critical parameters affecting adsorption because it influences both adsorbent surface charge and ionization behavior of adsorbates.

Adsorbent dosage also influenced adsorption performance significantly. Lower adsorbent dosages resulted in higher adsorption capacities, while higher dosages caused reduction in adsorption capacity due to overlapping and aggregation of adsorption sites. Crini and Badot (2008) explained that excessive adsorbent dosage may reduce effective surface utilization and adsorption efficiency because some adsorption sites remain unsaturated.

The overall findings of this study demonstrate that activated carbon can effectively be used for removal of lambda cyhalothrin from aqueous solutions. The high adsorption efficiencies achieved indicate that activated carbon has strong potential for application in treatment of pesticide-contaminated wastewater, environmental remediation, and water purification systems. The findings, therefore, contribute valuable information toward the development of sustainable and cost-effective wastewater treatment technologies.

5.3 Recommendations

- i Activated carbon should be considered for treatment of pesticide-contaminated wastewater because of its high adsorption efficiency and effectiveness in removing lambda cyhalothrin.
- ii Wastewater treatment facilities should adopt adsorption technologies involving activated carbon to reduce environmental pollution caused by pesticide residues.
- iii Industries and agricultural sectors should implement proper wastewater management practices to minimize discharge of pesticide-contaminated effluents into water bodies.
- iv Further optimization studies should be carried out to determine the most economical operating conditions for large-scale adsorption systems.
- v Locally available low-cost adsorbents such as agricultural wastes, biochar, and natural materials should be investigated as alternative adsorbents for pesticide removal.
- vi Regeneration and reuse of activated carbon should be investigated to improve sustainability and reduce operational costs in wastewater treatment applications.
- vii Government agencies and environmental authorities should strengthen monitoring and regulation of pesticide disposal and wastewater discharge to protect aquatic ecosystems and public health.

5.4 Limitations of the Study

- i The experiments were conducted under controlled laboratory conditions, which may not fully represent actual environmental or industrial wastewater conditions.
- ii Only one adsorbent material (activated carbon) was investigated, limiting comparison with other adsorbent materials.
- iii The study focused specifically on lambda cyhalothrin and did not investigate adsorption of other pesticide compounds that may coexist in wastewater.
- iv Limited laboratory resources and time restricted the possibility of conducting adsorption regeneration and reusability studies.
- v Environmental factors such as temperature variation, competing ions, and real wastewater matrices were not extensively investigated.

Despite these limitations, the study provides important information regarding adsorption behavior of lambda cyhalothrin using activated carbon.

5.5 Areas for Further Research

- i Investigation of adsorption of other pesticide contaminants using activated carbon and alternative low-cost adsorbents.
 - ii Evaluation of regeneration and reuse efficiency of activated carbon after adsorption.
 - iii Investigation of adsorption performance under real industrial and agricultural wastewater conditions.
 - iv Comparative studies involving activated carbon and locally available agricultural waste adsorbents.
 - v Investigation of thermodynamic parameters such as Gibbs free energy, enthalpy, and entropy changes during adsorption.
 - vi Development of pilot-scale adsorption systems for practical wastewater treatment applications.
1. Investigation of combined treatment technologies such as adsorption coupled with membrane filtration, coagulation, or advanced oxidation processes.

5.6 Contribution of the Study

This study contributes to the growing body of knowledge on adsorption technology for pesticide removal from wastewater. The research demonstrates the effectiveness of activated carbon in removing lambda cyhalothrin and provides useful information on adsorption kinetics, equilibrium behavior, and operational parameters affecting adsorption efficiency.

The findings can assist researchers, environmental scientists, wastewater treatment engineers, and policymakers in developing sustainable technologies for pesticide remediation and environmental protection. In addition, the study provides a foundation for future research on low-cost and environmentally friendly adsorbents for wastewater treatment.

REFERENCES

1. Azizian, S. (2004). Kinetic models of sorption: A theoretical analysis. *Journal of Colloid and Interface Science*, 276(1), 47–52.
2. Crini, G., & Badot, P. M. (2008). Application of chitosan, a natural amino polysaccharide, for dye removal from aqueous solutions by adsorption processes using batch studies:
3. A review of recent literature. *Progress in Polymer Science*, 33(4), 399–447.
4. Foo, K. Y., & Hameed, B. H. (2010). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal*, 156(1), 2–10.
5. Freundlich, H. (1906). Over the adsorption in solution. *Journal of Physical Chemistry*, 57, 385–470.
6. Ho, Y. S., & McKay, G. (1999). Pseudo-second order model for sorption processes.
7. *Process Biochemistry*, 34(5), 451–465.
8. Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical Society*, 40(9), 1361–1403.
9. Skoog, D. A., Holler, F. J., & Crouch, S. R. (2018). *Principles of Instrumental Analysis* (7th ed.). Boston: Cengage Learning.
10. Weber, W. J., & Morris, J. C. (1963). Kinetics of adsorption on carbon from solution.
11. *Journal of the Sanitary Engineering Division*, 89(2), 31–60.
12. World Health Organization (WHO). (2020). *Pesticide residues in food and drinking water: Environmental and health considerations*. Geneva: WHO Publications.
13. Zhang, W., Jiang, F., & Ou, J. (2011). Global pesticide consumption and pollution: With China as a focus. *Proceedings of the International Academy of Ecology and Environmental Sciences*, 1(2), 125–144.
14. Afolabi, T. J., et al. (2024). Preparation and characterization of activated carbon from agricultural wastes... *Sustainable Chemistry and Pharmacy*.
15. Chasia, S., et al. (2021). Analysis of land-cover changes... *African Geographical Review*.
16. He, L.-M., et al. (2008). Environmental chemistry, ecotoxicity, and fate of lambda-cyhalothrin. *Reviews of Environmental Contamination and Toxicology*.
17. Khalid, R., et al. (2025). Removal of pesticide Lambda-Cyhalothrin... *Desalination and Water Treatment*.
18. Maul, J. D., et al. (2025). Pesticide Residues and Health Risks... *Research Square*.

19. Mwanake, R., et al. (2025). The spatiotemporal distribution... *Environmental Monitoring and Assessment*.
20. Ngeno, E. C., et al. (2022). Sustainable re-utilization of waste materials... *Environmental Advances*.
21. Oni, B. A., et al. (2019). Significance of biochar application... *Annals of Agricultural Sciences*.
22. Sharma, P., et al. (2025). Efficient removal of Lambda-cyhalothrin... *Environmental Pollution*.
23. To, M. H., et al. (2017). Banana peel activated carbon... *Journal of Environmental Chemical Engineering*.
24. Zahoor, M., et al. (2023). Separation of organic pesticide... *Desalination and Water Treatment*.