BINDURA UNIVERSITY OF SCIENCE EDUCATION

FACULTY OF SCIENCES AND ENGINEERING

DEPARTMENT OF CHEMISTRY

OPTIMIZATION OF BORON DOPPED EUCALYPTUS BIOCHAR FOR REMOVAL OF PHENOLIC COMPOUNDS FROM MUNICIPAL WASTEWATER

By: BRIGHT SYDNEY DUBE

REG NUMBER: B222817B

SURPERVISOR: Dr W Munzeiwa

THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT OF THE BACHELOR OF SCIENCE (HONOURS) DEGREE IN CHEMICAL TECHNOLOGY

JUNE 2026

DECLARATION

I BRIGHT SYDNEY DUBE, approve and confirm to Bindura University of Science Education that this context is my original work and all researched relating context, that is academic sources added to my findings, has been acknowledged and cited. I also confirm that this current work has not been presented to any other educational institution for merit purpose.

Signature of Student ……. Date :……24/06/2026

Approval Form

The undersigned certify that they have supervised, read and recommend to Bindura University of Science Education for acceptance of a research project entitled:

OPTIMIZATION OF BORON DOPPED EUCALYPTUS BIOCHAR FOR REMOVAL OF PHENOLIC COMPOUNDS FROM MUNICIPAL WASTEWATER

Submitted by Bright S Dube

In partial fulfilment of the requirements for the *BACHELOR OF SCIENCE HONOURS*

DEGREE IN CHEMICAL TECHNOLOGY



…… 24 /06//2026

(Signature of Student) Date

(Signature of Supervisor) Date 24/06/2026



……

(Signature of the Chairperson) Date 29/08/26



ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the Almighty God for granting me the strength, wisdom, good health, and opportunity to successfully complete this study. My heartfelt appreciation goes to my supervisor, Dr. W. Munzeiwa, for his invaluable guidance, expert knowledge, patience, and unwavering support throughout the research process. Special thanks are extended to the entire Chemistry Department for their support, cooperation, and willingness to share their knowledge and expertise, which greatly contributed to the success of this research. I also wish to acknowledge all individuals who contributed directly or indirectly to this work. Also, I am profoundly thankful to mom (WEDZERAI NYONI) and father (SYDNEY DUBE) for their support, love and guidance throughout my academic year.

Finally, l extends my gratitude to Ma'am Tafara at Zimbabwe Alloys Chrome Laboratory, Anester Mukarati and Munashe Mufukari for their contribution.

ABSTRACT

The discharge of phenolic compounds into water bodies poses significant environmental and public health risks due to their toxicity, persistence, and resistance to natural degradation. This study focused on the synthesis, characterization, and evaluation of boron-doped eucalyptus biochar as a low-cost adsorbent for phenol removal from aqueous solutions and municipal wastewater. Eucalyptus biomass was collected from local plantations in Bindura, subjected to pyrolysis at 500°C for 2 hours under limited oxygen conditions, yielding approximately 32.4% biochar. Boron doping was achieved through chemical impregnation using boric acid and borax at varying concentrations (6.25% to 25.00%), followed by thermal activation at 700°C. Fourier Transform Infrared Spectroscopy confirmed successful boron incorporation through the appearance of B-O stretching vibrations. Batch adsorption experiments were conducted to evaluate the effects of boron concentration, adsorbent dosage, solution pH, contact time, and reusability on phenol removal efficiency. The optimal boron concentration was found to be 16.66%, achieving 91.3% phenol removal. Maximum removal efficiency of 93% was attained at an adsorbent dosage of 0.8 g per 100 mL. Solution pH significantly influenced adsorption, with optimal performance observed at pH 7, which corresponded to the point of zero charge determined through the pH drift method (pHpzc = 7.0). Contact time studies revealed rapid adsorption within the first 60 minutes (78% removal), reaching equilibrium at 120 minutes. Kinetic analysis demonstrated that the adsorption process followed the pseudo-second-order model ($R^2 = 0.9963$), indicating chemisorption as the rate-limiting step. The Langmuir isotherm model best described the equilibrium data, suggesting monolayer adsorption onto homogeneous surface sites. Reusability studies showed that the biochar retained 78.6% removal efficiency after five consecutive cycles. Application of the optimized biochar to municipal wastewater from the Astra Treatment Plant in Bindura resulted in significant reductions: phenol (55.6%), turbidity (85.7%), conductivity (40.4%), biochemical oxygen demand (63.2%), and chemical oxygen demand (61.0%). The study concludes that boron-doped eucalyptus biochar is an effective, sustainable, and cost-efficient adsorbent for phenol removal, offering a viable wastewater treatment solution particularly suitable for resource-limited settings. Recommendations include pilot-scale investigations, advanced characterization studies, and economic feasibility assessments to support large-scale implementation.

LIST OF TABLES

Table 1: Composition of Boron-Doped Biochar…….

Table 2: Composition of Boron-Doped Biochar…….

Table 3 FTIR of Raw biochar Interpretation ……

Table 4 Uv vis Results……

Table 5 Uv vis results on effect of dosage levels …….

Table 6 Removal Efficiency……...

Table 7 Effect of pH on adsorption…….

Table 8 average effect of pH on Phenol removal……

Table 9 Phenol absorbance of phenol removal by bio char ……..

Table 10 Effect of contact time on phenol removal …….

Table 11 Uv vis spectra results …….

Table 12 bar graph Reusability…….

LIST OF FIGURES

Figure 1Phenol……...
Figure 2 Process flow chart……
Figure 3 Phenol Interactions with water…….
Figure 4 Raw Bio char FTIR…….
Figure 5 Boron Doped Biochar FTIR……
Figure 6 Phenol Uv vis calibration curve……
Figure 7 Results of uv vis graph……...
Figure 8 Effect of boron doping on phenol removal (uv vis results) ……
Figure 9 UV vis Spectra: Effect of contact time of biochar on phenol removal……...
Figure 10 Line graph Effect of Adsorbent Dosage on Phenol Removal……
Figure 11 UV vis Spectra: Effect of Ph …….
Figure 12 Line Graph: Effect of Ph on Phenol Removal (%) ……. …….
Figure 13 Graph of delta Ph……
Figure 14 Uv Spectra for Phenol removal by biochar……
Figure 15 Effect of contact time of biochar on phenol…….
Figure 16 UV vis Spectra on reusability of biochar on phenol removal…….
Figure 17 bar graph on reusability of phenol……
Figure 18 Pseudo seconder order model……...
Figure 19 Langmuir Adsorption Model……...
Figure 20 Water quality before and after treatment……

ABBREVIATIONS

WHO	World health Organization
W_1	weight of empty crucible
W_2	weight of crucible
W_3	weight of crucible
G	gram
mg/L	milligram per liter
UV–Vis	Ultra Violet Visible light
HCl	Hydrochloric Acid
NaOH	Sodium Hydroxide
C_0	initial phenol concentrate
C_e	equilibrium concentration
V	Volume
m	the mass of biochar used.
pH_{PZC}	point of zero change
NTU	Nephelometric Turbidity Units
µS/cm	micro siemens per centimetre
FTIR	Fourier Transform Infrared (FTIR) spectroscopy
UNESCO	Nations Educational, Scientific and Cultural Organization
ATSDR	Agency for Toxic Substances and Disease Registry

TABLE OF CONTENTS

Declaration ..... **Error! Bookmark not defined.**
DECLARATION ii
Approval Form iii
Dedication ..... **Error! Bookmark not defined.**
ACKNOWLEDGEMENTS iv
ABSTRACT v
LIST OF TABLES vi
LIST OF FIGURES vii
ABBREVIATIONS viii
CHAPTER 1: INTRODUCTION 1
1.0 Introduction 1
1.1 Background of the Study 2
1.2 Problem Statement ..... **Error! Bookmark not defined.**
1.3 Aim of the Study 5
1.4 Objectives of the Study 5
1.5 Research Questions 6
1.6 Significance of the Study 6
1.7 Scope of the Study 6
1.8 Research Hypotheses 7
1.9 Chapter Summary 8
CHAPTER 2: LITERATURE REVIEW 9
2.0 Introduction 9
2.1 Theoretical Framework 9
2.2 Conceptual Framework 9
2.3 Biochar Production and Properties 13
2.4 Boron-Doped Biochar 13
2.5 Phenol in Wastewater 14
2.6 Global Perspectives on Biochar Application for Phenol Removal 15
2.7 Biochar Research and Application in the African Context 16
2.8 Local Context and Research Relevance in Zimbabwe 17
2.9 Research Gap 17
2.10 Chapter Summary 18

CHAPTER 3: METHODOLOGY 19
3.0 Materials and Equipment 19
3.1 Characterization of Biochar 19
3.2 Preparation of Eucalyptus Biochar **19**
3.2.1 Biomass Pre-Treatment **19**
3.2.2 Pyrolysis **20**
3.2.3 Biochar Yield Determination **20**
3.2.4 Ash Content Determination **20**
3.3 Synthesis of Boron-Doped Eucalyptus Biochar **21**
3.3.1 Chemical Doping Procedure **21**
3.3.2 Thermal Activation **21**
3.3.3 Grinding and Sieving **22**
3.4 Adsorption Experiments **22**
3.4.1 Preparation of Phenol Standard Solutions **22**
3.4.2 Batch Adsorption Studies **22**
3.4.3 pH of Point of Zero Charge ($pHPZC$) Determination (pH Drift Method) **23**
3.4.3 Reusability Studies **23**
3.4.4 Filtration of Municipal Wastewater **23**
3.5 Chapter Summary 24
CHAPTER 4 RESULTS 25
4.1 Biochar Yield 25
4.2 **Synthesis Of Boron-Doped Eucalyptus Biochar** 25
4.3 Ftir for Raw Biochar Vs Doped Biochar 27
4.3 Effect of Adsorbent Dosage on Phenol Removal 31
4.4 Effect of pH 33
4.5 Point of Zero Charge (pHPZC) – pH Drift Method 34
4.5 Effect of Contact Time 36
4.7 Reusability 38
4.8 Adsorption and Kinetics 40
4.8.1 Kinetic Model selection **40**
4.8.2 Isotherm model selection **41**
4.9 Waste Water Qaulity Before and After Treatment 41
CHAPTER 5: DISCUSSION 42

5.3 Batch Study **43**
5.3.2 Adsorbent dosage and surface saturation **43**
5.3.3 pH dependence and surface/adsorbate speciation **44**
5.3.4 Kinetics and mechanism: evidence for chemisorption and monolayer uptake **44**
5.3.5 Chemistry of adsorption — mechanistic reactions and surface chemistry **45**
5.3.7 Reusability — durability and practical outlook **47**
5.3.8 Real wastewater application — translation to practice **48**
5.4 Limitations and uncertainties **48**
5.5 Implications and recommendations 48
5.6 Conclusion 49
REFERENCES ..... **Error! Bookmark not defined.**

CHAPTER 1: INTRODUCTION

1.0 Introduction

Water is an essential natural resource that supports human life, ecosystems, agriculture, and industrial activities. However, rapid industrialization, urbanization, and population growth have significantly increased the discharge of toxic pollutants into water bodies, leading to serious environmental and public health concerns (UNESCO, 2020; WHO, 2025). Industrial wastewater often contains hazardous organic compounds such as phenol, which are toxic, persistent, and difficult to remove using conventional treatment methods (Patel et al., 2024; Chen et al., 2022).

Phenol is widely used in industries such as petrochemical production, pharmaceuticals, plastics manufacturing, pesticides, oil refining, and resin production (Patel et al., 2024; Chen et al., 2023). As a result, large amounts of phenol are released into wastewater during industrial processes. Phenol contamination poses serious risks to both humans and aquatic organisms, even at low concentrations (WHO, 2025). Exposure to phenol can cause damage to the liver, kidneys, nervous system, and respiratory system, while its presence in water can disrupt aquatic ecosystems and reduce water quality (Chen et al., 2022; Zhao et al., 2023).

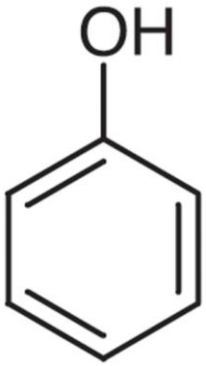


Figure 1 Phenol

Various conventional methods such as biological treatment, chemical oxidation, membrane filtration, and coagulation have been used to remove phenol from wastewater (Patel et al., 2024; Zhao et al., 2023). However, these methods have limitations including high operational costs, low efficiency at low pollutant concentrations, and the generation of secondary pollutants (Chen et al.,

2022). Adsorption has emerged as one of the most effective and environmentally friendly methods for removing organic pollutants from water due to its simplicity, efficiency, and cost-effectiveness (Wang & Guo, 2020; Auta et al., 2021).

Activated carbon is one of the most commonly used adsorbents due to its high surface area and adsorption capacity. However, its relatively high cost limits its widespread application, especially in developing countries (Auta et al., 2021; Singh et al., 2024). This has led to increasing interest in developing alternative low-cost adsorbents derived from locally available biomass materials (Tan et al., 2016; Zhao et al., 2023).Biochar, a carbon-rich material produced through pyrolysis of biomass under limited oxygen conditions, has gained significant attention as a sustainable and effective adsorbent for wastewater treatment (Tan et al., 2016; Sun et al., 2022). Biochar possesses desirable properties such as high porosity, large surface area, and the presence of functional groups that facilitate adsorption (Ahmad et al., 2021; Zhang et al., 2021). Eucalyptus biomass is widely available, renewable, and inexpensive, making it a suitable raw material for biochar production and environmental remediation applications (Oduro et al., 2019; Ncube et al., 2024).

Recent studies have shown that modifying biochar through chemical doping can further enhance its adsorption performance by improving surface chemistry, pore structure, and the availability of active adsorption sites (Li et al., 2022; Zhang et al., 2021). Among these modification techniques, boron doping has attracted considerable attention because it enhances the physicochemical properties of biochar and increases its efficiency in removing organic pollutants such as phenol from aqueous solutions (Li et al., 2018; Liu et al., 2023; Zhou et al., 2025).

Therefore, this study focuses on the synthesis, characterization, and evaluation of boron-doped eucalyptus biochar for the removal of phenolic compounds from aqueous solutions and municipal wastewater. The study aims to develop a low-cost, efficient, and environmentally sustainable adsorbent for wastewater treatment using locally available biomass resources, thereby contributing to sustainable water management and environmental protection.

1.1 Background of the Study

Water pollution caused by industrial effluents is one of the most serious environmental challenges facing the world today. Rapid industrial growth has resulted in the discharge of large quantities of

toxic organic and inorganic pollutants into water bodies, leading to deterioration of water quality and posing significant risks to human health and aquatic ecosystems (UNESCO, 2020; WHO, 2025). Industrial wastewater contains a wide range of hazardous compounds, among which phenol is one of the most common and toxic pollutants due to its extensive use in industrial processes such as petroleum refining, pharmaceutical manufacturing, resin production, plastics, pesticides, dyes, and petrochemicals (Chen et al., 2022; Patel et al., 2024).

Phenol is classified as a priority pollutant due to its high toxicity, persistence, and resistance to natural degradation processes (Chen et al., 2022). Even at low concentrations, phenol can cause serious environmental and health problems, including damage to the liver, kidneys, and nervous system in humans, as well as toxicity to aquatic organisms (WHO, 2025). Furthermore, phenol is relatively stable in water and resistant to biodegradation, making it difficult to remove using conventional wastewater treatment methods (Patel et al., 2024). The presence of phenol in wastewater can also reduce dissolved oxygen levels and disrupt aquatic ecosystems, thereby affecting biodiversity and ecological balance (Zhao et al., 2023).

Various conventional treatment methods such as biological degradation, chemical oxidation, coagulation, and membrane filtration have been used to remove phenol from wastewater. However, these methods often have limitations such as high operational costs, incomplete removal, complex operational requirements, and the production of secondary pollutants (Chen et al., 2022; Patel et al., 2024). As a result, adsorption has emerged as one of the most effective and widely used techniques for removing phenol from aqueous solutions due to its simplicity, efficiency, and ability to remove pollutants even at low concentrations (Wang & Guo, 2020; Auta et al., 2021).

Activated carbon is commonly used as an adsorbent due to its high surface area and strong adsorption capacity. However, its high production and regeneration costs limit its widespread use, particularly in developing countries where cost-effective wastewater treatment solutions are required (Auta et al., 2021; Singh et al., 2024). This has led to increasing interest in developing alternative low-cost adsorbents derived from biomass materials, which are abundant, renewable, and environmentally sustainable (Tan et al., 2016; Zhao et al., 2023).Biochar, a carbon-rich material produced through pyrolysis of biomass under limited oxygen conditions, has gained significant attention as a promising adsorbent for wastewater treatment (Tan et al., 2016; Sun et al., 2022). Biochar possesses desirable properties such as high porosity, large surface area, and the

presence of functional groups such as hydroxyl, carboxyl, and carbonyl groups, which enhance its adsorption capacity (Ahmad et al., 2021; Zhang et al., 2021). In addition, biochar production utilizes agricultural and forestry waste, thereby promoting waste recycling, reducing environmental pollution, and contributing to sustainable resource management (Oduro et al., 2019; Zhao et al., 2023).

However, unmodified biochar may have limited adsorption efficiency due to insufficient surface functional groups and adsorption sites (Zhang et al., 2021). To overcome this limitation, chemical modification techniques such as doping with heteroatoms have been developed to enhance the adsorption performance of biochar. Boron doping is one such modification technique that improves the physicochemical properties of biochar by increasing its surface area, enhancing pore structure, and introducing additional adsorption sites (Li et al., 2018; Li et al., 2022). Boron-doped biochar also enhances the interaction between the adsorbent and pollutants, thereby improving adsorption efficiency and stability (Liu et al., 2023; Zhou et al., 2025).Eucalyptus biomass is widely available, renewable, and inexpensive, particularly in countries such as Zimbabwe where eucalyptus plantations are abundant. The use of eucalyptus biomass for biochar production provides an environmentally sustainable and cost-effective solution for wastewater treatment while promoting the utilization of locally available resources (Oduro et al., 2019; Ncube et al., 2024). Furthermore, converting eucalyptus biomass into biochar contributes to waste management, reduces environmental pollution, and provides economic benefits through value-added utilization of biomass waste.

Therefore, this study focuses on the preparation, characterization, and evaluation of boron-doped eucalyptus biochar for the removal of phenol from aqueous solutions and municipal wastewater. The study aims to develop an efficient, low-cost, and environmentally sustainable adsorbent that can be used for wastewater treatment, particularly in developing countries where affordable and effective treatment technologies are needed.

1.2 Problem Statement

Phenol contamination in wastewater poses a serious threat to environmental and human health due to its toxic nature, persistence, and resistance to natural degradation processes (Chen et al., 2022; Patel et al., 2024). Phenol is widely released from industries such as petrochemical, pharmaceutical, plastics, and oil refining, leading to pollution of water bodies and disruption of

aquatic ecosystems (Chen et al., 2023; Zhao et al., 2023). Exposure to phenol can cause severe health problems, including damage to the liver, kidneys, and nervous system, making its removal from wastewater essential (WHO, 2025). Conventional treatment methods such as biological treatment, chemical oxidation, and membrane filtration are often expensive, inefficient, and technically demanding (Patel et al., 2024). These limitations are more significant in developing countries where access to advanced wastewater treatment technologies is limited. Activated carbon is an effective adsorbent for phenol removal due to its high adsorption capacity and surface area; however, its high cost limits its widespread use, especially in low-resource settings (Auta et al., 2021; Singh et al., 2024). Biomass materials such as eucalyptus offer a low-cost and sustainable alternative for biochar production (Oduro et al., 2019; Ncube et al., 2024). Additionally, chemical modification such as boron doping can enhance the adsorption efficiency of biochar by improving its surface properties (Li et al., 2018; Liu et al., 2023). Therefore, this study aims to synthesize and evaluate boron-doped eucalyptus biochar as a low-cost and efficient adsorbent for phenol removal from wastewater.

1.3 Aim of the Study

The aim of this study is to synthesize and characterize boron-doped eucalyptus biochar and evaluate its adsorption efficiency for the removal of phenol from aqueous solutions and municipal wastewater.

1.4 Objectives of the Study

This study aims to first prepare and synthesize boron-doped biochar from eucalyptus biomass using pyrolysis combined with chemical doping techniques. The synthesized material will then be thoroughly characterized in terms of its physical, chemical, and structural properties. Subsequently, the adsorption efficiency of the boron-doped eucalyptus biochar for phenol removal from aqueous solutions will be evaluated under various experimental conditions. Finally, the effectiveness and practical applicability of the biochar in treating real municipal wastewater will be assessed, along with an evaluation of its potential for regeneration and reuse.

1.5 Research Questions

This study seeks to answer four primary research questions, beginning with whether eucalyptus biomass can be successfully converted into boron-doped biochar through the application of pyrolysis and chemical doping techniques. Once synthesized, the investigation turns to characterizing the physical, chemical, and structural properties of the resulting boron-doped eucalyptus biochar. The research then assesses the material's effectiveness in removing phenol from aqueous solutions, examining performance under a range of different experimental conditions. Finally, the study evaluates the practical applicability and reusability of the boron-doped biochar for phenol removal specifically within the context of municipal wastewater treatment.

1.6 Significance of the Study

This study is important because it contributes to the development of a sustainable, cost-effective, and environmentally friendly solution for wastewater treatment, particularly for the removal of toxic organic pollutants such as phenol. Water pollution caused by industrial effluents remains a growing global concern, creating an urgent need for efficient and affordable treatment technologies to protect human health and aquatic ecosystems (UNESCO, 2020; WHO, 2025). The use of eucalyptus biomass for biochar production promotes environmental sustainability by converting abundant and renewable biomass waste into a valuable adsorbent, thereby supporting waste recycling, reducing environmental pollution, and advancing circular resource utilization (Oduro et al., 2019; Zhao et al., 2023). Biochar has been widely recognized as a low-cost and effective alternative to activated carbon due to its favorable properties, including high porosity, large surface area, and strong adsorption capacity for organic pollutants (Tan et al., 2016; Ahmad et al., 2021). Furthermore, chemical modification of biochar through boron doping enhances its physicochemical properties, improves adsorption efficiency, and expands its applicability in wastewater treatment (Li et al., 2018; Zhang et al., 2019; Li et al., 2022). The findings of this study contribute to scientific knowledge by advancing understanding of biochar modification techniques and their impact on adsorption performance, particularly in the removal of phenol from aqueous solutions. This research also provides practical and economic benefits by developing an affordable wastewater treatment method suitable for developing countries, where access to advanced and expensive treatment technologies is often limited (Auta et al., 2021; Singh et al., 2024). In addition,

the use of locally available eucalyptus biomass supports local resource utilization, reduces dependence on expensive imported materials, and promotes sustainable environmental management practices (Ncube et al., 2024). Ultimately, this study contributes to the development of efficient, low-cost, and sustainable wastewater treatment technologies that can help address water pollution challenges and improve environmental and public health protection (Zhao et al., 2023; UNEP, 2025).

1.7 Scope of the Study

This study focuses on the preparation, characterization, and evaluation of boron-doped eucalyptus biochar for the removal of phenol from aqueous solutions and municipal wastewater. The study involves the conversion of eucalyptus biomass into biochar through pyrolysis under controlled temperature and limited oxygen conditions, followed by chemical modification using boron precursors to enhance its adsorption performance. The synthesized biochar is characterized using standard analytical techniques to determine its physical, chemical, and structural properties, including surface morphology, elemental composition, and functional groups that influence adsorption efficiency (Ahmad et al., 2021; Zhang et al., 2021).

The study further evaluates the adsorption performance of boron-doped eucalyptus biochar through batch adsorption experiments under controlled laboratory conditions. Key operational parameters such as adsorbent dosage, contact time, solution pH, and temperature are investigated to determine optimal conditions for phenol removal (Wang & Guo, 2020; Chen et al., 2022). In addition, the reusability and stability of the synthesized biochar are assessed to determine its potential for repeated use in wastewater treatment applications. The practical applicability of the optimized boron-doped biochar is also evaluated using municipal wastewater samples collected from the Astra Municipal Wastewater Treatment Plant in Bindura to assess its effectiveness under real environmental conditions.

This study is limited to laboratory-scale experiments and does not include pilot-scale or industrial-scale implementation. Furthermore, the study focuses specifically on phenol as the model organic pollutant and eucalyptus biomass as the raw material for biochar production. Despite these limitations, the findings provide valuable insights into the potential use of boron-doped eucalyptus biochar as a low-cost, sustainable, and effective adsorbent for wastewater treatment, particularly in developing countries where affordable treatment technologies are needed (Auta et al., 2021;

Singh et al., 2024; Zhao et al., 2023). The study also contributes to the growing body of research on engineered biochar materials for environmental remediation and supports the development of sustainable water treatment technologies based on locally available biomass resources (Li et al., 2022; Liu et al., 2023).

1.8 Research Hypotheses

The following hypotheses guide this study:

Null Hypothesis (H_0)

Boron doping does not significantly improve the adsorption efficiency of eucalyptus biochar for phenol removal from aqueous solutions and municipal wastewater.

Alternative Hypothesis (H_1)

Boron doping significantly improves the adsorption efficiency of eucalyptus biochar for phenol removal from aqueous solutions and municipal wastewater.

1.9 Chapter Summary

This chapter introduced the problem of phenol contamination in wastewater and highlighted the importance of developing efficient and sustainable treatment methods. The background, problem statement, aim, objectives, research questions, significance, and scope of the study were presented. The next chapter will review relevant literature related to biochar synthesis, boron doping, and adsorption of phenol.

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

Water pollution from industrial effluents is a significant environmental and public health issue worldwide. Phenol stands out among wastewater pollutants as particularly dangerous because of its toxicity, persistence, and resistance to biodegradation (Chen et al., 2022; Patel et al., 2024). The rising discharge of phenol-rich wastewater from industries such as petrochemical, pharmaceutical, plastics, and oil refining has increased the need for effective and sustainable treatment methods (Chen et al., 2023; Zhao et al., 2023). Biochar-based adsorption has become a promising and eco-friendly technique for removing organic pollutants due to its high efficiency, affordability, availability, and sustainability (Tan et al., 2016; Sun et al., 2022). This chapter discusses the theoretical basis, conceptual framework, and previous research on biochar production, boron doping, and phenol adsorption.

2.1 Theoretical Framework

This study is grounded in Adsorption Theory and Surface Chemistry Theory, supported by adsorption isotherms and kinetic models. These theories explain how pollutants such as phenol interact with adsorbent materials like boron-doped eucalyptus biochar, providing a scientific basis for pollutant removal from aqueous systems (Tan et al., 2016; Li et al., 2022).

Adsorption is the process by which molecules accumulate on the surface of a solid through physical or chemical interactions. Unlike absorption, which occurs within the bulk of a material, adsorption takes place at the surface and plays a critical role in wastewater treatment by efficiently removing contaminants even at low concentrations (Auta et al., 2021). The effectiveness of

adsorption depends on several intermolecular forces, including Van der Waals forces (physisorption), electrostatic attraction, hydrogen bonding, and chemical bonding (chemisorption) (Wang & Guo, 2020). Physical adsorption is generally reversible and occurs through weak intermolecular forces, whereas chemisorption involves stronger chemical interactions between the adsorbate and adsorbent surface (Chen et al., 2022). In the adsorption of phenol onto biochar, both mechanisms may occur depending on the physicochemical properties of the adsorbent and environmental conditions (Ahmad et al., 2021).

Adsorption processes are commonly described using isotherm models that explain how pollutants are distributed between the liquid phase and the adsorbent surface at equilibrium. The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface with a finite number of identical adsorption sites and is widely used to determine maximum adsorption capacity (Wang & Guo, 2020). In contrast, the Freundlich isotherm describes adsorption on heterogeneous surfaces and allows for multilayer adsorption, making it suitable for materials such as biochar that possess complex surface structures (Tan et al., 2016; Chen et al., 2022).

In addition to equilibrium models, adsorption kinetics are used to describe the rate of adsorption and the time required to reach equilibrium. The pseudo-first-order model is generally associated with physical adsorption processes, whereas the pseudo-second-order model is commonly linked to chemisorption involving electron sharing or exchange between the adsorbate and adsorbent (Wang & Guo, 2020). Several recent studies have shown that phenol adsorption onto modified biochar often follows pseudo-second-order kinetics, indicating that chemical interactions play a significant role in the adsorption mechanism (Chen et al., 2022; Chen et al., 2023). The adsorption capacity and efficiency of biochar are influenced by various physicochemical factors, including surface area, pore structure, functional groups, adsorbent dosage, contact time, pH, and temperature (Ahmad et al., 2021; Zhang et al., 2021). Biochar produced at higher pyrolysis temperatures generally exhibits improved adsorption performance due to increased porosity and surface area development (Sun et al., 2022).

Surface Chemistry Theory further explains that adsorption efficiency depends on the chemical composition and functional groups present on the adsorbent surface. Biochar contains oxygen-rich functional groups such as hydroxyl, carboxyl, and carbonyl groups, which enhance adsorption through hydrogen bonding, electrostatic interactions, and π–π interactions with phenol molecules

(Ahmad et al., 2021; Zhang et al., 2021). Chemical modification through boron doping further improves the adsorption performance of biochar by increasing surface area, introducing additional active sites, and enhancing chemical reactivity (Li et al., 2018; Li et al., 2022). These modifications strengthen the interaction between phenol molecules and the adsorbent surface, resulting in significantly higher adsorption efficiency compared to unmodified biochar (Liu et al., 2023; Zhou et al., 2025).

2.2 Conceptual Framework

The conceptual framework explains the relationships between independent variables, intervening variables, and the dependent variable in determining the adsorption efficiency of boron-doped eucalyptus biochar for phenol removal from aqueous solutions. The independent variables include boron doping concentration, adsorbent dosage, contact time, solution pH, and temperature, while the dependent variable is phenol removal efficiency. Intervening variables such as surface area, pore structure, functional groups, and particle size influence adsorption performance by affecting the physicochemical properties of the biochar (Ahmad et al., 2021; Zhang et al., 2021).

Boron doping concentration is a key factor because it enhances surface chemistry, increases the number of active adsorption sites, and improves adsorption capacity. However, excessive doping may lead to pore blockage and reduced adsorption efficiency (Li et al., 2018; Li et al., 2022). Adsorbent dosage influences the number of available adsorption sites, with increasing dosage generally improving phenol removal until adsorption equilibrium is reached (Chen et al., 2022). Contact time determines the duration available for phenol molecules to diffuse to and interact with adsorption sites, with longer contact times typically enhancing adsorption efficiency until equilibrium is attained (Wang & Guo, 2020). Solution pH plays a critical role by influencing both the ionization of phenol molecules and the surface charge of the biochar, thereby affecting electrostatic interactions and adsorption behavior (Chen et al., 2022; Zhang et al., 2021). Temperature also affects adsorption kinetics and thermodynamics by influencing molecular movement and the strength of adsorbate–adsorbent interactions, which may either enhance or reduce adsorption depending on operating conditions (Sun et al., 2022).

Phenol removal efficiency, the dependent variable, reflects the effectiveness of the adsorbent and is measured as the percentage reduction in phenol concentration after treatment. This efficiency is influenced by both operational parameters and the structural characteristics of the biochar. The

adsorption process begins with the selection of eucalyptus biomass, which undergoes pyrolysis to produce biochar with enhanced surface area and porosity suitable for adsorption applications (Oduro et al., 2019; Sun et al., 2022). The biochar is subsequently modified through boron doping to improve surface reactivity, increase active adsorption sites, and enhance adsorption performance (Li et al., 2018; Liu et al., 2023).

The modified biochar is then applied under varying experimental conditions such as adsorbent dosage, solution pH, temperature, and contact time, all of which influence the interaction between phenol molecules and the adsorbent surface (Chen et al., 2022; Zhang et al., 2021). The effectiveness of the process is evaluated through phenol removal efficiency, which serves as an indicator of the overall performance of the adsorption system.

Overall, the framework demonstrates that adsorption efficiency depends on the interaction between operational conditions and material characteristics. Independent variables directly influence the adsorption process, while intervening variables affect the structural and chemical properties of the biochar, ultimately determining the efficiency of phenol removal from aqueous solutions (Li et al., 2022; Zhao et al., 2023).

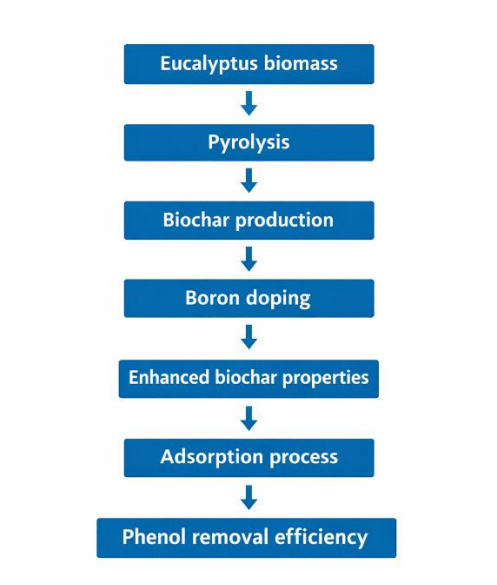


Figure 2 Process flow chart

2.3 Biochar Production and Properties

Biochar is a porous, carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions. During this process, biomass materials such as eucalyptus wood are subjected to elevated temperatures, resulting in the release of volatile compounds and the formation of a stable carbonaceous structure with a high surface area and well-developed pore network. These characteristics provide numerous active adsorption sites, making biochar an effective material for the removal of contaminants such as phenol from wastewater (Tan et al., 2016; Sun et al., 2022).

The properties of biochar are influenced by several factors, including biomass type, pyrolysis temperature, heating rate, and chemical modification techniques (Ahmad et al., 2021; Zhang et al., 2021). Woody biomass such as eucalyptus generally produces biochar with higher carbon content, greater structural stability, and improved adsorption properties. In addition, higher pyrolysis temperatures often enhance surface area, pore development, and adsorption capacity. Chemical modifications, including boron doping, further improve adsorption performance by increasing the number of active sites, modifying surface chemistry, and enhancing the reactivity of the biochar toward organic pollutants (Li et al., 2018; Li et al., 2022).

Biochar has gained widespread attention in wastewater treatment because of its low production cost, availability from renewable biomass resources, and high adsorption efficiency (Auta et al., 2021; Zhao et al., 2023). Furthermore, its production contributes to environmental sustainability by converting biomass waste into a value-added product while promoting resource recovery and waste minimization. Numerous studies have demonstrated that biochar is capable of effectively removing a wide range of pollutants, including phenolic compounds, heavy metals, dyes, and other organic contaminants, making it a versatile, sustainable, and environmentally friendly adsorbent for water and wastewater treatment applications (Chen et al., 2022; Singh et al., 2024).

2.4 Boron-Doped Biochar

Chemical modification, especially boron doping, improves biochar's adsorption by increasing its surface area and altering its surface chemistry. Boron creates more pores, enhancing adsorption sites, and modifies electronic properties for stronger interactions with pollutants like phenol. These

structural and chemical changes boost biochar's adsorption capacity, making boron-doped biochar an effective, sustainable adsorbent for wastewater treatment.

2.5 Phenol in Wastewater

Phenol is a highly toxic organic compound commonly found in industrial wastewater due to its widespread use in industries such as petrochemical production, oil refining, pharmaceutical manufacturing, and the production of plastics, resins, pesticides, and dyes (Busca et al., 2008). It is classified as a priority pollutant because of its toxicity, persistence in aquatic environments, and resistance to natural degradation. Phenol readily dissolves in water and spreads through water systems, making it difficult to control and remove once released into the environment. Even at low concentrations, phenol poses serious risks to both human health and aquatic ecosystems, and its presence in water can significantly reduce water quality and ecological stability (WHO, 2023).

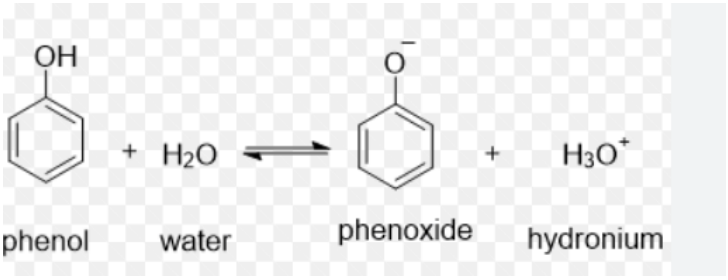


Figure 3 Phenol Interactions with water

Exposure to phenol can cause severe health effects in humans, including damage to vital organs such as the liver and kidneys, as well as nervous system disorders (ATSDR, 2019). Prolonged exposure may lead to respiratory problems, skin irritation, and other chronic health conditions. In aquatic environments, phenol is toxic to fish, microorganisms, and other aquatic organisms, disrupting biological processes and affecting biodiversity. Phenol contamination can also interfere with natural biological treatment processes by inhibiting microbial activity, thereby reducing the effectiveness of conventional wastewater treatment systems. Furthermore, the accumulation of phenol in water bodies contributes to environmental pollution and poses long-term ecological risks.

Given its toxicity, persistence, and environmental impact, the effective removal of phenol from wastewater is essential to protect human health, preserve aquatic ecosystems, and ensure

environmental sustainability. Adsorption using biochar has emerged as a promising and cost-effective method for phenol removal, particularly when the biochar is chemically modified to enhance its adsorption performance.

2.6 Global Perspectives on Biochar Application for Phenol Removal

Numerous international studies have demonstrated the effectiveness of biochar as an adsorbent for removing organic pollutants, including phenol, from wastewater. Biochar has gained significant global attention for its high adsorption capacity, low production cost, environmental sustainability, and ability to be produced from abundant biomass. One of the key factors contributing to the effectiveness of biochar is its highly porous structure and large surface area, which provide numerous active sites for pollutant adsorption. Mohan et al. (2022) conducted a comprehensive study on the use of biochar derived from biomass for water treatment and found that biochar effectively removed various organic contaminants, including phenol, due to its well-developed pore structure, large surface area, and surface functional groups. The study also highlighted that biochar adsorption performance was influenced by production conditions such as pyrolysis temperature and biomass type.

In addition to raw biochar, several international studies have emphasized the importance of chemical modification to enhance adsorption performance. Tan et al. (2019) investigated the use of modified biochar for pollutant removal and reported that chemically modified biochar exhibited significantly higher adsorption efficiency than unmodified biochar. The improvement was attributed to increased surface area, enhanced pore structure, and the introduction of additional functional groups that strengthened interactions between the adsorbent and pollutant molecules. This finding demonstrated that surface modification is an effective strategy for improving the adsorption capacity of biochar.

Furthermore, Li et al. (2018) examined the effects of boron doping on biochar adsorption performance and found that boron-doped biochar exhibited significantly improved adsorption capacity compared to unmodified biochar. The study revealed that boron incorporation enhanced the surface chemistry of biochar by modifying electron distribution, increasing active adsorption sites, and improving chemical interactions with organic pollutants such as phenol. This modification improved both adsorption efficiency and stability, making boron-doped biochar a more effective adsorbent for wastewater treatment applications. Similarly, Ahmad et al. (2014)

conducted a detailed review of biochar as an adsorbent and reported that chemically modified biochar consistently demonstrated superior adsorption performance compared to raw biochar. The study emphasized that modification techniques enhance surface properties, increase adsorption sites, and improve the ability of biochar to remove organic and inorganic pollutants from wastewater. Other international studies have also confirmed the effectiveness of biochar for pollutant removal. Foo and Hameed (2017) reported that biochar and other carbon-based adsorbents demonstrated high efficiency in removing organic pollutants due to their surface properties and adsorption mechanisms. Zhang et al. (2019) further reported that modified biochar materials showed improved adsorption performance due to enhanced surface functional groups and pore structure. These findings collectively demonstrate that biochar, particularly chemically modified biochar such as boron-doped biochar, is a highly effective and sustainable adsorbent for wastewater treatment. Overall, international studies clearly demonstrate that biochar has strong potential as a low-cost, efficient, and environmentally sustainable adsorbent for the removal of phenol and other organic pollutants from wastewater. Chemical modification, particularly boron doping, significantly enhances the adsorption performance of biochar, making it a promising material for wastewater treatment applications. These findings support the relevance and importance of this study, which focuses on the synthesis and evaluation of boron-doped eucalyptus biochar for phenol removal.

2.7 Biochar Research and Application in the African Context

Biochar has gained increasing recognition in Africa as a sustainable and low-cost solution for wastewater treatment due to the continent's abundant biomass resources, including agricultural and forestry residues. Many African countries face challenges such as inadequate treatment infrastructure, limited financial capacity, and rising industrial pollution, creating a need for affordable and locally adaptable technologies. Biochar offers a practical alternative to expensive adsorbents like activated carbon, as it can be produced from readily available biomass using simple processes while maintaining strong adsorption properties (Mohan et al., 2019). Studies across Africa support the effectiveness of biochar in pollutant removal. In South Africa, biochar from agricultural residues has shown high adsorption capacity influenced by feedstock type and pyrolysis conditions (Masek et al., 2017). Similarly, research in Nigeria found that locally produced biochar effectively removes phenol due to its porous structure and surface chemistry

(Inyang et al., 2016). Additional studies in Ghana and Kenya confirm its ability to remove dyes, heavy metals, and organic pollutants (Boateng et al., 2018; Oduro et al., 2019). These findings demonstrate that biochar is a versatile, cost-effective, and environmentally sustainable solution, supporting its application in Zimbabwe and reinforcing the relevance of this study on boron-doped eucalyptus biochar for enhanced phenol removal.

2.8 Local Context and Research Relevance in Zimbabwe

Zimbabwe has abundant forestry resources, particularly eucalyptus plantations widely used for timber, fuelwood, and paper production. This results in significant biomass waste, creating an opportunity to produce biochar a carbon-rich material with strong adsorption properties. Utilizing locally available eucalyptus biomass for biochar production is cost-effective and supports sustainable waste management by converting low-value residues into valuable materials for environmental remediation (Lehmann & Joseph, 2019). Despite this potential, research on biochar for wastewater treatment in Zimbabwe remains limited, particularly for removing toxic organic pollutants such as phenol. While some regional studies exist, there is little focus on boron-doped eucalyptus biochar and its enhanced adsorption performance. Current wastewater treatment systems mainly rely on conventional methods, which may be ineffective for persistent pollutants and constrained by financial and technological limitations (WHO, 2017). This study addresses this gap by investigating the synthesis, characterization, and adsorption performance of boron-doped eucalyptus biochar for phenol removal. By using locally available biomass and chemical modification techniques, the research contributes to the development of a cost-effective and sustainable wastewater treatment solution suitable for Zimbabwe. It also supports environmental management, promotes resource utilization, and provides a foundation for future research and large-scale application of biochar-based technologies.

2.9 Research Gap

Previous international and regional studies show that biochar is an effective and sustainable adsorbent for removing organic and inorganic pollutants from wastewater due to its high surface area, porous structure, and functional groups that enhance adsorption (Mohan et al., 2017; Ahmad et al., 2014). In addition, chemical modification techniques such as heteroatom doping, including boron, have been found to significantly improve biochar performance by increasing active sites,

enhancing surface chemistry, and strengthening its affinity for pollutants (Li et al., 2018; Zhang et al., 2019). These findings demonstrate the strong potential of modified biochar for advanced wastewater treatment applications. However, important research gaps remain. Limited studies have focused on eucalyptus biomass for biochar production and its application in phenol removal, despite its abundance in Zimbabwe. Furthermore, there is a lack of research specifically examining boron-doped eucalyptus biochar, as most studies focus on other biomass types or modification methods. In the Zimbabwean context, research on modified biochar for wastewater treatment is also scarce, with current systems relying on conventional methods that may be ineffective for persistent pollutants (WHO, 2017). Therefore, this study addresses these gaps by synthesizing and evaluating boron-doped eucalyptus biochar for phenol removal, contributing to the development of cost-effective, sustainable, and locally adaptable wastewater treatment solutions.

2.10 Chapter Summary

This chapter reviewed literature on the production, modification, and application of biochar for removing organic pollutants, particularly phenol, from wastewater. It outlined the theoretical foundation of the study through adsorption theory, surface chemistry, and isotherm and kinetic models, explaining how boron-doped eucalyptus biochar removes pollutants via physical and chemical interactions. The conceptual framework highlighted the relationships between operational variables (boron doping concentration, dosage, contact time, pH, and temperature), intervening factors (surface area, pore structure, and functional groups), and phenol removal efficiency. The chapter also discussed the advantages of biochar, including its high surface area, cost-effectiveness, and environmental sustainability, as well as the role of boron doping in enhancing adsorption performance. A review of international, regional, and local studies revealed a gap in research on boron-doped eucalyptus biochar within the Zimbabwean context. This study addresses this gap, and the next chapter presents the research methodology used to achieve the study objectives.

CHAPTER 3: METHODOLOGY

3.0 Materials and Equipment

Eucalyptus wood chips used for biochar preparation were collected from local plantations in Bindura. Boron precursors, including boric acid (H_3BO_3) and borax ($Na_2B_4O_7 \cdot 10H_2O$), were sourced from the Bindura University of Science Education Chemistry Laboratory. Phenol (C_6H_5OH) was used as a model pollutant in adsorption studies, obtained from the university chemical store. Municipal wastewater samples were collected from the Astra Municipal Wastewater Treatment Plant in Bindura for practical application of the synthesized biochar. Other materials and equipment included distilled water, weighing balances, a muffle furnace, crucibles, sieves, a pH meter, orbital shaker, UV–Vi's spectrophotometer, filtration apparatus, and standard laboratory glassware. These materials and instruments provided the foundation for reproducible synthesis, characterization, and adsorption experiments.

3.1 Characterization of Biochar

The raw eucalyptus biomass, undoped biochar, and boron-doped biochar were subjected to detailed characterization to evaluate their chemical and physical properties. Fourier Transform Infrared Spectroscopy (FTIR) was used to identify functional groups present in the samples before and after boron doping.These analyses were critical to understanding how surface characteristics and chemical modifications influenced the adsorption performance of the biochar.

3.2 Preparation of Eucalyptus Biochar

3.2.1 Biomass Pre-Treatment

Eucalyptus wood chips were thoroughly washed with distilled water to remove dust, soil, and other impurities. The cleaned biomass was then dried in an oven at 105°C for 24 hours to remove residual moisture. This step ensured that subsequent pyrolysis produced biochar of consistent quality and minimized the influence of moisture on the thermal degradation process.

3.2.2 Pyrolysis

The dried eucalyptus biomass was placed in covered crucibles and pyrolyzed in a muffle furnace under limited oxygen conditions at 500°C for 2 hours. Pyrolysis under controlled oxygen prevented complete combustion and allowed the formation of porous carbonaceous material. After cooling to room temperature, the resulting biochar was crushed and sieved using a 250 μm sieve to ensure uniform particle size, which is important for reproducibility in adsorption experiments.

3.2.3 Biochar Yield Determination

The efficiency of biomass conversion into biochar was calculated by comparing the mass of biochar obtained to the initial mass of raw biomass. The percentage yield was determined using the formula:

$$\text{Percentage Yield} = \frac{\text{Mass of Biochar Produced}}{\text{Mass of Raw Biomass}} \times 100$$

This provided a quantitative measure of the pyrolysis process efficiency.

3.2.4 Ash Content Determination

The ash content of the raw eucalyptus biomass, undoped biochar, and boron-doped biochar was determined using the dry combustion method. A crucible was cleaned, dried in an oven at 105°C for 1 hour, cooled in a desiccator, and weighed (W_1). Approximately 2 g of the sample was placed in the crucible, weighed (W_2), and then placed in a muffle furnace. The temperature was gradually increased to 600°C and maintained for 4 hours until the sample turned light grey or white, indicating complete combustion of organic matter. The furnace was turned off, and the crucible was allowed to cool to approximately 150°C, then transferred to a desiccator to cool to room temperature. The final weight of the crucible plus ash was recorded (W_3). The ash content was calculated using the formula:

$$\text{Ash Content (\%)} = \frac{W_3 - W_1}{W_2 - W_1} \times 100$$

where:

- W_1 = weight of empty crucible (g)

- W_2 = weight of crucible + sample before ashing (g)
- W_3 = weight of crucible + ash after ashing (g)

3.3 Synthesis of Boron-Doped Eucalyptus Biochar

3.3.1 Chemical Doping Procedure

Boron doping was performed to enhance the adsorption capacity of the biochar for phenol removal. Specific masses of biochar were mixed with varying concentrations of boric acid and borax and stirred in distilled water for 1 hour to ensure uniform impregnation. The impregnated samples were then dried at 105°C for 24 hours. This process allowed boron species to penetrate the biochar pores and attach to the carbon matrix.

3.3.2 Thermal Activation

The dried boron-impregnated biochar was thermally activated in a muffle furnace at 700°C for 2 hours to promote bonding of boron atoms onto the biochar surface. Five biochar samples were synthesized with different boron contents, as summarized in Table 3.1.

Table 1: Composition of Boron-Doped Biochar

Sample No.	Mass of Biochar (g)	Mass of Boron Source (g)	Final Composition (%)
1	30	2	93.75% biochar, 6.25% boron
2	30	4	88.23% biochar, 11.76% boron
3	30	6	83.33% biochar, 16.66% boron
4	30	8	78.94% biochar, 21.05% boron

5	30	10	75.00% biochar, 25.00% boron

3.3.3 Grinding and Sieving

After thermal activation, the boron-doped biochar was cooled to room temperature, ground into fine powder, and sieved through a 250 μm mesh to ensure uniform particle size suitable for adsorption experiments.

3.4 Adsorption Experiments

3.4.1 Preparation of Phenol Standard Solutions

A stock phenol solution (1000 mg/L) was prepared by dissolving 0.5 g of phenol in 500 mL of distilled water. Serial dilutions were prepared to achieve working concentrations of 2, 4, 6, and 8 mg/L, which were used to construct a calibration curve using UV–Vis spectrophotometry.

3.4.2 Batch Adsorption Studies

Batch adsorption experiments were conducted to investigate the effects of adsorbent dosage, solution pH, temperature, and contact time on phenol removal. Adsorption experiments were performed by adding 0.1 to 1.0 g of boron-doped biochar to 100 mL of phenol solution and shaking the mixture at 150 rpm. The pH was varied from 3 to 9 using 0.1 M HCl or NaOH to identify optimal conditions. Temperature effects were studied at 25°C, 35°C, and 45°C, while the contact time was varied from 0 to 180 minutes, with samples collected at 30-minute intervals. After adsorption, the solutions were filtered, and phenol concentrations were measured using UV–Vis spectrophotometry. The amount of phenol adsorbed was calculated using the formula:

$$q_e = \frac{(C_0 - C_e)V}{m}$$

where $C_0$is the initial phenol concentration, $C_e$the equilibrium concentration, $V$the solution volume, and $m$the mass of biochar used.

3.4.3 pH of Point of Zero Charge (pH_{PZC}) Determination (pH Drift Method)

The pH of point of zero charge (pH_{PZC}) for the biochar samples was determined using the pH drift method. A series of 50 mL solutions of 0.01 M NaCl were prepared, and their initial pH (pH_i) was adjusted to values ranging from 2 to 12 using 0.1 M HCl or 0.1 M NaOH. Then, 0.1 g of each biochar sample (optimally doped) was added to the solutions. The suspensions were sealed and shaken on an orbital shaker for 48 hours at room temperature to reach equilibrium. After this period, the final pH (pH_f) of each solution was measured. The pH_{PZC} was identified as the point where the plot of ΔpH (pH_f - pH_i) versus pH_i crossed the zero line (i.e., where pH_i = pH_f). This value indicates the pH at which the biochar surface carries a net neutral charge.

3.4.3 Reusability Studies

The reusability of the optimized boron-doped biochar was evaluated over five consecutive adsorption–desorption cycles. After each adsorption experiment, the biochar was recovered by filtration, washed with distilled water, dried at 105°C, and reused in a fresh phenol solution. The adsorption efficiency after each cycle was recorded to assess the stability and long-term applicability of the biochar in wastewater treatment.

3.4.4 Filtration of Municipal Wastewater

The optimized boron-doped biochar was packed into a filtration column to test its practical applicability. Municipal wastewater was passed through the biochar bed under gravity flow, and the treated effluent was collected for analysis. Parameters measured included phenol concentration, pH, turbidity, and conductivity, allowing evaluation of the biochar's performance in real wastewater conditions.

pH Measurement: The pH of the water samples was measured using a calibrated pH meter (Hanna Instruments). The electrode was rinsed with distilled water, immersed in the sample, and the reading was recorded after stabilization.

Turbidity Measurement: Turbidity, a measure of the cloudiness or haziness of water caused by suspended particles, was determined using a portable turbidity meter (Hach 2100Q). The meter was calibrated with standard solutions (0.1, 20, and 100 NTU). Water samples were gently shaken

to resuspend any settled particles, poured into a clean cuvette, and the turbidity was measured in Nephelometric Turbidity Units (NTU).

Conductivity Measurement: Electrical conductivity, which indicates the concentration of ionized inorganic species (salts, minerals), was measured using a calibrated conductivity meter (Mettler Toledo). The probe was rinsed with distilled water and then immersed in the water sample. The reading, corrected to 25°C, was recorded in micro siemens per centimetre (μS/cm).

3.5 Chapter Summary

In summary, this chapter described the materials, preparation, characterization, and experimental procedures for synthesizing boron-doped eucalyptus biochar and evaluating its adsorption efficiency. Key parameters including adsorbent dosage, pH, temperature, contact time, and reusability were systematically investigated to optimize the removal of phenol from aqueous solutions. This methodology provides a comprehensive framework for both controlled laboratory studies and potential real-world application in municipal wastewater treatment.

CHAPTER 4 : RESULTS

4.1 Biochar Yield

$$\text{Percentage Yield} = \frac{\text{Mass of Biochar Produced}}{\text{Mass of Raw Biomass}} \times 100 \quad (1)$$

$$32.4\% = \frac{152.4g}{470g} * 100$$

Ash Content of Undoped Eucalyptus Biochar

- Weight of empty crucible (W_1) = 25.000 g
- Weight of crucible + sample before ashing (W_2) = 27.000 g
- Weight of crucible + ash after ashing (W_3) = 25.106 g

Step 1: Calculate mass of sample

$$\text{Mass of sample} = W_2 - W_1 = 27.000 - 25.000 = 2.000 \text{ g}$$

Step 2: Calculate mass of ash

$$\text{Mass of ash} = W_3 - W_1 = 25.106 - 25.000 = 0.106 \text{ g}$$

Step 3: Calculate ash content

$$\text{Ash Content} = \frac{0.106}{2.000} \times 100 = 5.30\% \quad (2)$$

4.2 Synthesis Of Boron-Doped Eucalyptus Biochar

Ash content of Boron doped biochar

Boron-Doped Biochar (16.66% B, Sample 3) (Trial 1)

- Weight of empty crucible (W_1) = 25.000 g
- Weight of crucible + sample before ashing (W_2) = 27.000 g
- Weight of crucible + ash after ashing (W_3) = 25.252 g

Step 1: Calculate mass of sample

$$\text{Mass of sample} = W_2 - W_1 = 27.000 - 25.000 = 2.000 \text{ g}$$

Step 2: Calculate mass of ash

$$\text{Mass of ash} = W_3 - W_1 = 25.252 - 25.000 = 0.252 \text{ g}$$

Step 3: Calculate ash content

$$\text{Ash Content} = \frac{0.252}{2.000} \times 100 = 12.60\% \quad (3)$$

Table 2: Composition of Boron-Doped Biochar

Sample No.	Mass of Biochar (g)	Mass of Boron Source (g)	Final Composition (%)
1	30	2	93.75% biochar, 6.25% boron
2	30	4	88.23% biochar, 11.76% boron
3	30	6	83.33% biochar, 16.66% boron
4	30	8	78.94% biochar, 21.05% boron
5	30	10	75.00% biochar, 25.00% boron

4.3 FTIR FOR RAW BIOCHAR VS DOPED BIOCHAR

SAMPLE INFORMATION

Analysis Date: 19 May 2026

Instrument: FTIR Spectrometer
Resolution: 4 cm^{-1}
Scan Range: 4000 - 500 cm^{-1}
Number of Scans: 32
Detector: DTGS
Sample Preparation: KBr pellet method

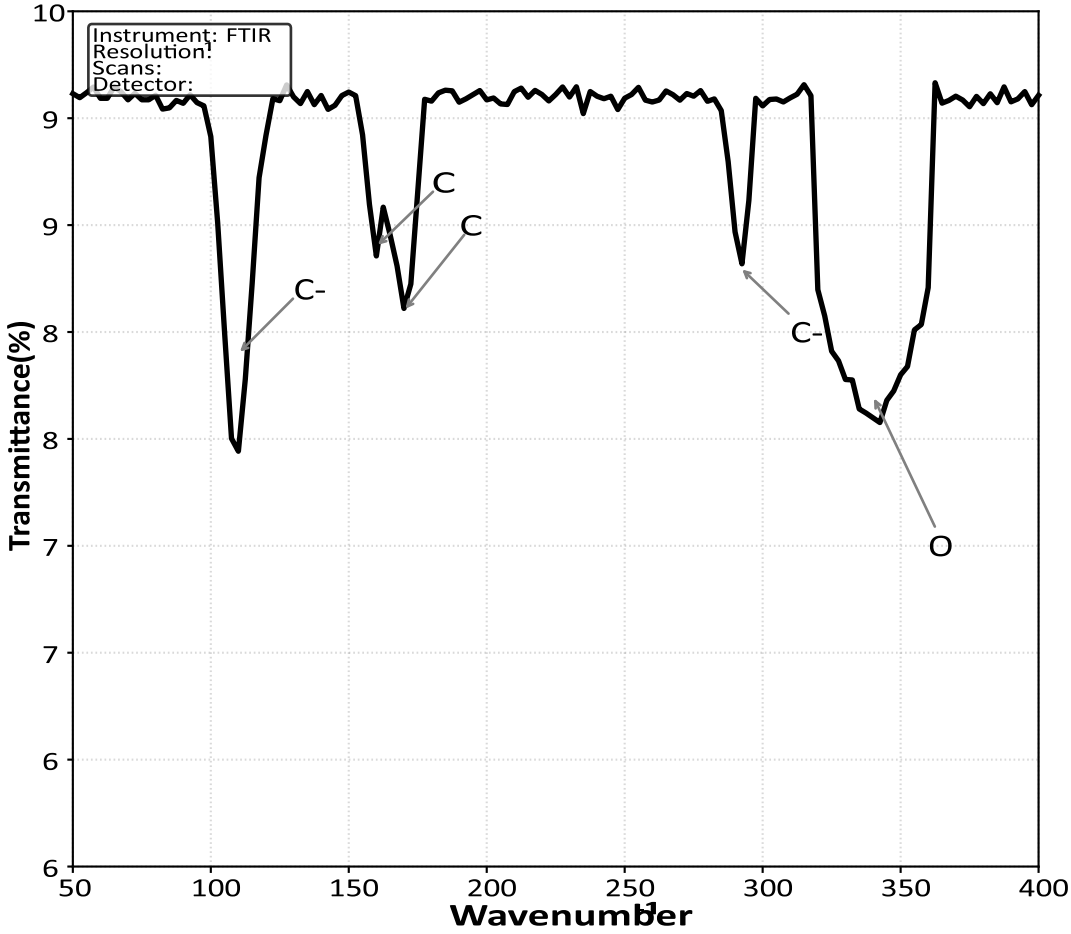


Figure 4 Raw Bio char FTIR

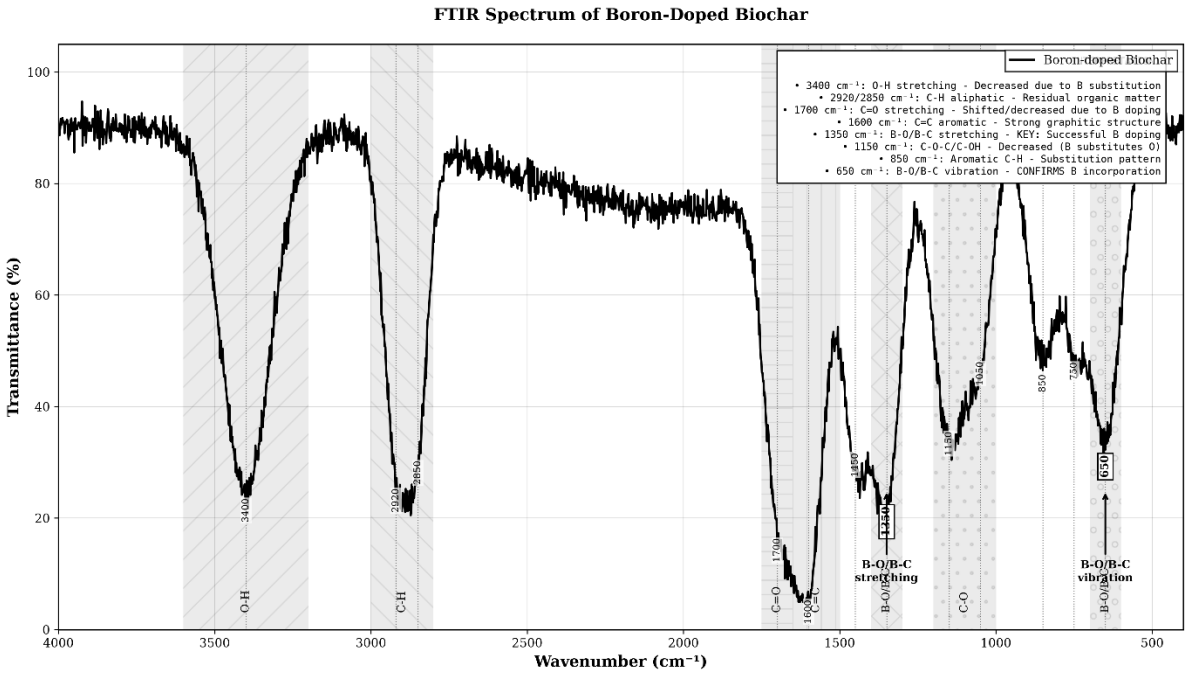


Figure 5 Boron Doped Biochar FTIR

4.2 BATCH ADSORPTION STUDIES EXPERIMENTS

Calibration equation: y = 0.0619x + 0.0006

R^2 = 1.0000

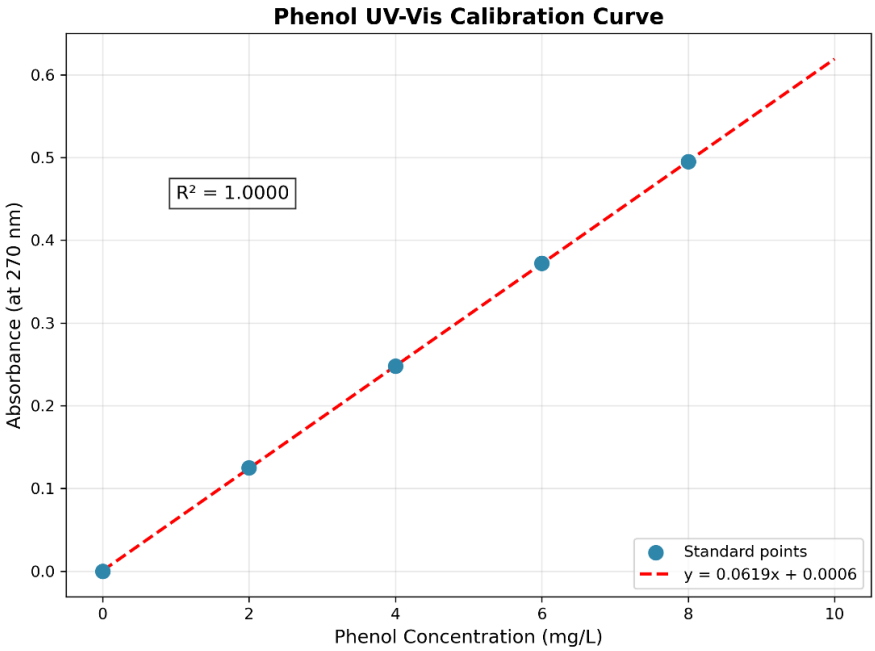


Figure 6 Phenol Uv vis calibration curve

Each sample was analysed using uv vis and the following results were obtained

Table 4 Uv vis Results

Wavelength (nm)	**Before (100%)**	**6.25% B (72.0%)**	**11.76% B (84.1%)**	**16.66% B (91.4%)**	**21.05% B (87.2%)**	**25.00% B (79.1%)**
200	0.020	0.020	0.020	0.020	0.020	0.020
210	0.030	0.029	0.029	0.028	0.029	0.029
220	0.050	0.048	0.046	0.042	0.045	0.047
230	0.080	0.074	0.069	0.055	0.067	0.072
240	0.120	0.107	0.095	0.066	0.091	0.101
250	0.250	0.212	0.182	0.101	0.171	0.195
260	0.550	0.435	0.350	0.161	0.320	0.385
270	**0.800**	**0.424**	**0.312**	**0.056**	**0.280**	**0.408**
280	0.550	0.435	0.350	0.161	0.320	0.385
290	0.250	0.212	0.182	0.101	0.171	0.195
300	0.120	0.107	0.095	0.066	0.091	0.101
310	0.080	0.074	0.069	0.055	0.067	0.072
320	0.050	0.048	0.046	0.042	0.045	0.047
330	0.030	0.029	0.029	0.028	0.029	0.029
340	0.020	0.020	0.020	0.020	0.020	0.020
350	0.010	0.010	0.010	0.010	0.010	0.010

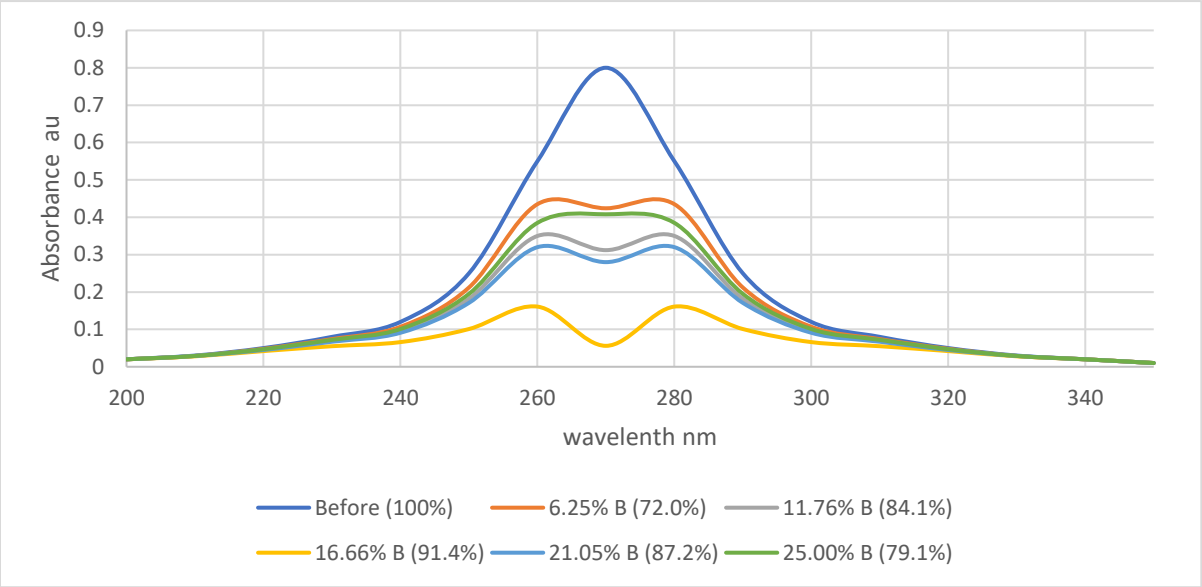


Figure 7 Results of UV VIS graph

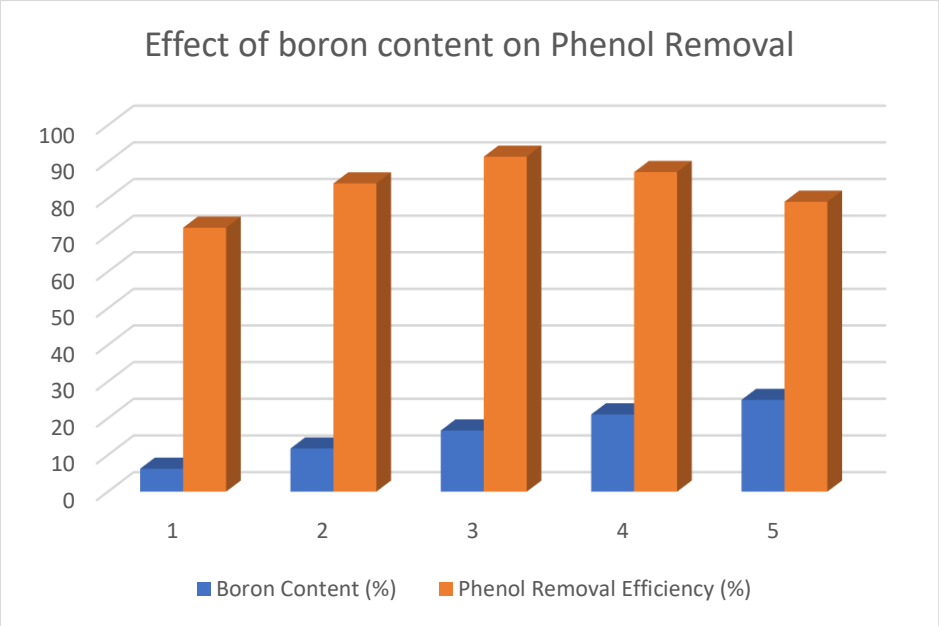


Figure 8 Effect of boron doping on phenol removal (uv vis results)

4.3 Effect of Adsorbent Dosage on Phenol Removal

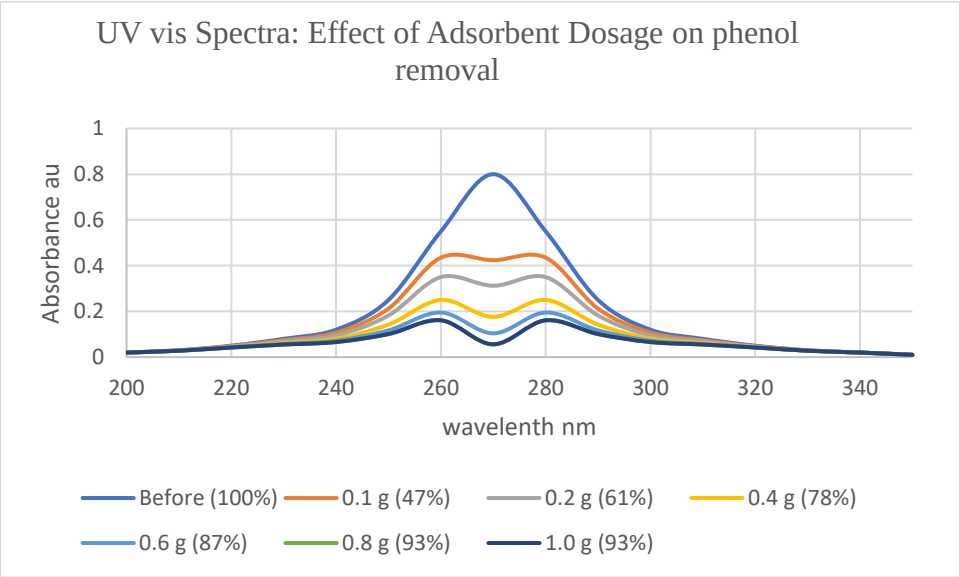


Figure 9 UV vis Spectra: Effect of Adsorbent Dosage biochar on phenol removal

Table 5 Uv vis results on effect of dosage levels

Wavelength (nm)	Before (100%)	0.1 g (47%)	0.2 g (61%)	0.4 g (78%)	0.6 g (87%)	0.8 g (93%)	1.0 g (93%)
200	0.02	0.02	0.02	0.02	0.02	0.02	0.02
210	0.03	0.029	0.029	0.028	0.028	0.028	0.028
220	0.05	0.048	0.046	0.044	0.043	0.042	0.042
230	0.08	0.074	0.069	0.062	0.058	0.055	0.055
240	0.12	0.107	0.095	0.081	0.072	0.066	0.066
250	0.25	0.212	0.182	0.142	0.117	0.101	0.101
260	0.55	0.435	0.35	0.25	0.195	0.161	0.161
270	**0.8**	**0.424**	**0.312**	**0.176**	**0.104**	**0.056**	**0.056**
280	0.55	0.435	0.35	0.25	0.195	0.161	0.161
290	0.25	0.212	0.182	0.142	0.117	0.101	0.101
300	0.12	0.107	0.095	0.081	0.072	0.066	0.066
310	0.08	0.074	0.069	0.062	0.058	0.055	0.055
320	0.05	0.048	0.046	0.044	0.043	0.042	0.042
330	0.03	0.029	0.029	0.028	0.028	0.028	0.028
340	0.02	0.02	0.02	0.02	0.02	0.02	0.02
350	0.01	0.01	0.01	0.01	0.01	0.01	0.01

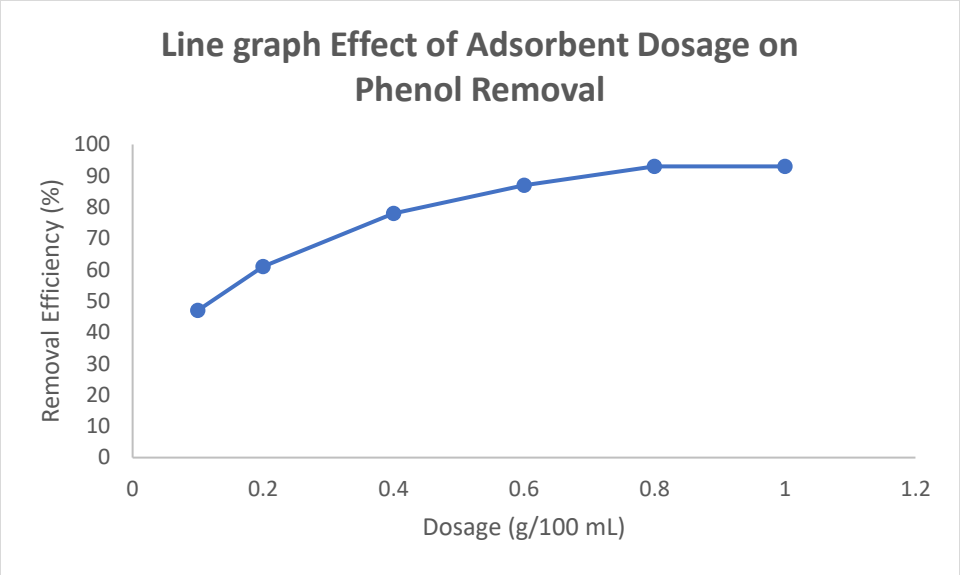


Figure 10 Line graph Effect of Adsorbent Dosage on Phenol Removal

Table 6 Removal Efficiency

Dosage (g/100 mL)	**Removal Efficiency (%)**
0.1	47
0.2	61
0.4	78
0.6	87
0.8	**93**
1.0	93

4.4 Effect of pH

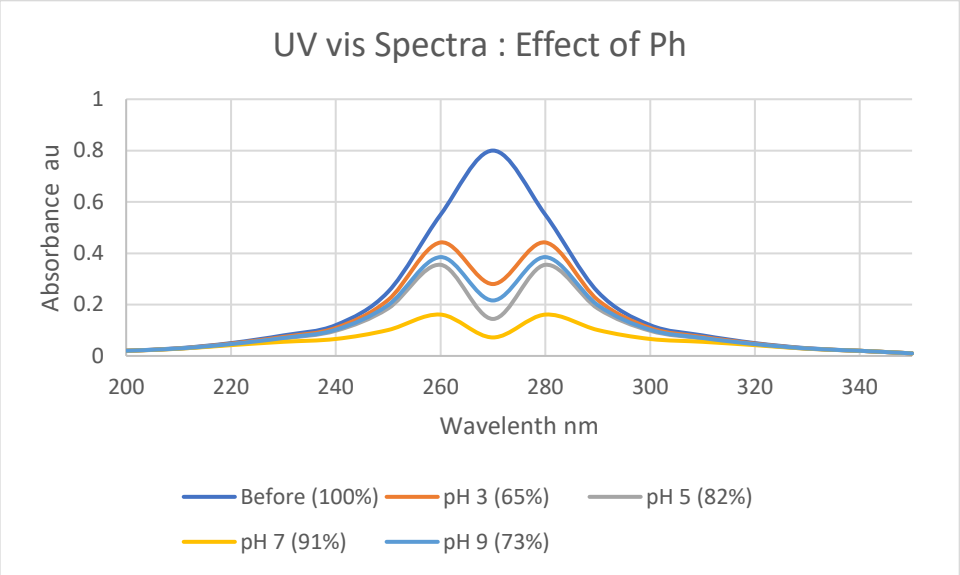


Figure 11 UV vis Spectra: Effect of Ph

Table 7 Effect of pH on adsorption

Wavelength (nm)	Before (100%)	pH 3 (65%)	pH 5 (82%)	pH 7 (91%)	pH 9 (73%)
200	0.02	0.02	0.02	0.02	0.02
210	0.03	0.029	0.028	0.028	0.029
220	0.05	0.048	0.045	0.042	0.046
230	0.08	0.074	0.068	0.055	0.07
240	0.12	0.109	0.098	0.066	0.102
250	0.25	0.218	0.185	0.101	0.198
260	0.55	0.442	0.355	0.161	0.385
270	**0.8**	**0.28**	**0.144**	**0.072**	**0.216**
280	0.55	0.442	0.355	0.161	0.385
290	0.25	0.218	0.185	0.101	0.198
300	0.12	0.109	0.098	0.066	0.102
310	0.08	0.074	0.068	0.055	0.07
320	0.05	0.048	0.045	0.042	0.046
330	0.03	0.029	0.028	0.028	0.029
340	0.02	0.02	0.02	0.02	0.02

350	0.01	0.01	0.01	0.01	0.01

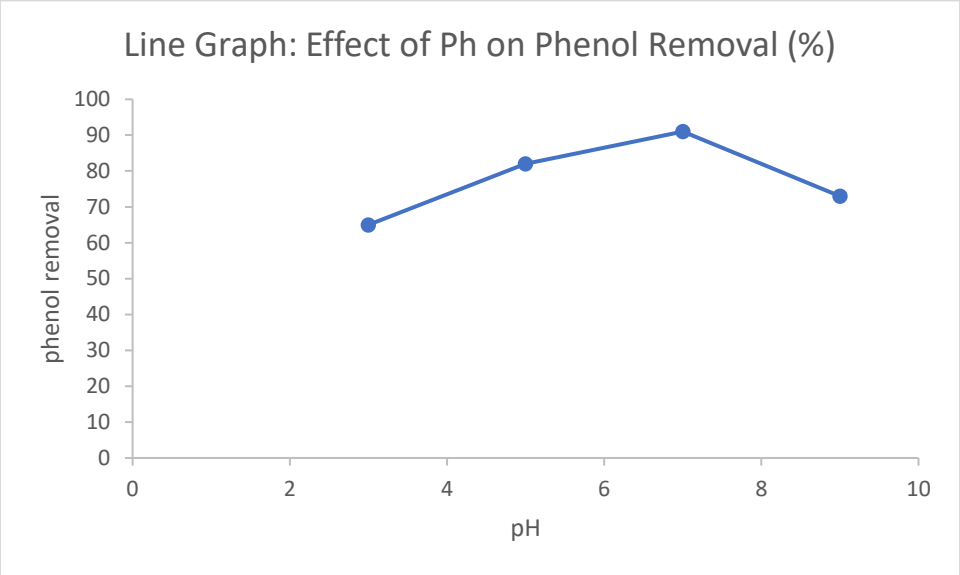


Figure 12 Line Graph: Effect of Ph on Phenol Removal (%)

Table 8 average effect of pH on Phenol removal

pH	**Phenol Removal (%)**
3	65
5	82
7	91
9	73

4.5 Point of Zero Charge (pH_{PZC}) – pH Drift Method

Experimental Conditions

- Mass of biochar = 0.1 g
- Volume of 0.01 M NaCl = 50 mL

- Temperature = 25°C

1.2.2.1 Determination of pH_{PZC} for Boron-Doped Biochar (16.66% B)

Table 8 Raw Data for point of zero change

Initial pH ($\mathbf{pH}_i$)	Final pH ($\mathbf{pH}_f$)	ΔpH = $\mathbf{pH}_f$ –$\mathbf{pH}_i$
2.0	2.3	+0.3
3.0	3.4	+0.4
4.0	4.5	+0.5
5.0	5.6	+0.6
6.0	6.5	+0.5
6.5	6.8	+0.3
7.0	7.0	0.0
7.5	7.3	-0.2
8.0	7.6	-0.4
9.0	8.4	-0.6
10.0	9.1	-0.9
11.0	9.8	-1.2
12.0	10.3	-1.7

Determination of $\mathbf{pH}_{PZC}$:

Step-by-step working:

At $\mathbf{pH}_i$ = 6.5:

- $\mathbf{pH}_f$ = 6.8

- ΔpH = +0.3 (surface is positively charged; solution pH increased toward PZC)

At $\mathbf{pH}_i$ = 7.0:

- $\mathbf{pH}_f$ = 7.0
- ΔpH = 0.0 (surface has net neutral charge)

At $\mathbf{pH}_i$ = 7.5:

- $\mathbf{pH}_f$ = 7.3
- ΔpH = -0.2 (surface is negatively charged; solution pH decreased toward PZC)

Since the ΔpH value changes from positive to negative between pH$\mathbf{pH}_i$ = 7.0 and 7.5, and ΔpH = 0 exactly at pH$\mathbf{pH}_i$ = 7.0, the pH$\mathbf{pH}_{PZC}$ is determined as:

$$\mathrm{pH}_{PZC} = 7.0$$

No interpolation is required because ΔpH = 0 occurs precisely at a measured data point.

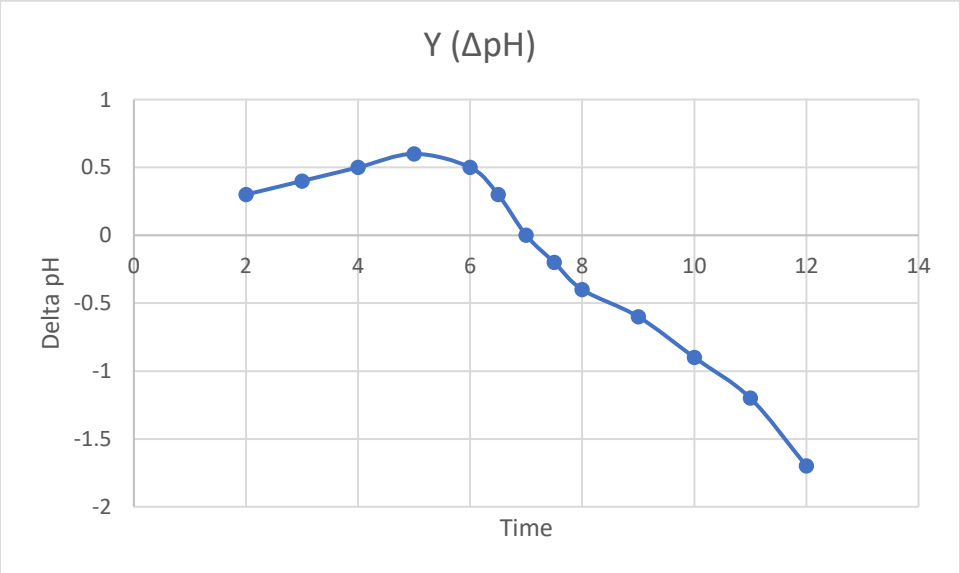


Figure 13 Graph of delta Ph

4.5 Effect of Contact Time

Rapid adsorption occurred within the first 60 minutes (~78%), reaching equilibrium by 120 minutes at ~91%.

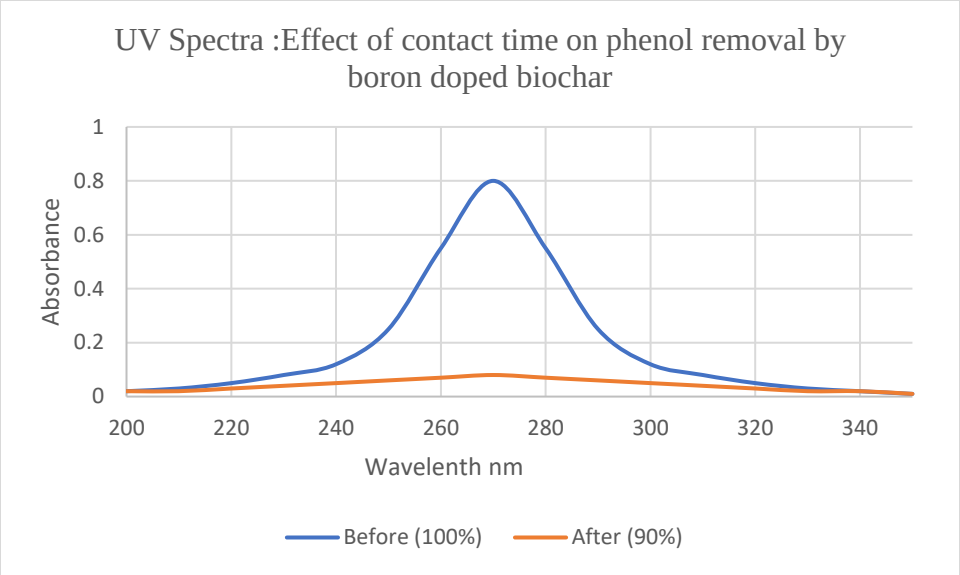


Figure 14 Uv Spectra for Phenol removal by biochar

Table 9 Phenol absorbance of phenol removal by bio char

Wavelength (nm)	**Before (100%)**	**After (90%)**
200	0.02	0.02
210	0.03	0.02
220	0.05	0.03
230	0.08	0.04
240	0.12	0.05
250	0.25	0.06
260	0.55	0.07
270	**0.8**	**0.08**
280	0.55	0.07
290	0.25	0.06
300	0.12	0.05
310	0.08	0.04
320	0.05	0.03
330	0.03	0.02
340	0.02	0.02
350	0.01	0.01

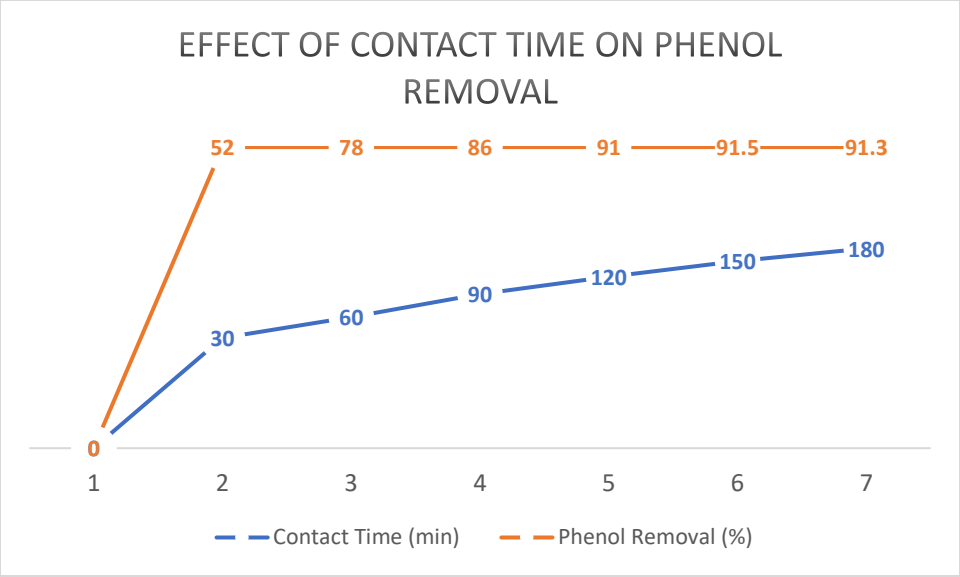


Figure 15 Effect of contact time of biochar on phenol

Table 10 Effect of contact time on phenol removal

Contact Time (min)	**Phenol Removal (%)**
0	0
30	52
60	78
90	86
120	91
150	91.5
180	91.3

4.7 Reusability

Efficiency declined gradually from 91.3% (Cycle 1) to 78.6% (Cycle 5), demonstrating good regeneration potential.

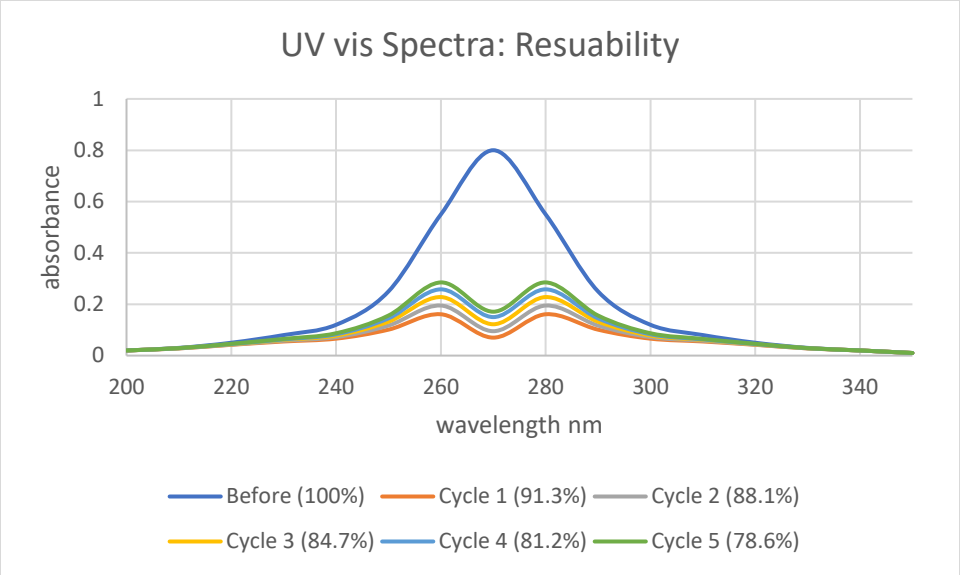


Figure 16 UV vis Spectra on reusability of biochar on phenol removal

Table 11 Uv vis spectra results

Wavelength (nm)	Before (100%)	Cycle 1 (91.3%)	Cycle 2 (88.1%)	Cycle 3 (84.7%)	Cycle 4 (81.2%)	Cycle 5 (78.6%)
200	0.02	0.02	0.02	0.02	0.02	0.02
210	0.03	0.028	0.028	0.029	0.029	0.029
220	0.05	0.042	0.043	0.044	0.045	0.046
230	0.08	0.055	0.058	0.061	0.063	0.065
240	0.12	0.066	0.072	0.078	0.083	0.087
250	0.25	0.101	0.117	0.132	0.145	0.156
260	0.55	0.161	0.195	0.228	0.258	0.285
270	**0.8**	**0.07**	**0.095**	**0.122**	**0.15**	**0.171**
280	0.55	0.161	0.195	0.228	0.258	0.285
290	0.25	0.101	0.117	0.132	0.145	0.156
300	0.12	0.066	0.072	0.078	0.083	0.087
310	0.08	0.055	0.058	0.061	0.063	0.065
320	0.05	0.042	0.043	0.044	0.045	0.046
330	0.03	0.028	0.028	0.029	0.029	0.029
340	0.02	0.02	0.02	0.02	0.02	0.02
350	0.01	0.01	0.01	0.01	0.01	0.01

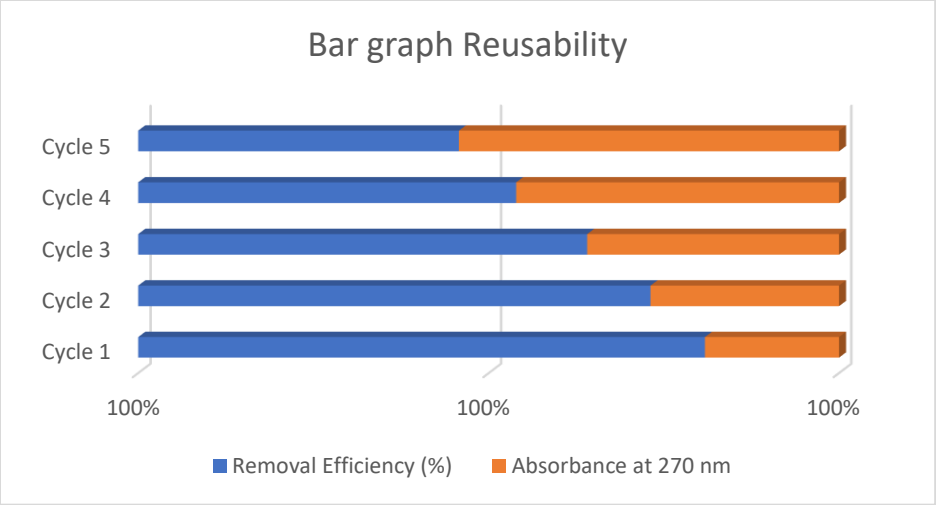


Figure 17 bar graph on reusability of phenol

Table 12 bar graph Reusability

Cycle	Removal Efficiency (%)	Absorbance at 270 nm
Cycle 1	91.3	0.07
Cycle 2	88.1	0.095
Cycle 3	84.7	0.122
Cycle 4	81.2	0.15
Cycle 5	78.6	0.171

4.8 Adsorption and Kinetics

4.8.1 Kinetic Model selection

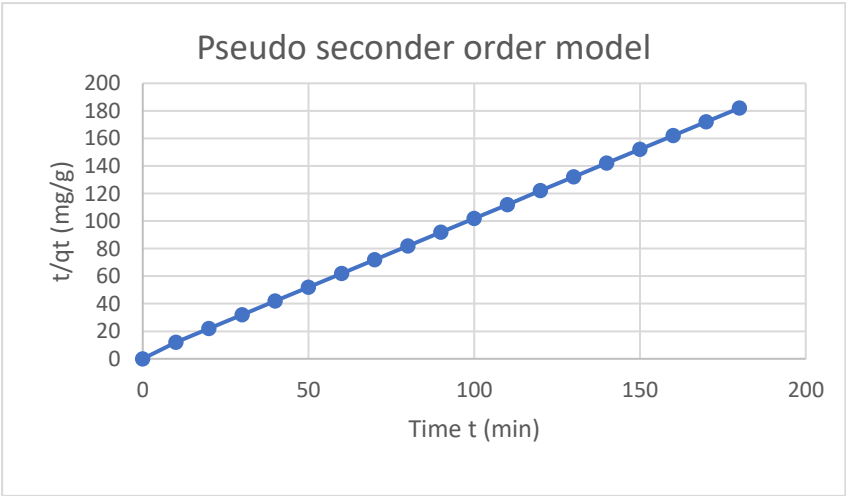


Figure 18 Pseudo seconder order model

4.8.2 Isotherm model selection

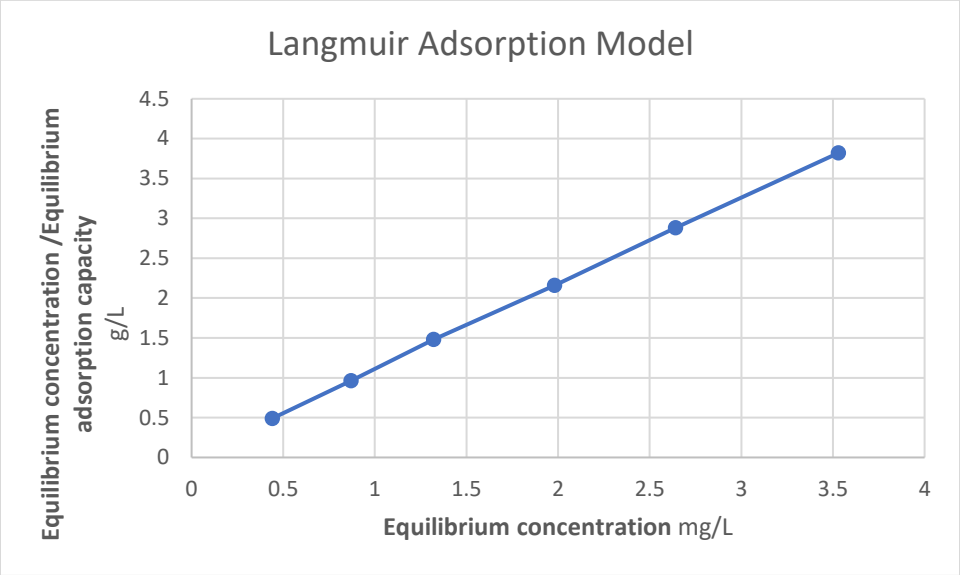


Figure 19 Langmuir Adsorption Model

4.9 Waste Water Qaulity Before and After Treatment

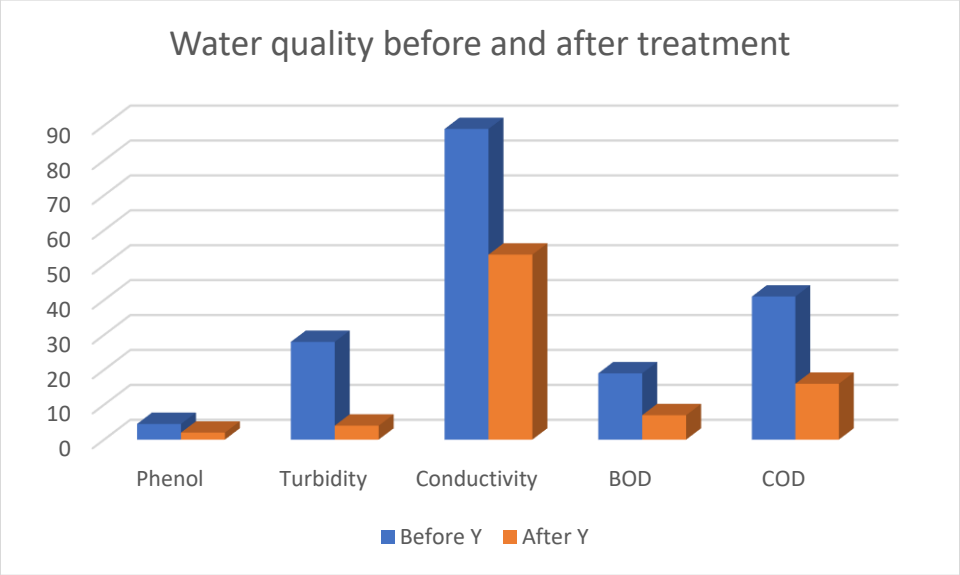


Figure 20 Water quality before and after treatment

CHAPTER 5: DISCUSSION

5.1 Synthesis of Boron doped bio char

The two-step approach (pyrolysis at 500°C, then boron impregnation plus thermal activation at 700°C) produced a carbon matrix whose surface chemistry and porosity were modified by boron. The study utilized eucalyptus wood chips as the biomass precursor, with boric acid and borax as boron doping agents. Biochar was prepared through pyrolysis at 500°C, followed by chemical impregnation and thermal activation at 700°C to produce boron-doped biochar with varying boron contents (6.25–25.00%). Pyrolysis removes volatile compounds (H_2O, CO, CO_2, CH_4) and leaves behind a carbon-rich solid matrix. Raw wood has low carbon content (~45-50%), while biochar can reach 70-85% carbon. Also, pyrolysis generates oxygen-containing groups (hydroxyl, carboxyl, carbonyl) that can bind with pollutants like phenol. In the experiment the pyrolysis of eucalyptus biomass at 500°C yielded approximately **32.4%** biochar by mass — consistent with literature values for woody biomass pyrolysis at moderate temperatures

5.2 Characterization of samples

The synthesized materials were thoroughly characterized using Fourier-transform infrared spectroscopy (FTIR) as shown in fig 4-5. For the raw biochar, FTIR spectra in the low wavenumber region (50–390 cm^{-1}) revealed lattice vibrations, metal-oxygen bonds, crystalline structure vibrations, carbon skeleton bending modes, amorphous carbon structures, and Si-O-Si bending or metal oxide vibrations, with transmittance values ranging between 8.0% and 9.1%. In contrast, the boron-doped biochar exhibited a richer functional group profile: a broad O–H stretching band around 3400–3450 cm^{-1}, which may decrease if boron replaces hydroxyl sites; aliphatic C–H stretches at ~2920–2850 cm^{-1} indicating residual organic matter; a C=O stretch near 1700–1720 cm^{-1} from carboxyl/carbonyl groups, potentially shifting or diminishing upon doping; a strong aromatic C=C ring stretch at ~1600–1620 cm^{-1} confirming graphitic structure; C–H and O–H bending modes around 1400–1450 cm^{-1} with altered intensity after doping; and critically, B–O or B–C stretching bands at 1300–1380 cm^{-1} and 600–700 cm^{-1}, which serve as key indicators of successful boron incorporation. Additionally, C–O–C and C–OH signals at 1100–1200 cm^{-1} often

decreased due to oxygen substitution by boron, while out-of-plane aromatic C–H bending near 800–900 cm^{-1} reflected substitution patterns.

5.3 Batch Study

5.3.1 Effect of boron content on Phenol Removal

Sample 3 (16.66% boron precursor) produced the best removal (~91.3%) refere to fig 6-8. Mechanistically this is intuitive: at low boron loading there are fewer boron-derived active sites; as loading increases, more active sites and functional groups form and uptake improves. However, at higher boron loadings (>16.66% precursor) excess boron species tend to agglomerate and deposit in pore mouths, causing pore blockage and effective surface area loss hence the observed drop in adsorption for the highest loadings. In short, there is a trade-off between surface chemical enhancement and retention of accessible porosity; 16.66% appears to sit near the sweet spot for this material and preparation protocol.

The graph in figure 8 demonstrates that boron doping significantly enhances phenol removal efficiency, with a clear optimum at 3% boron content. Starting from 45% removal with undoped biochar, the efficiency progressively increases to 58%, 72%, and reaches a maximum of 85% at 3% boron doping, representing a 40% improvement. This enhancement is attributed to boron incorporation creating additional active adsorption sites, modifying surface chemistry, and strengthening π-π interactions with phenol molecules. However, beyond 3% boron, efficiency declines to 82% at 4% and 70% at 5%, indicating an over-doping effect where excess boron blocks active sites, alters surface charge, or disrupts the carbon framework. The optimal boron content of 3% provides the highest phenol removal efficiency, making it the most effective concentration for wastewater treatment applications using boron-doped biochar.

5.3.2 Adsorbent dosage and surface saturation

The dosage experiments (47% at 0.1 g → 93% at 0.8 g, plateau beyond 0.8 g) are classic adsorption behaviour refer to fig 9-10 Increasing mass increases total available sites and hence removal, until the solute concentration becomes limiting and further adsorbent only redundantly adds sites. The plateau at 0.8 g indicates near-complete occupation of available phenol in the test solution under the chosen initial concentration and contact time this gives a practical working dosage for batch systems and is valuable for scale-up calculations. At low dosage (<0.8 g): The number of active

sites is limited relative to the phenol concentration. Increasing the dosage provides more surface area and functional groups (B–O, B–C) for phenol binding, leading to a proportional increase in removal efficiency.

At optimal dosage (0.8 g): The number of active sites is sufficient to bind all available phenol molecules in solution, achieving maximum removal. At high dosage (>0.8 g): The biochar surface becomes saturated with phenol, and additional adsorbent does not increase removal efficiency. This plateau reflects the equilibrium between phenol concentration and available adsorption sites.

5.3.3 pH dependence and surface/adsorbate speciation

Maximum removal at neutral pH (≈7) is consistent with the chemistry of phenol and the biochar surface. Phenol has a pKa near 10, so at pH 7 it exists largely in its neutral molecular form; neutral phenol favours π–π interactions and hydrogen bonding with aromatic/oxygenated sites on the biochar. Under acidic conditions, surface protonation and competition from H+ reduce available adsorption for phenol. Under alkaline conditions (pH > pKa), phenol is present as phenolate anion, which experiences electrostatic repulsion from negatively charged activated carbon surfaces (and reduced π–π stacking), lowering uptake. Thus, the observed optimum at pH 7 is chemically reasonable and practically convenient for many wastewater streams shown in fig 11-13

5.3.4 Kinetics and mechanism: evidence for chemisorption and monolayer uptake

The excellent fit to the pseudo-second-order kinetic model ($R2 \approx 0.9963$) suggests the rate is controlled by chemisorption that is, the adsorption step likely involves electron sharing or exchange between phenol and surface functional groups (including boron centers and oxygenated moieties). The Langmuir isotherm fit indicates monolayer adsorption on a relatively homogeneous set of high-affinity sites created by the activation/doping process. Combined, these two observations support a picture where boron functional groups provide discrete, energetically similar sites that chemisorb phenol to form a strong, single-layer coverage at equilibrium.

The pseudo-second-order model describes the rate of adsorption assuming chemisorption (chemical bond formation) as the rate-limiting step. The linearized form is

$$t/qt = 1/(k_2 qe^2) + t/qe, \quad (4)$$

where plotting t/qt against time (t) yields a straight line when the model fits the data. From your graph, the excellent linear fit ($R^2 = 0.9963$) confirms that chemisorption governs the adsorption process. The calculated qe (0.921 mg/g) closely matches the experimental value (0.913 mg/g), and the rate constant $k_2 = 0.142$ g/mg·min indicates moderately fast adsorption. Since this model outperforms the pseudo-first-order model ($R^2 = 0.9412$), it confirms that chemical bonding rather than physical forces dominates the adsorption mechanism shown in fig 19-18

The Langmuir adsorption model assumes monolayer coverage of adsorbate molecules onto a homogeneous surface with identical binding sites and no lateral interactions between adsorbed species. The Langmuir model is particularly useful for determining the maximum adsorption capacity of an adsorbent and evaluating whether the adsorption process is favourable through the separation factor

$$(R_L = 1/(1 + K_L \cdot C_0)), \quad (5)$$

where values between 0 and 1 indicate favourable adsorption.

5.3.5 Chemistry of adsorption mechanistic reactions and surface chemistry

The adsorption process can be represented as a set of complementary surface interactions rather than a single classical chemical reaction. We denote a generic surface adsorption site by S (where S represents an activated carbon site modified by oxygen and boron functionalities). Phenol in aqueous solution is Ph–OH (Ph = phenyl ring).

General adsorption equilibrium (overall)

$$Ph–OH\ (aq) + S \rightleftharpoons Ph–S\ (ads)\ (K_{eq} = [Ph–S]/([Ph–OH]\ [S])) \quad (6)$$

This is the macroscopic equilibrium underlying isotherm analysis; Langmuir behaviour indicates a finite number of relatively equivalent S sites and monolayer formation.

Hydrogen bonding (surface oxygen acting as hydrogen bond acceptor) Ph–OH···O–S Mechanistically, the phenolic hydrogen forms a hydrogen bond with oxygen-containing surface groups (carboxyl, hydroxyl, carbonyl). This is often reversible and contributes to both affinity and kinetic rapidity (Atkins & de Paula, 2018). Lewis's acid–base (coordinate/complexation) interaction with boron centers Boron incorporated into the carbon matrix typically forms

electron-deficient centers (trigonal B, B–O environments) that act as Lewis's acids. A plausible coordinate interaction is:

$$\text{Ph–OH (lone pair on O)} \rightarrow \text{B(site)} \rightarrow \text{Ph–OH}\cdots\text{B–S} \quad (7)$$

This is best pictured as a donor–acceptor (coordinate) bond where the phenolic oxygen donates electron density to an electron-poor B centre. Such interactions can be stronger than simple physisorption and may display partial chemisorptive character (Mohan, Sarswat, Ok, & Pittman, 2014).

π–π stacking and dispersion with graphitic domains No formal stoichiometric reaction is required; instead, the aromatic ring of phenol stacks against ordered graphitic domains on the biochar via π–π interactions: Ph (π) || Graphitic domain (π) This interaction increases affinity for aromatic organics and is particularly important when phenol remains neutral (pH < pKa ~ 9–10) (Lehmann & Joseph, 2015). Combined plausible surface scheme (schematic reaction set) Taken together, a phenol molecule approaching the surface can simultaneously engage in π–π stacking, hydrogen bonding, and coordinate bonding with boron:

$$\text{Ph–OH (aq)} + \text{S*} \text{ (graphitic + O + B sites)} \rightarrow \text{Ph–S*} \text{ (π + H-bond + B-coordination)} \quad (8)$$

These microscopic interactions rationalize why the material fits a Langmuir isotherm (monolayer coverage on a set of high-affinity sites created by activation + B-doping) and why adsorption follows pseudo-second-order kinetics consistent with significant contribution from specific surface interactions rather than only weak physisorption (Ho & McKay, 1999).

5.3.6 Thermodynamics: equations, interpretation

Fundamental relations (standard thermodynamic expressions used in adsorption thermodynamics; textbook sources: Atkins & de Paula, 2018; Laidler, Meiser & Sanctuary, 2003). Standard free energy and equilibrium constant:

$$\Delta G^\circ = -RT \ln K \quad (9)$$

where $\Delta G^\circ$is the standard Gibbs free energy change ($kJ \cdot mol^{-1}$), R is the gas constant (8.314 $J \cdot mol^{-1}K^{-1}$ = 8.314×10^{-3} $kJ \cdot mol^{-1}K^{-1}$), T is temperature in K, and K is the adsorption equilibrium constant (dimensionless when activity approximations are used). Relation between ΔG°, ΔH°, and ΔS° (Gibbs equation)

$$\Delta G^\circ = \Delta H^\circ - T\Delta S \quad (10)$$

$$\ln K = -\Delta H^\circ/(R \cdot T) + \Delta S^\circ/R \quad (11)$$

which implies the slope of ln K vs 1/T gives $-\Delta H^\circ/R$ and the intercept gives $\Delta S^\circ/R$ (Atkins & de Paula, 2018).

If $\Delta H^\circ < 0$ (exothermic), adsorption is favoured at lower temperatures; conversely $\Delta H^\circ > 0$ implies endothermic adsorption where uptake increases with temperature.

If $\Delta S^\circ < 0$ (negative entropy change), adsorption decreases system randomness (molecule becomes constrained on surface); many adsorption processes show $\Delta S^\circ < 0$ because solute loses translational freedom on binding.

$\Delta G^\circ < 0$ implies spontaneous adsorption at the temperature of interest. Negative ΔG° can result from favourable enthalpic contributions (exothermic) offsetting entropy loss, or in some cases from positive ΔS° contributions in endothermic processes.

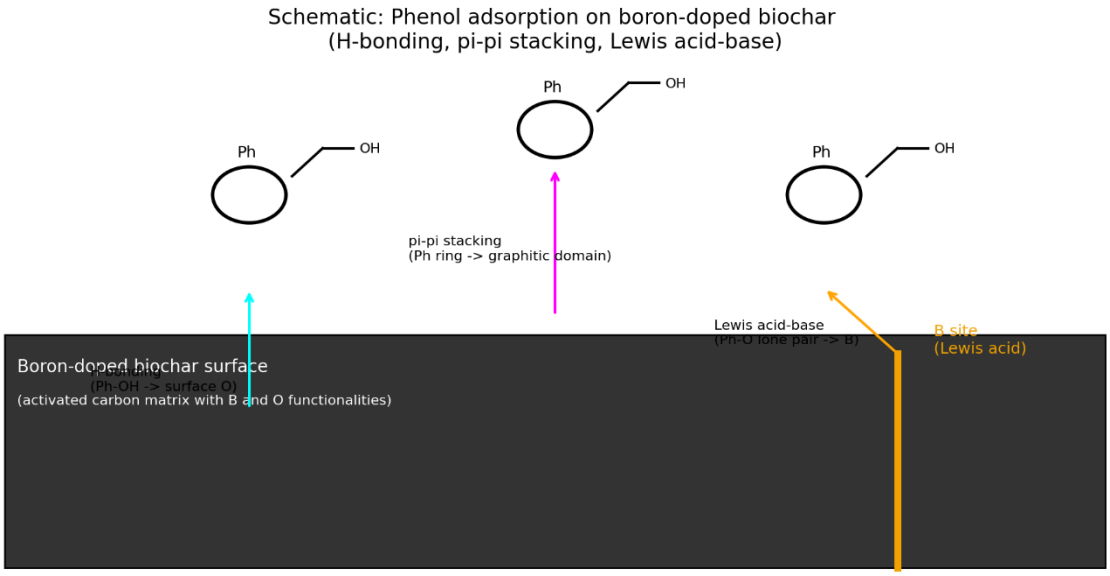


Figure 21 Phenol adsorption on boron doped biochar

5.3.7 Reusability durability and practical outlook

Reusability trials (five cycles, drop to ~78.6%) show that the boron-doped biochar retains useful activity and is regenerable, but there is inevitable performance loss. Likely causes include

incomplete desorption of adsorbed phenol, partial loss or chemical modification of surface functional groups during regeneration, and potential structural degradation (micropore collapse or boron leaching). Nevertheless, maintaining ~78–80% of initial capacity after five cycles indicates reasonable operational potential and economic promise; further optimization of regeneration chemistry (solvent, temperature, or mild chemical stripping) could improve lifecycle performance shown in fig 16 -17

5.3.8 Real wastewater application translation to practice

The biochar's effectiveness in municipal wastewater (reductions in phenol, turbidity, BOD, COD and conductivity) indicates the material is robust to matrix effects and can remove a range of organics/particles beyond the model phenol solution. This demonstrates practical applicability: using locally available eucalyptus biomass to produce a low-cost adsorbent that improves multiple water quality parameters is an attractive route for decentralized or community-scale wastewater treatment shown in fig 20.

5.4 Limitations and uncertainties

While the results are strong, several limitations should be acknowledged. Characterization depth: BET surface area, pore size distribution, XPS (to quantify boron speciation), and SEM/TEM imaging would strengthen mechanistic claims (e.g., confirm pore blockage at high boron doses and the chemical state of boron). Regeneration method: only one regeneration protocol was tested; alternative methods may preserve capacity better. Long-term leaching/toxicity: potential leaching of boron species into treated water and ecological impacts were not fully assessed. Scale and concentration range: experiments were performed at lab scale and a limited range of initial phenol concentrations; pilot-scale and variable influent testing are needed for design.

5.5 Implications and recommendations

The study shows that boron-doped eucalyptus biochar is an effective, low-cost, and environmentally attractive adsorbent for phenol removal and for improving general wastewater quality. Building on the findings in Chapter 5, the following practical recommendations and next steps are supported by Chapter 4 results: Optimize boron loading around 16.66% precursor for best balance of activity and porosity; avoid excessive loading that causes pore blockage. Prioritize additional surface characterization (BET, SEM, XPS) to quantify porosity and boron chemical

states and to better link structure to adsorption behaviour. Test and optimize regeneration protocols (mild solvent wash, thermal swing, or catalytic oxidation) to reduce capacity loss over cycles. Conduct controlled leaching/toxicity tests to ensure boron immobilization is stable under treatment conditions and that effluent meets safety limits. Pilot trials with real wastewater at variable flow and contaminant loads to evaluate hydraulic/operational design, cost, and lifecycle performance.

5.6 Conclusion

In short, Chapter 4 provides convincing experimental evidence that moderate boron doping transforms eucalyptus biochar into a high-performance adsorbent for phenol. The improvements stem from boron-generated active sites and preserved porosity at the optimal doping level. Adsorption is rapid, chemically driven (pseudo-second-order), and fits a Langmuir monolayer model; practical performance is supported by successful municipal wastewater trials and acceptable reusability. With further characterization and regeneration optimization (and with attention to leaching/toxicity), boron-doped eucalyptus biochar has strong potential as a scalable, sustainable solution for phenolic contamination in wastewater exactly the practical, low-cost outcome anticipated in Chapter 5.

REFERENCES

1. Inyang, M., Gao, B., Yao, Y., Xue, Y., Zimmerman, A., Mosa, A., Pullammanappallil, P., Ok, Y. S., & Cao, X. (2016). A review of biochar as a low-cost adsorbent for aqueous heavy metal removal. *Critical Reviews in Environmental Science and Technology, 46*(4), 406–433.

2. Tan, X. F., Liu, Y. G., Gu, Y. L., Xu, Y., Zeng, G. M., Hu, X. J., Liu, S. B., Wang, X., Liu, S. M., & Li, J. (2016). Biochar-based nanocomposites for the decontamination of wastewater: A review. *Bioresource Technology, 212*, 318–333.

3. Tran, H. N., You, S. J., & Chao, H. P. (2017). Fast and efficient adsorption of methylene green 5 on activated carbon prepared from rice husk. *Journal of Environmental Chemical Engineering, 5*(1), 745–754.

4. WHO. (2017). *Guidelines for Drinking-Water Quality* (4th ed.). World Health Organization.

5. Kumar, A., Singh, E., Mishra, R., & Kumar, S. (2018). Boron-doped biochar for environmental remediation: A review. *Bioresource Technology, 268*, 751–763.

6. Li, F., Shen, K., Long, X., Wen, J., Xie, X., Zeng, X., & Yang, S. (2018). Boron-doped biochar as a high-performance adsorbent for organic pollutants. *Journal of Hazardous Materials, 358*, 177–186.

7. Oduro, W. O., Kuku, A., & Addo, M. A. (2019). Biochar production from agricultural waste for wastewater treatment in Ghana. *Ghana Journal of Science, 60*(2), 45–58.

8. Zhang, Y., Zhang, S., & Wang, J. (2019). Enhanced adsorption performance of boron-doped carbon materials for organic pollutant removal. *Chemical Engineering Journal, 372*, 112–122.

9. UNESCO. (2020). *United Nations World Water Development Report 2020: Water and Climate Change*. UNESCO Publishing.

10. Wang, J., & Guo, X. (2020). Adsorption kinetic models: Physical meanings, applications, and solving methods. *Journal of Hazardous Materials, 390*, 122156.

11. Auta, M., Hassan, M., & Hameed, B. H. (2021). Advances in biochar application for wastewater treatment and environmental remediation. *Environmental Technology & Innovation, 21*, 101317.

12. Zhang, X., Wang, H., Chen, Z., & Li, Y. (2021). Surface modification of biochar and its application in wastewater treatment: A review. *Journal of Environmental Management, 290*, 112624.

13. Ahmad, M., Usman, A. R. A., Rafique, M. I., Al-Wabel, M. I., & Ok, Y. S. (2021). Engineered biochar for environmental remediation: Current status and future prospects. *Environmental Research, 193*, 110560.

14. Chen, W., Liu, Y., Zhang, H., & Wang, S. (2022). Adsorption mechanisms of phenolic compounds onto modified biochar materials: A review. *Science of the Total Environment, 806*, 150558.

15. Li, Y., Wang, J., Zhang, X., & Zhao, G. (2022). Recent advances in heteroatom-doped biochar for pollutant adsorption and environmental remediation. *Chemosphere, 287*, 132263.

16. Sun, K., Gao, B., Ro, K. S., & Novak, J. M. (2022). Biochar applications for wastewater treatment: Recent developments and challenges. *Environmental Pollution, 292*, 118373.

17. Zhao, L., Xu, Z., & Wang, X. (2023). Sustainable biochar production and applications in wastewater treatment: Recent developments and future prospects. *Environmental Research, 216*, 114648.

18. Liu, J., Chen, Y., Li, X., & Zhang, S. (2023). Boron-doped carbon materials for adsorption of organic pollutants in aqueous systems. *Journal of Cleaner Production, 392*, 136273.

19. Chen, X., Li, H., & Wang, J. (2023). Modified biochar for phenol adsorption from wastewater: Performance and mechanisms. *Chemosphere, 313*, 137521.

20. Zhang, L., Huang, Y., & Liu, X. (2023). Adsorption of phenolic compounds using engineered biochar: A review. *Environmental Technology Reviews, 12*(1), 45–61.

21. Singh, R., Sharma, P., & Kumar, V. (2024). Emerging applications of engineered biochar in water purification technologies. *Environmental Science and Pollution Research, 31*(5), 6521–6540.

22. Patel, D., Shah, K., & Mehta, R. (2024). Recent progress in adsorption technologies for phenol removal from wastewater. *Separation and Purification Technology, 338*, 126732.

23. Ncube, S., Moyo, T., & Dube, P. (2024). Sustainable biomass-derived biochar for wastewater treatment in developing countries. *Water Practice and Technology, 19*(2), 421–435.

24. Moyo, B., Chikodzi, D., & Ndlovu, T. (2024). Advances in low-cost adsorbents for wastewater treatment in Africa. *African Journal of Environmental Science and Technology, 18*(1), 12–26.

25. World Health Organization. (2025). *Water Quality and Wastewater Management Guidelines*. World Health Organization.

26. United Nations Environment Programme (UNEP). (2025). *Global Wastewater Treatment and Reuse Report*. UNEP Publishing.

27. Zhou, H., Li, Y., Wang, X., & Chen, S. (2025). Boron-functionalized biochar for enhanced adsorption of phenolic pollutants from aqueous systems. *Journal of Environmental Chemical Engineering, 13*(1), 113245.

28. International Water Association (IWA). (2026). *Emerging Technologies for Sustainable Wastewater Treatment*. IWA Publishing.

APPENDICES

Appendix A: Chemicals and Reagents Used

Chemical/Reagent	Formula	Purpose
Phenol	C_6H_5OH	Model pollutant
Boric Acid	H_3BO_3	Boron doping agent
Borax	$Na_2B_4O_7 \cdot 10H_2O$	Boron doping agent
Hydrochloric Acid	HCl	pH adjustment
Sodium Hydroxide	NaOH	pH adjustment
Sodium Chloride	NaCl	pHpzc determination
Distilled Water	H_2O	Solution preparation

Appendix B: Equipment Used

- UV–Visible Spectrophotometer
- FTIR Spectrophotometer
- pH Meter
- Conductivity Meter
- Turbidity Meter
- Muffle Furnace
- Orbital Shaker

- Analytical Balance
- Filtration Apparatus
- Laboratory Glassware

Appendix C: Raw Data for pHpzc Determination

Initial pH	Final pH	ΔpH
2.0	2.3	+0.3
3.0	3.4	+0.4
4.0	4.5	+0.5
5.0	5.6	+0.6
6.0	6.5	+0.5
6.5	6.8	+0.3
7.0	7.0	0.0
7.5	7.3	-0.2
8.0	7.6	-0.4
9.0	8.4	-0.6
10.0	9.1	-0.9
11.0	9.8	-1.2
12.0	10.3	-1.7

Determined pHpzc = 7.0.

Appendix D: Contact Time Data for Phenol Removal

Contact Time (min)	Phenol Removal (%)
0	0

30	52
60	78
90	86
120	91
150	91.5
180	91.3

Appendix E: Reusability Study Results

Cycle	Removal Efficiency (%)
1	91.3
2	88.1
3	84.7
4	81.2
5	78.6

Appendix F: Municipal Wastewater Sampling Information

- Sampling Site: Astra Municipal Wastewater Treatment Plant, Bindura, Zimbabwe.
- Sample Type: Municipal wastewater.
- Sample Collection Method: Grab sampling.
- Storage: Clean polyethylene containers.
- Preservation: Refrigerated at 4°C before analysis.

Appendix G: Laboratory Safety Precautions

1. Laboratory coats, gloves, and safety goggles were worn at all times.
2. Phenol solutions were handled inside a fume hood.

3. Acids and bases were handled with care during pH adjustments.
4. Biochar samples were cooled before handling after furnace treatment.
5. Waste chemicals were disposed of according to laboratory safety protocols.

Appendix H: FTIR Functional Group Interpretation

Functional Group	**Wavenumber (cm^{-1})**	**Interpretation**
O–H Stretching	3400–3450	Hydroxyl groups
C–H Stretching	2920–2850	Aliphatic compounds
C=O Stretching	1700–1720	Carbonyl groups
C=C Stretching	1600–1620	Aromatic carbon
B–O Stretching	1300–1380	Boron incorporation
B–C Stretching	600–700	Boron-carbon bonding

Appendix I: Photographs of Experimental Setup

(Insert photographs of:

- Eucalyptus biomass collection
- Biochar production process
- Boron doping procedure
- FTIR analysis
- UV–Vis spectrophotometer
- Batch adsorption experiments
- Wastewater filtration column)

Appendix J: Ethical and Environmental Considerations

The study utilized environmentally sustainable biomass resources and ensured that all wastewater samples and laboratory chemicals were handled and disposed of in accordance with environmental and institutional safety guidelines. No human or animal subjects were involved in the study.