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CHARACTERIZATION OF FUNCTIONALIZED CARBON DOTS DERIVED FROM BANANA PEELS FOR ENHANCED ADSORPTION OF ANIONIC DYES FROM TEXTILE WASTE WATER.

By

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FINAL YEAR PROJECT PROPOSAL REPORT

CHARACTERIZATION OF FUNCTIONALIZED CARBON DOTS DERIVED FROM BANANA PEELS FOR ENHANCED ADSORPTION OF ANIONIC DYES FROM TEXTILE WASTE WATER

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ABSTRACT

Freshwater contamination from textile effluents remains a major environmental challenge due to the persistence of synthetic reactive dyes. In this study, ethylenediamine-functionalized carbon dots (EDA-CDs) were synthesized via a one-step hydrothermal process using banana peel biomass and evaluated for adsorption of anionic reactive dyes. A full factorial experimental design was employed to investigate the effects of initial dye concentration, adsorbent dosage, and contact time on dye removal efficiency Characterization techniques (FTIR, XRD, and SEM) indicated the formation of amorphous nitrogen-doped carbon nanostructures containing abundant surface functional groups. Adsorption performance reached a maximum removal efficiency of 91.89% under optimized conditions. ANOVA results revealed that contact time was the most significant factor influencing adsorption, followed by initial dye concentration and adsorbent dosage ($p < 0.05$). Kinetic data fitted best with the pseudo-second-order model ($R^2 = 93.4\%$), indicating surface-controlled adsorption, while Langmuir isotherm provided a better equilibrium fit than Freundlich, suggesting monolayer adsorption on homogeneous sites. The study demonstrates that banana peel-derived EDA-functionalized carbon dots are efficient, low-cost, and sustainable adsorbents for reactive dye removal and offer strong potential for wastewater treatment applications.

Keywords: Carbon dots, banana peel, adsorption, ethylenediamine, reactive dyes, wastewater treatment

DECLARATION

I,KICHONCHO FRANCIS, hereby declare that this dissertation entitled "CHARACTERIZATION OF FUNCTIONALIZED CARBON DOTS DERIVED FROM BANANA PEELS FOR IMPROVED ADSORPTION OF ANIONIC DYES FROM TEXTILE WASTE WATER" is my original work and has not been submitted to any institution of higher learning for any academic award.

I further declare that all sources of information used in this study have been duly acknowledged and cited in accordance with accepted academic standards.

KICHONCHO FRANCIS.

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Date: 8/06/2026

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Table of content

Table of tables

Table of figures

CHAPTER 1: INTRODUCTION

1.1 Background of the Study

Freshwater resources are increasingly under pressure due to rapid population growth, industrial expansion, and climate change(Petrosillo et al., 2025). Industrial activities contribute significantly to water pollution, with the textile industry being one of the largest contributors globally(Kuyucu et al., 2025). It is estimated that the textile sector accounts for approximately 17–20% of industrial wastewater pollution worldwide(Ratnam et al., 2023a), mainly due to high water consumption and chemical-intensive dyeing processes Wastewater Treatment.

Textile wastewater typically contains a mixture of synthetic dyes, salts, surfactants, and auxiliary chemicals. Among these, synthetic dyes are of particular concern because even small concentrations (as low as 1 mg/L),(Tolkou et al., 2024) can cause visible coloration of water bodies and significantly reduce light penetration, thereby affecting photosynthetic activity in aquatic ecosystems(Dey et al., 2024). This leads to reduced dissolved oxygen levels and disruption of aquatic life.

Synthetic dyes are broadly classified into cationic, anionic, and non-ionic dyes, depending on their charge properties(Ratnam et al., 2023b). Among these, anionic reactive dyes are the most widely used in cotton and cellulose-based textile dyeing due to their high fiber reactivity, bright coloration, and cost-effectiveness(Kuyucu et al., 2025).

However, these dyes are highly soluble, chemically stable, and resistant to biodegradation due to their complex aromatic structures and sulfonated groups(Kuyucu et al., 2025). As a result, they persist in aquatic environments even after conventional treatment processes.

Conventional wastewater treatment systems(Ratnam et al., 2023a), particularly biological treatment processes, are widely used in textile effluent treatment plants. While these systems are effective in reducing organic load and partial dye removal, they are not efficient in completely degrading synthetic dyes.

This limitation is mainly attributed to the structural stability of reactive dyes, which contain complex aromatic rings and sulfonate functional groups that resist microbial breakdown. Consequently, treated effluents often retain residual dye concentrations ranging from 5–50 mg/L(Kuyucu et al., 2025), depending on the efficiency of the treatment system.

The discharge of such partially treated wastewater into natural water bodies leads to persistent environmental pollution, including reduced water transparency, ecological imbalance(Dey et al., 2024), and potential toxic and carcinogenic effects on aquatic organisms and humans.

Therefore, there is a need for more efficient tertiary treatment technologies capable of achieving higher removal efficiencies for anionic dyes from textile wastewater.

Among advanced wastewater treatment techniques, adsorption has emerged as one of the most effective and economically viable methods for dye removal due to its simplicity, high efficiency, and operational flexibility(Tolkou et al., 2024).

In recent years, research has focused on the development of low-cost, sustainable, and environmentally friendly adsorbents derived from agricultural waste materials(Ratnam et al., 2023a). This approach not only reduces treatment costs but also promotes waste valorization.

Banana peels, which constitute approximately 35–50% of banana fruit mass, are an abundant agricultural waste in many developing countries, including Uganda. They are rich in cellulose, hemicellulose, lignin, and other carbon-rich compounds that provide functional groups suitable for adsorption processes(Kuyucu et al., 2025).

Through controlled carbonization and nanotechnology-based synthesis, banana peel biomass can be converted into carbon dots, which are nanoscale carbon materials (typically <10 nm) characterized by high surface area, good dispersibility, and tunable surface chemistry(Ssebagala & Rwahwire, 2025).

However, unmodified carbon dots often exhibit limited adsorption efficiency due to insufficient active binding sites(Ratnam et al., 2023b). To overcome this limitation, surface modification using ethylenediamine was employed in this study. Ethylenediamine introduces amine ($–NH_2$) functional

groups onto the carbon dot surface(Ssebagala & Rwahwire, 2025), enhancing electrostatic attraction between the adsorbent and negatively charged anionic dye molecules.

This modification significantly improves adsorption performance by increasing active sites, surface polarity, and chemical interaction potential.

Therefore, in this study, ethylenediamine-modified carbon dots derived from banana peels were synthesized and applied for the adsorption of anionic dyes from textile wastewater. The adsorption process was further optimized using statistical experimental design to evaluate the effects of key operational parameters on removal efficiency.

1.2 Problem statement.

Despite the widespread application of conventional wastewater treatment technologies, the removal of anionic reactive dyes from textile effluents remains a persistent environmental challenge. Textile wastewater is typically characterized by high concentrations of synthetic dyes, with reported dye concentrations ranging from approximately 10–200 mg/L(Kuyucu et al., 2025), depending on the dyeing process and operational conditions. Even after conventional biological treatment, residual dye concentrations of 5–50 mg/L may still persist in effluents(Ratnam et al., 2023a), which is significantly above environmentally acceptable levels.

Regulatory discharge standards for colored wastewater are stringent, with many environmental guidelines requiring dye concentrations to be reduced to below 1–5 mg/L or near complete decolorization before discharge into natural water bodies(NER (National Environmental Regulations), 1999). However, conventional treatment systems often fail to achieve these levels due to the high stability, solubility, and complex aromatic structure of anionic reactive dyes, which resist biodegradation. Consequently, inadequately treated effluents continue to be released into aquatic systems, reducing light penetration, disrupting photosynthetic activity, and contributing to long-term ecological toxicity.

In parallel, large quantities of banana peel waste are generated globally, accounting for approximately 35–50% of the total banana fruit mass(Tolkou et al., 2024), and are often disposed of through landfilling or open dumping, contributing to environmental pollution. Although banana peel biomass contains cellulose, hemicellulose, and lignin with potential adsorption sites, its direct

use as an adsorbent is limited by low surface reactivity and poor adsorption efficiency(Dey et al., 2024).

Although carbon dot-based materials derived from biomass have shown promising adsorption performance, there remains limited understanding of how ethylenediamine functionalization improves adsorption capacity toward anionic dyes under multivariable operational conditions(Ssebagala & Rwahwire, 2025). Furthermore, insufficient studies have systematically optimized process parameters and interaction effects using statistical experimental design in systems that mimic real textile wastewater conditions.

Therefore, there is a need to develop a low-cost, efficient, and sustainable adsorbent derived from banana peel waste and enhanced through ethylenediamine modification, capable of achieving high removal efficiency of anionic reactive dyes under optimized conditions that meet environmental discharge standards.

1.3 Main Objective

To synthesize in situ ethylenediamine-functionalized carbon dots from banana peels and evaluate their performance for adsorption of anionic reactive dyes from textile wastewater

1.4 Specific Objectives

1.4.1 To synthesize in situ ethylenediamine-functionalized carbon dots from banana peel powder and determine their physicochemical properties

1.4.2 To investigate the effects of adsorbent dosage, contact time, and initial dye concentration on the adsorption efficiency of anionic reactive dyes.

1.4.3 To model and evaluate the adsorption process.

1.5 Research Questions

i. What are the structural, morphological, and functional properties of the one-step synthesized ethylenediamine-functionalized carbon dots?
ii. How do operational parameters such as adsorbent dosage, contact time, and initial dye concentration influence dye removal efficiency?

iii. What mechanisms govern the adsorption of anionic reactive dyes onto the synthesized functionalized carbon dots?

1.6 Scope of the Study

This study focused on the synthesis of in situ ethylenediamine-functionalized carbon dots derived from banana peels and their application in the adsorption of anionic reactive dyes from aqueous solutions under controlled laboratory conditions.

Batch adsorption experiments were conducted using a three-factor, three-level full factorial design (Montgomery & Al-Mahasneh, n.d.) to evaluate the effects of initial dye concentration, adsorbent dosage, and contact time on dye removal efficiency. The adsorption performance was quantified using UV–Visible spectrophotometry, while statistical analysis was performed using the General Linear Model (GLM) and Analysis of Variance (ANOVA) to determine the significance and interaction effects of the process variables(Montgomery & Al-Mahasneh, n.d.).

In addition, adsorption equilibrium data were analyzed using Langmuir and Freundlich isotherm models, while kinetic data were fitted to pseudo-first-order, pseudo-second-order, and intraparticle diffusion models to describe the adsorption mechanism and rate-controlling steps. The study was limited to batch system operations at laboratory scale and did not extend to pilot-scale or industrial-scale application.

1.7 Significance of the Study

This study is significant because it demonstrates the potential of converting banana peel agricultural waste into ethylenediamine-functionalized carbon dots for dye adsorption from wastewater. The study therefore provides a sustainable approach for simultaneous agricultural waste valorization and treatment of dye-contaminated industrial effluents.

At the national level, the study supports Uganda's Vision 2040 by promoting value addition to agricultural resources and advancing environmentally sustainable industrial practices. The utilization of banana peel waste contributes to waste reduction while enhancing resource efficiency(P, 2013)

The study also contributes to Sustainable Development Goal 6 (Clean Water and Sanitation), particularly Target 6.3, by offering an effective approach for improving water quality through the removal of persistent dye pollutants from wastewater.

In addition, the findings support national environmental policies, including the NRM Manifesto (2021–2026), which emphasizes pollution control and improved effluent treatment. The developed adsorption system provides a practical basis for enhancing compliance with discharge standards(We et al., 2026).

From a scientific perspective, the study contributes to the field of nanomaterial-based adsorption by demonstrating the effectiveness of surface-modified carbon dots and providing insights into adsorption behavior under optimized conditions. The results offer a foundation for future research and potential scale-up for industrial applications.

CHAPTER 2: LITERATURE REVIEW

This chapter reviewed literature on textile wastewater pollution, adsorption technology, biomass-derived carbon dots, surface functionalization, adsorption modeling, and statistical optimization techniques. Previous studies show that anionic reactive dyes remain major environmental pollutants, while many conventional adsorbents are limited by high cost and low efficiency(Yaseen & Scholz, 2019). Biomass-derived carbon dots have emerged as promising sustainable adsorbents, although their performance often requires functional modification(Ssebagala & Rwahwire, 2025). Ethylenediamine functionalization has been reported to enhance adsorption through the introduction of amino-functional groups that improve interactions with dye molecules(Ratnam et al., 2023b). Based on these identified gaps, the present study focuses on the synthesis of ethylenediamine-functionalized carbon dots from banana peels and their application in the adsorption of anionic reactive dyes using kinetic, isotherm, and statistical modeling approaches(Strebel et al., 2024).

2.1 Textile Wastewater and Dye Pollution

2.1.1 Nature of Textile Wastewater

Textile wastewater is among the most complex industrial effluents due to the presence of multiple chemical additives used during dyeing and finishing processes. These include synthetic dyes, salts, surfactants, fixing agents, and dispersants. As a result, textile effluents are typically characterized by high color intensity, elevated chemical oxygen demand (COD), and significant salinity, making them difficult to treat using conventional methods(Yaseen & Scholz, 2019).

Fabric Preparation → Dyeing → Washing → Finishing → Wastewater Discharge

↓

High COD + Dyes + Salts + Chemicals

Figure 2. 1Typical flow of textile wastewater generation and discharge

This wastewater, if discharged untreated, leads to severe environmental degradation of receiving water bodies(Angiro et al., 2020).

2.2 Synthetic Dyes and Their Classification

Synthetic dyes are widely used due to their strong coloration ability, chemical stability, and resistance to fading. They are classified into reactive, acid, basic, direct, vat, and disperse dyes. Among these, reactive dyes are most commonly used in the textile industry due to their ability to form covalent bonds with fibers, especially cotton(Yaseen & Scholz, 2019).

However, their high solubility and aromatic structure make them resistant to biodegradation, resulting in their persistence in wastewater streams.

2.3 Environmental Impacts of Dye Pollution

Even at low concentrations, dyes significantly affect water quality. They reduce light penetration, inhibit photosynthetic activity in aquatic ecosystems, and may produce toxic, mutagenic, or carcinogenic by-products. Consequently, dye pollution poses risks to both aquatic life and human health(Dutta et al., 2021b).

2.4 Adsorption as a Wastewater Treatment Technique

Adsorption is a surface-based separation process in which contaminants accumulate on the surface of a solid adsorbent. It is widely applied in wastewater treatment due to its simplicity, low cost, and high efficiency(Kurnia et al., 2024).

The effectiveness of adsorption depends on factors such as surface area, pore structure, surface chemistry, contact time, initial dye concentration, and pH of the solution(Dey et al., 2024).

Dye molecules in solution

↓

Diffusion to adsorbent surface

↓

Attachment to active sites

↓

Equilibrium adsorption (q_e)

Figure 2. 2Basic adsorption mechanism.

2.5 Carbon Dots (CDs): Emerging Nano adsorbents

2.5.1 Definition and Properties

Carbon dots are nanoscale carbon-based materials with particle sizes typically below 10 nm. They possess unique properties such as high surface area, excellent water solubility, tunable surface chemistry, and strong chemical stability. These characteristics make them suitable for adsorption, sensing, and environmental applications(Tewari et al., 2026a).

2.5.2 Sources of Carbon Dots

Carbon dots can be synthesized from both synthetic and natural precursors. Common sources include citric acid, glucose, urea, and biomass waste materials such as fruit peels, plant leaves, and agricultural residues(Yasin et al., 2025a).

Source Type	**Examples**	**Sustainability**
Synthetic	Citric acid, urea	Low
Biomass	Banana peels, rice husks	High
Industrial waste	Soot, carbon black	Moderate

Table 2-1Common precursors for carbon dot synthesis

2.5.3 Carbon Dots and Biochar

2.5.3.1 Carbon Dots are nanoscale carbon-based materials typically less than **10 nm in particle size**, often reported in the range of **1–10 nm**, depending on synthesis conditions. They are characterized by strong fluorescence emission, abundant surface functional groups, and high water dispersibility. Their nanoscale size results in a high surface-area-to-volume ratio, typically exceeding **100 m²/g in some reported systems**, which enhances their reactivity in adsorption and catalytic applications. They are commonly synthesized through hydrothermal treatment, microwave-assisted synthesis, or mild carbonization of biomass precursors (Rahmat et al., 2016).

2.5.3.2 In contrast, biochar is a bulk carbonaceous material produced through high-temperature pyrolysis of biomass, usually in the range of **300–700°C** under limited oxygen conditions. Biochar particles are typically in the **micrometer to millimeter scale (µm–mm range)** and exhibit a porous structure with surface areas commonly ranging from **10–500 m²/g depending on feedstock and pyrolysis conditions** (Yasin et al., 2025b). It is mainly used in soil amendment, carbon sequestration, and adsorption applications. Although both materials originate from biomass, literature shows clear quantitative and structural differences. Carbon Dots exist at the **nanometer scale (<10 nm)** and exhibit fluorescence due to quantum confinement and surface defect states, whereas biochar exists at the **bulk scale (>10⁴ nm)** and does not exhibit intrinsic fluorescence under UV irradiation. These differences in size and optical properties fundamentally distinguish Carbon Dots from conventional biochar and confirm their classification as nanomaterials rather than bulk carbonized solids (Rahmat et al., 2016).

2.5.4 Synthesis Methods of Carbon Dots

Several methods exist for carbon dot synthesis; Hydrothermal carbonization (most suitable for biomass),Pyrolysis, Microwave-assisted synthesis and Solvothermal synthesis

Among these, hydrothermal carbonization is widely preferred because it is simple, environmentally friendly, and allows simultaneous carbonization and surface functionalization(Ssebagala & Rwahwire, 2025).

Banana peel powder + water + ethylenediamine

↓

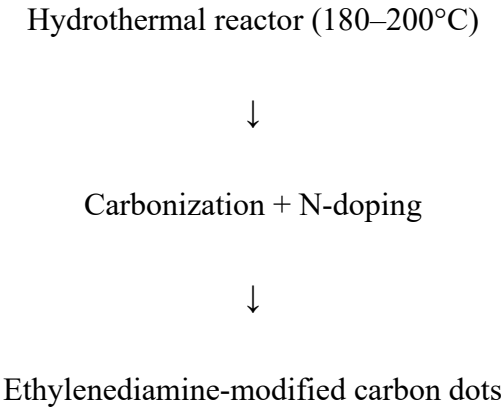


Figure 2. 3Hydrothermal synthesis process of carbon dots

2.5.5 Biomass-Derived Carbon Dots

Biomass materials are increasingly used for carbon dot synthesis due to their abundance, low cost, and sustainability. Banana peels are particularly suitable because they contain cellulose, hemicellulose, lignin, and other carbon-rich compounds(Huzaisham et al., 2020).

In many developing countries, banana waste is generated in large quantities and is often discarded, contributing to environmental pollution. Converting this waste into functional nanomaterials provides both environmental and economic benefits(Yasin et al., 2025b).

2.5.6 Surface Functionalization of Carbon Dots

2.5.6.1 Importance of Functionalization

Unmodified carbon dots often have limited adsorption capacity due to insufficient active sites. Surface functionalization enhances adsorption performance by introducing reactive functional groups(Ratnam et al., 2023a).

2.5.6.2 Ethylenediamine Modification

Ethylenediamine facilitates the introduction of amino ($–NH_2$) functional groups onto the surface of carbon dots during synthesis. These surface functionalities significantly enhance the adsorption performance of the material toward anionic dyes through multiple interaction mechanisms.

Firstly, electrostatic attraction occurs between the protonated amino groups ($–NH_2^+$) on the carbon dot surface and the negatively charged dye ions, promoting strong adsorption affinity. Secondly, hydrogen bonding interactions between the functional groups of the adsorbent and dye molecules further stabilize the adsorption process. Thirdly, surface complexation contributes to additional binding between the adsorbent and dye species, improving overall adsorption capacity(Zhou et al., 2018a)

$CD–NH_2^+ + Dye–SO_3^- \rightarrow$ Electrostatic attraction → Adsorption

Figure 2. 4Interaction between modified carbon dots and anionic dye

This modification significantly enhances adsorption efficiency compared to unmodified carbon dots(Ratnam et al., 2023a).

2.6 Anionic Reactive Dyes

2.6.1 Characteristics

Anionic reactive dyes contain sulfonate ($-SO_3^-$) groups that make them highly soluble in water. They are widely used in textile dyeing due to their strong fiber bonding and bright coloration(Strebel et al., 2024). Common examples include Reactive Black 5, Reactive Blue 19, and Reactive Red 120.

2.6.2 Environmental Impact

These dyes persist in water bodies due to their chemical stability and resistance to biodegradation. Their presence reduces light penetration and disrupts aquatic ecosystems. Even concentrations as low as 1–10 mg/L can cause visible pollution(Yaseen & Scholz, 2019).

2.6.3 Adsorption Mechanisms and Modeling

Adsorption behavior is commonly described using kinetic and isotherm models.

2.6.3.1 Kinetic Models

Adsorption kinetics were evaluated using pseudo-first-order (PFO), pseudo-second-order (PSO), and intraparticle diffusion models to investigate the adsorption mechanism and rate-controlling steps. The pseudo-first-order model is commonly associated with physical adsorption processes in which adsorption occurs through weak intermolecular interactions. In contrast, the pseudo-second-order model is generally used to describe chemisorption mechanisms involving stronger chemical interactions between the adsorbent surface and adsorbate molecules. The intraparticle diffusion model was applied to assess the contribution of pore diffusion and mass transfer processes during adsorption.

2.6.3.2 Isotherm Models

Adsorption equilibrium behavior was analyzed using the Langmuir and Freundlich isotherm models. The Langmuir isotherm model assumes monolayer adsorption occurring on a homogeneous surface with identical adsorption sites and uniform adsorption energies. Conversely, the Freundlich isotherm model describes adsorption on heterogeneous surfaces with non-uniform adsorption energies and possible multilayer adsorption behavior. These models were used to provide insight into the adsorption mechanism, surface characteristics, and interaction behavior between the adsorbent and dye molecules (Ada et al., 2009)(Mafra et al., 2013)

2.7 Statistical Optimization in Adsorption

Modern adsorption studies increasingly employ advanced statistical and experimental design techniques to optimize process conditions and improve the reliability of adsorption models. Commonly applied approaches include full factorial design, General Linear Model (GLM), Analysis of Variance (ANOVA), and Response Surface Methodology (RSM)(Hidayat et al., 2023). These statistical tools enable systematic evaluation of the effects of experimental variables, determination of interaction effects between factors, optimization of adsorption conditions, and development of predictive models for adsorption performance.

Key variables studied include adsorbent dosage, contact time, and initial dye concentration.

Variable	Effect
Dosage	Increases active sites
Contact time	Controls equilibrium
Initial concentration	Driving force for adsorption

Table 2-2key operational variables in adsorption

2.8 Research Gap

Despite extensive research on adsorption technologies for dye removal, several critical gaps remain in existing literature.

Firstly, most studies on carbon dot adsorbents involve multi-step synthesis routes, where carbon dots are first synthesized and then separately modified. This approach increases production cost, introduces additional processing steps, and may reduce surface activity due to post-synthesis treatment limitations(Ratnam et al., 2023b).

Secondly, although biomass-derived carbon dots have been widely reported, banana peel-derived carbon dots remain underexplored, particularly in functionalized forms targeting anionic reactive dyes commonly found in textile wastewater(Yasin et al., 2025a).

Thirdly, many previous adsorption studies have focused on single-variable optimization methods, which fail to capture interaction effects between key operational parameters such as adsorbent dosage, contact time, and initial dye concentration. This limits the predictive reliability of adsorption behavior under real conditions(Bhaumik & Kumar, 2016).

Additionally, several reported studies do not adequately integrate adsorption kinetics, isotherm modeling, and statistical optimization within a single framework, resulting in incomplete mechanistic interpretation of adsorption processes(Kurnia et al., 2024).

Finally, there is limited research on applying one-step hydrothermal functionalization using ethylenediamine, which simultaneously carbonizes biomass and introduces amino functional groups to enhance adsorption performance(Ssebagala & Rwahwire, 2025).

These gaps collectively highlight the need for a more efficient, sustainable, and statistically optimized adsorption system based on functionalized biomass-derived nanomaterials.

2.9 Contribution of the Present Study.

This study directly addresses the identified limitations through the development of a simplified, sustainable, and statistically optimized adsorption system based on ethylenediamine-functionalized carbon dots derived from banana peel waste.

2.9.1 One-Step Green Synthesis Approach

Unlike conventional multi-step procedures, this study adopts a one-step hydrothermal carbonization process, where banana peel powder is simultaneously carbonized and functionalized using ethylenediamine(Ssebagala & Rwahwire, 2025).

This approach eliminates intermediate synthesis stages, reduces chemical consumption, and ensures in-situ incorporation of nitrogen-containing functional groups (-NH_2), which enhances adsorption performance toward anionic dye molecules.

Thus, the study provides a cost-effective and environmentally friendly alternative to conventional carbon dot synthesis routes.

2.9.2 Utilization of Banana Peel Waste as a Sustainable Precursor

This study promotes the valorization of banana peel waste, an abundant agricultural by-product, through its conversion into a functional nano-adsorbent material. By transforming biomass waste into carbon dots with adsorption potential, the study contributes to sustainable waste management and resource utilization.

The conversion of banana peel biomass into functionalized carbon-based nanomaterials supports environmental sustainability through waste reduction and aligns with circular economy principles by converting low-value agricultural residues into value-added products. In addition, the approach offers the potential for low-cost adsorbent production using readily available biomass resources(Yasin et al., 2025b)

Therefore, the study addresses the existing research gap associated with the underutilization of abundant agricultural wastes in the synthesis of functional nanomaterials for wastewater treatment applications.

2.9.3 Enhanced Surface Functionalization for Improved Adsorption

The incorporation of ethylenediamine during the synthesis process facilitates in-situ nitrogen doping and promotes the formation of amino-functionalized carbon dots. The introduction of nitrogen-containing functional groups, particularly amino ($–NH_2$) groups, enhances the surface chemistry and adsorption capability of the synthesized material.

These functional groups improve adsorption performance through several mechanisms, including electrostatic attraction between protonated amino groups ($–NH_2^+$) on the adsorbent surface and negatively charged sulfonate (SO_3^-) groups of anionic reactive dyes. In addition, hydrogen bonding interactions and the increased availability of surface-active sites further contribute to enhanced dye adsorption(Zhou et al., 2018a)

Consequently, the functionalized carbon dots synthesized in this study are expected to exhibit improved adsorption efficiency compared to unmodified carbon dots or carbon materials subjected to post-synthesis surface modification methods reported in previous studies.

2.9.4 Integrated Kinetic, Isotherm, and Statistical Modeling

To overcome the limitations associated with relying on a single analytical model, this study adopted an integrated modeling approach combining kinetic, isotherm, and statistical analyses. Kinetic modeling involved the application of pseudo-first-order (PFO), pseudo-second-order (PSO), and intraparticle diffusion models to investigate adsorption rates and possible rate-controlling mechanisms. In addition, adsorption equilibrium behavior was evaluated using the Langmuir and Freundlich isotherm models to assess surface characteristics and adsorption mechanisms.

Furthermore, statistical optimization and evaluation of experimental variables were performed using General Linear Model (GLM) analysis and Analysis of Variance (ANOVA). These statistical

tools were employed to determine the significance of process variables and their interaction effects on adsorption performance(Hidayat et al., 2023)

The integration of kinetic, isotherm, and statistical modeling provided a more comprehensive mechanistic and predictive understanding of the adsorption process by enabling identification of adsorption rate mechanisms, evaluation of adsorption surface behavior, and assessment of variable interactions influencing dye removal efficiency.

2.10 Application Under Controlled Multi-Variable Conditions

Unlike many previous studies, this research evaluates adsorption performance under a full factorial experimental design, considering adsorbent dosage, Contact time and Initial dye concentration

This allows simultaneous evaluation of individual and interaction effects, improving reliability and real-world applicability of the findings(Montgomery & Al-Mahasneh, n.d.).

2.11 Conceptual Link to the Present Study

Based on the identified research gaps, the present study proposes a novel adsorption approach involving the conversion of banana peel waste into functionalized carbon-based nanomaterials for textile wastewater treatment. The study employed ethylenediamine during the synthesis process as a one-step surface functionalization strategy aimed at enhancing the physicochemical and adsorption properties of the synthesized material.

The resulting functionalized carbon dots were subsequently applied as adsorbents for the removal of anionic reactive dyes from aqueous solutions. To comprehensively evaluate adsorption performance and mechanism, the study employed kinetic, isotherm, and statistical modeling approaches for analysis and interpretation of the adsorption behavior.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter describes the materials, synthesis procedures, adsorption experiments, analytical methods, and statistical analyses used in the study. The methodology focused on the synthesis of ethylenediamine-functionalized carbon dots from banana peels through a one-step hydrothermal carbonization process and their application in the removal of reactive dyes from textile wastewater. A three-factor, three-level full factorial design was employed to evaluate the effects of operational variables on dye removal efficiency(Montgomery & Al-Mahasneh, n.d.).

Previous studies reported limitations associated with high operational costs, simplified single-dye systems, and limited applicability to real industrial wastewater containing mixed reactive dyes. Therefore, this study utilized actual mixed reactive dye wastewater collected from a textile industry to improve practical relevance and adsorption evaluation under realistic conditions(Ratnam et al., 2023a).

The following sections present the experimental procedures and analytical methods used in the study.

3.2 Materials and Equipment

The materials used in this study included fresh banana peels collected locally, ethylenediamine (EDA) as the surface functionalization agent, distilled water, deionized water, and reactive dye samples obtained from a textile industry.

Additional materials used during the study included dialysis tubing with a molecular weight cut-off of 1–3 kDa, 0.22 μm syringe filters, centrifuge tubes, and filter papers. These materials were utilized during purification, filtration, separation, and sample handling processes throughout the synthesis and adsorption experiments.

The equipment used in this study included an electric grinder and mortar and pestle for sample size reduction and homogenization of banana peel biomass. Hydrothermal synthesis was carried out using a hydrothermal autoclave reactor, while separation of suspended particles was achieved using a centrifuge operating at 4000 rpm. A UV–Visible spectrophotometer was used for absorbance measurements and determination of dye concentration during adsorption studies. Mass measurements were performed using an analytical balance with an accuracy of ±0.001 g. Other

laboratory apparatus employed included measuring cylinders and volumetric flasks for accurate preparation and handling of solutions

3.3 Synthesis of Ethylenediamine-Functionalized Carbon Dots

3.3.1 Raw Material Preparation

Fresh banana peels were collected and washed thoroughly with distilled water to remove dirt and surface impurities.

The cleaned peels were spread under sunlight and dried for approximately two weeks until constant weight was achieved to ensure adequate moisture removal.

Figure 3. 1Fresh Banana Peels Before Drying

3.3.2 Size Reduction

The dried banana peels were initially crushed using a mortar and pestle to obtain coarse particles.

The coarse particles were then ground using an electric grinder for approximately one day to obtain fine banana peel powder.

Fine particle size was necessary to increase surface area and improve hydrothermal carbonization efficiency.

*Figure 3. 2**Crushed** Banana Peels*

3.3.3 Hydrothermal Synthesis

A mass of 24.43 g of banana peel powder was mixed with 250 mL of deionized water in a reaction vessel.

Approximately 4 mL of ethylenediamine was then added as the nitrogen-containing surface functionalization agent.

The mixture was stirred thoroughly using a laboratory stirrer at approximately 250 rpm for 20 minutes to ensure homogeneous dispersion before transfer into a Teflon-lined autoclave reactor.

The hydrothermal synthesis of the carbon-based adsorbent was carried out under controlled conditions, with the reaction maintained at a temperature of 200°C for a duration of 8 hours. These conditions were selected to ensure adequate carbonization, polymerization, and structural development of the biomass precursor into a stable carbonaceous material suitable for adsorption applications.

After completion of carbonization, the reactor was allowed to cool naturally to room temperature (approximately 25 ± 2°C).

Because the yield per batch was relatively small, the synthesis process was repeated five times to obtain sufficient adsorbent for characterization and adsorption experiments.

Banana peel powder + water + ethylenediamine

↓

Hydrothermal reactor (180–200°C)

↓

Carbonization + N-doping

↓

Ethylenediamine-modified carbon dots(Ssebagala & Rwahwire, 2025)

Figure 3. 3Hydrothermal Carbonization Process

3.4 Purification of Carbon Dots

3.4.1 Filtration

The synthesized suspension was filtered using a 0.22 µm syringe filter to remove large carbonaceous particles and impurities.

3.4.2 Dialysis

The filtered solution was transferred into dialysis tubing with molecular weight cutoff of 1–3 kDa and dialyzed against distilled water for 12 hours to remove residual impurities and unreacted chemicals.

3.4.3 Drying and Storage

The purified carbon dot solution was sun-dried to obtain solid ethylenediamine-functionalized carbon dots.

Approximately 17 g of dried modified carbon dots were obtained after purification and drying.

The dried material was stored in clean airtight containers for subsequent adsorption studies.

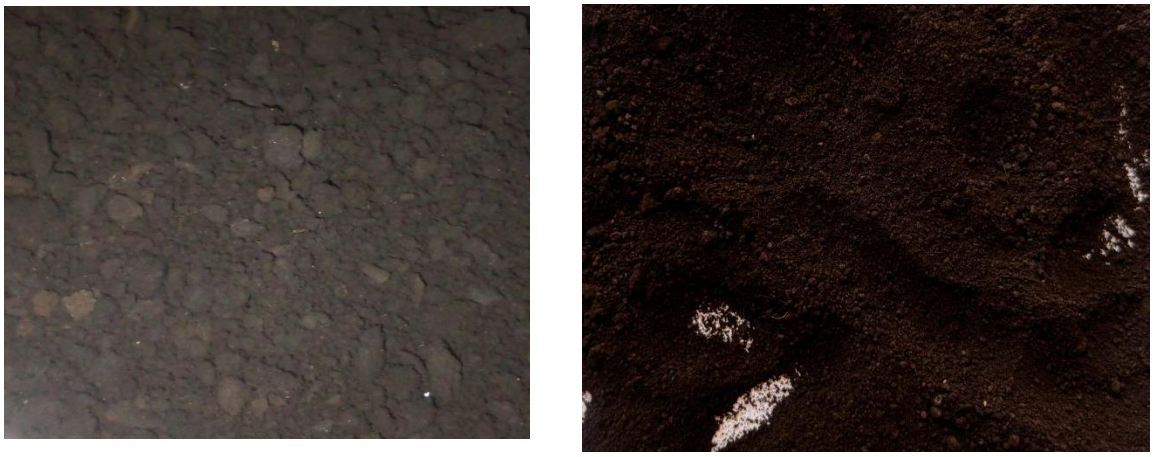


Figure 3. 4 Purified Carbon Dot Solution After Dialysis

Figure 3. 5Dried Ethylenediamine-Functionalized Carbon Dots

3.5 Characterization of Synthesized Ethylenediamine-Functionalized Carbon Dots.

3.5.1 SEM Characterization Methodology

The surface morphology of the synthesized adsorbent material was examined using Scanning Electron Microscopy (SEM). Prior to analysis, the dried sample was finely ground and mounted onto an SEM specimen stub using conductive carbon tape. To improve conductivity and minimize charging effects during imaging, the sample was coated with a thin conductive layer where necessary(Dutta et al., 2021b).

SEM imaging was performed at a magnification of 500× with a scale bar of 100 µm to evaluate the general surface texture, porosity, and morphological features of the synthesized carbonaceous material. The analysis focused on identifying structural characteristics such as surface roughness, pore distribution, particle aggregation, and overall surface heterogeneity relevant to adsorption applications(Strebel et al., 2024).

Due to the relatively low magnification employed, the SEM analysis was not intended for direct visualization or size determination of individual carbon dots, whose dimensions are typically below 10 nm. Instead, the technique was used to assess the bulk surface morphology and aggregated carbonaceous structures formed during hydrothermal synthesis and drying(Ssebagala & Rwahwire, 2025). Therefore, SEM observations were interpreted as indicative of the overall

textural and morphological properties of the synthesized adsorbent material rather than discrete nanoscale carbon dots.

For precise nanoscale characterization and confirmation of carbon dot size and morphology, higher-resolution techniques such as Transmission Electron Microscopy (TEM) would be more appropriate(Ratnam et al., 2023a).

3.5.2 Fourier Transform Infrared (FTIR) Analysis

Fourier Transform Infrared (FTIR) spectroscopy was used to identify the functional groups present on the surface of the synthesized ethylenediamine-modified carbon dots. The analysis was performed over a wavenumber range of 4000–500 cm^{-1}. The sample was scanned in transmittance mode to detect characteristic absorption bands corresponding to surface functional groups introduced during hydrothermal synthesis and amine modification(Ssebagala & Rwahwire, 2025).

3.5.3 Ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) analysis was conducted to determine the crystalline or amorphous nature of the synthesized ethylenediamine-modified carbon dots. The powdered sample was analyzed using an X-ray diffractometer operating with Cu-Kα radiation (λ = 1.5406 Å). The scan was performed over a 2θ range of approximately 3° to 90° at a scanning speed of 0.02°/min.

The diffraction pattern obtained was used to identify structural ordering, crystallite formation, and degree of graphitization of the carbon-based material(Tewari et al., 2026a).

3.6 Collection and Preparation of Reactive Dye Samples

Reactive dye samples were collected from Fine Spinners Uganda Ltd.

Four commonly used textile reactive dyes were selected because they represent industrial dye formulations used during cotton processing.

The dyes were identified based on observed color, commercial naming, and reactive functional groups.

Observed Color	Dye Name	Type	Functional Group
Yellow	Indofix Yellow WHE 4G/Yellow 3GL	Reactive	MCT / VS
Red/Orange	REM BR/Reactive	Reactive	VS / MCT–VS
Green/Turquoise	REM Turq GN 266%	Reactive	VS-based
Black/Dark	Removal Royal RGB	Reactive	MCT–VS

Table 3-1Reactive Dyes Used in the Study

Table 3-2Reactive Dyes Used in the Study

The selected dyes are known for their resistance to biodegradation and persistence in textile wastewater systems.

3.6.1 Justification for Dye Mixing Ratios

The dye mixing ratios used in this study were selected to simulate conditions commonly observed in textile wastewater, where different dyes are usually discharged together rather than individually. Mixed dye systems were therefore considered more representative of real industrial effluents than single-dye solutions (Yaseen & Scholz, 2019).

The selected proportions were intended to ensure that each dye was sufficiently present in the solution to allow proper evaluation of adsorption performance and competitive adsorption effects between dye molecules. The mixing ratios also enabled assessment of the ability of the synthesized Carbon Dots to remove multiple dyes simultaneously under realistic wastewater conditions.

In addition, the selected ratios were guided by previous adsorption studies involving mixed dye systems and reactive dyes in aqueous solutions(Arslantaş et al., 2022; Ratnam et al., 2023a). Preliminary experimental observations, including solution stability and measurable absorbance responses, were also considered before selecting the final dye proportions for adsorption experiments.

Therefore, the dye mixing ratios were scientifically selected to provide reliable evaluation of adsorption efficiency under simulated textile wastewater conditions rather than being chosen arbitrarily.

3.6.2 Preparation of Reactive Dye Solutions

A mixed dye stock solution was prepared by weighing 0.5 g of each reactive dye to obtain a total dye mass of 2.0 g.

The combined dyes were transferred into a 1 L volumetric flask and dissolved in distilled water to obtain a stock solution concentration of 2000 mg/L.

Working dye solutions were prepared at three different concentrations, namely 20 mg/L, 60 mg/L, and 100 mg/L, by appropriate serial dilution of the stock dye solution. This ensured accurate control of initial concentration levels for evaluating their effect on adsorption performance under batch experimental conditions.

The mixed dye system was used to simulate real textile wastewater conditions more realistically than single-dye adsorption systems(Ratnam et al., 2023b).

Figure 3. 6Mixed Reactive Dye Stock Solution

3.7 Experimental Design for Adsorption Studies

Adsorption experiments were conducted using a three-factor, three-level full factorial design (3^3)(Montgomery & Al-Mahasneh, n.d.).

The adsorption study considered three independent variables that were systematically varied to evaluate their influence on dye removal efficiency. These variables included the initial dye concentration, which determines the availability of adsorbate molecules in solution; the adsorbent dosage, which reflects the amount of active adsorption sites available for interaction; and the contact time, which governs the duration available for adsorption equilibrium to be established.

These parameters were selected because they are key operational factors that directly influence adsorption capacity, rate, and overall removal efficiency in batch adsorption systems.

Factor	Levels		
Dye concentration(mg/l)	20	60	100
Adsorbent dosage(g/l)	0.1	0.3	0.5
Contact time(min)	60	90	150

Table 3. 1Experimental Factors and Levels

The adsorption experiments were conducted under carefully controlled laboratory conditions to ensure consistency and reliability of the results. The initial pH of the dye solution was maintained at 7.2 to simulate near-neutral aqueous conditions commonly found in natural and industrial effluents. All experiments were performed at room temperature (25 ± 2°C) to minimize the influence of temperature variations on adsorption behavior.

During the adsorption process, the dye solutions were agitated at a constant speed of 250 rpm to enhance mass transfer between the adsorbate and adsorbent and to ensure uniform mixing. After the adsorption equilibrium was reached, the mixtures were separated using centrifugation at 4000 rpm for 5 minutes to efficiently remove the adsorbent particles from the solution prior to analysis.

These controlled operational parameters were selected to provide stable experimental conditions for evaluating the adsorption performance and to ensure reproducibility of the results.

3.8 Batch Adsorption Procedure

A total of 27 experimental runs were conducted according to the factorial design.

In each experiment:

100 mL of dye solution was transferred into a beaker.

A predetermined mass of carbon dots was added according to the required dosage.

The mixture was agitated at 250 rpm using a laboratory shaker.

The adsorption process was allowed to proceed for the specified contact time

The pH of all adsorption experiments was maintained at approximately 7.2 throughout the study.

After adsorption, the suspension was centrifuged at 4000 rpm for 5 minutes to separate adsorbent particles from solution.

The supernatant was then collected for UV–Visible spectrophotometric analysis.

Figure 3. 7Batch Adsorption Experimental Setup

3.9 UV–Visible Spectrophotometric Analysis

Residual dye concentration was determined using a UV–Visible spectrophotometer.

The maximum absorbance wavelength (600 λmax) for the mixed reactive dye solution was first determined experimentally and used throughout all absorbance measurements.

Standard dye solutions of known concentrations were prepared to establish the calibration curve(Hidayat et al., 2023).

The calibration regression equation obtained was:

Equation 3.1

Equation . 3-1

Ao (Absorbance) = 0.01291 + 0.003227C

Where:

Ao = absorbance

C = dye concentration (mg/L)

The calibration model showed excellent linearity with:

The calibration model showed excellent linearity with:

- $R^2 = 99.4\%$
- Adjusted $R^2 = 99.3\%$
- $p < 0.001$ indicating strong correlation between absorbance and concentration.

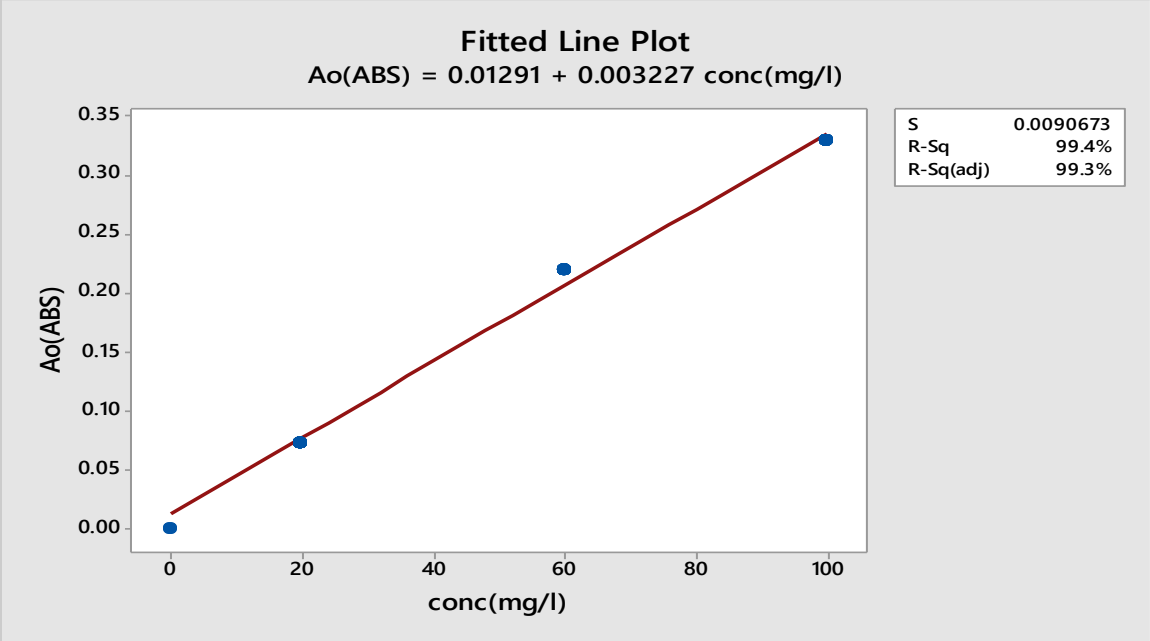


Figure 3. 8UV–Visible Calibration Curve

3.9.1 Determination of Percentage Dye Removal

Percentage dye removal was calculated using Equation 3.2.

Equation 3. 3-2

$$\%\text{Removal} = \frac{C_0 - C_t}{C_0} \times 100$$

Where:

Co = initial dye concentration (mg/L)

Ct= final dye concentration after adsorption (mg/L)

Following calibration, the validated Minitab regression model was used to convert absorbance data into concentration values (Ct), which were then used to compute adsorption parameters such as percentage removal and equilibrium adsorption capacity (q_e). These processed outputs were then exported within Minitab and used as input data for further statistical evaluation(Strebel et al., 2024).

A factorial experimental design (General Linear Model) was subsequently performed in Minitab to evaluate the effects of contact time, initial concentration, and adsorbent dosage on adsorption performance. This allowed simultaneous analysis of main effects and interaction effects using statistically processed response data(Hidayat et al., 2023).

3.9.2 Determination of Adsorption Capacity

Adsorption capacity was calculated using Equation

equation 3. 3-3

$$q_t = \frac{(\mathrm{C0} - \mathrm{Ce})\mathrm{V}}{\mathrm{m}}$$

Where:

- q_t= adsorption capacity (mg/g)
- V= solution volume (L)
- m= adsorbent mass (g)(Tolkou et al., 2024)

Optimization of the adsorption process was achieved directly through the Full Factorial Design (FFD) framework. All possible combinations of the selected factors were experimentally evaluated, and the adsorption performance was measured in terms of percentage dye removal and adsorption capacity.

Unlike Response Surface Methodology (RSM), no predictive quadratic model was developed. Instead, optimization was based on direct comparison of experimental outcomes obtained from the factorial runs. The optimum conditions were identified as the specific combination of factor levels that produced the highest observed dye removal efficiency (Dey et al., 2024; Hidayat et al., 2023).

To ensure methodological rigor, analysis of variance (ANOVA) was applied to determine the statistical significance of main effects and interaction effects. This helped to confirm which factors had a meaningful influence on adsorption performance and ensured that the identified optimum conditions were statistically supported rather than randomly obtained (Bhaumik & Kumar, 2016; Montgomery & Al-Mahasneh, n.d.).

3.10 Adsorption Isotherm Modelling

Adsorption equilibrium data were analyzed using Langmuir and Freundlich isotherm models.

3.10.1 Langmuir Isotherm Model.

equation 3. 3-4

$$\frac{\mathrm{Ce}}{q_e} = \frac{1}{q_{\max}} + \frac{1}{K_L q_{\max}} \cdot$$

3.10.2 Freundlich Isotherm Model

equation 3. 3-5

$$\log\ q_e = \log\ K_f + \frac{1}{n} \log\ C_e$$

3.11 Adsorption Kinetic Modelling

Adsorption kinetics were evaluated using three commonly applied models: the pseudo-first-order model, pseudo-second-order model, and intraparticle diffusion model. These models were employed to understand the adsorption rate mechanism and to identify the potential rate-controlling steps governing the uptake of the adsorbate. The pseudo-first-order and pseudo-second-order models were used to describe the overall adsorption kinetics, while the intraparticle diffusion model was applied to assess whether diffusion within the pores of the adsorbent contributed significantly to the rate-limiting process.

3.11.1 Pseudo-First-Order Model

equation 3. 3-6

$$\ln (q_e - q_t) = \ln\ q_e - K_1 t$$

3.11.2 Pseudo-Second-Order Model

equation 3. 3-7

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e}$$

3.11.3 Intraparticle Diffusion Model

equation 3. 3-8

$$q_t = (kid) + \sqrt{t} + C$$

3.12 Statistical Analysis

Experimental data were analyzed using Minitab statistical software. Analysis of variance (ANOVA) and the General Linear Model (GLM) were employed to evaluate the main effects and interaction effects of the selected adsorption variables, as well as to determine their statistical significance. The adequacy of the model was assessed using the coefficient of determination (R^2), adjusted R^2, and predicted R^2, together with diagnostic tools such as residual plots and normal probability plots to verify model assumptions. In addition, the variance inflation factor (VIF) was used to assess multicollinearity among the independent variables. Statistical significance was determined at a 95% confidence level, corresponding to a significance level of $p < 0.05$

3.12.1 Justification for Full Factorial Design

A Full Factorial Design (FFD) was selected in this study because several experimental factors, including pH, contact time, adsorbent dosage, and dye concentration, were expected to influence dye adsorption simultaneously. FFD is suitable because it enables evaluation of both the individual effects of each factor and the interaction effects between variables within the same experiment. This approach is widely applied in adsorption and process optimization studies because interactions between variables can significantly influence system performance.

The design was preferred over fractional factorial design because fractional designs reduce the number of experimental runs by omitting some factor combinations, which may result in loss of important interaction information and reduced prediction accuracy. In contrast, FFD evaluates all possible combinations of factors and levels, thereby improving the reliability, reproducibility, and statistical validity of the experimental results (Montgomery & Al-Mahasneh, n.d.).

Response Surface Methodology (RSM) was not selected as the primary optimization tool because the major objective of this study was first to identify and understand the significant factors influencing adsorption performance before developing advanced predictive models. RSM is generally more suitable for detailed process optimization after significant variables have already been identified ((Zhou et al., 2018b) Therefore, FFD provided a simpler, systematic, and more appropriate approach for evaluating adsorption conditions in this study.

Optimization was achieved by conducting experiments generated from the factorial matrix and analyzing the results using analysis of variance (ANOVA) to determine the factors and interactions that significantly affected dye removal efficiency. The optimum conditions were selected based on the highest percentage dye removal and adsorption capacity obtained experimentally.

3.13 Safety and Study Limitations

Laboratory safety procedures were strictly observed throughout the study.

Personal protective equipment including gloves and laboratory coats was used during chemical handling and hydrothermal synthesis procedures.

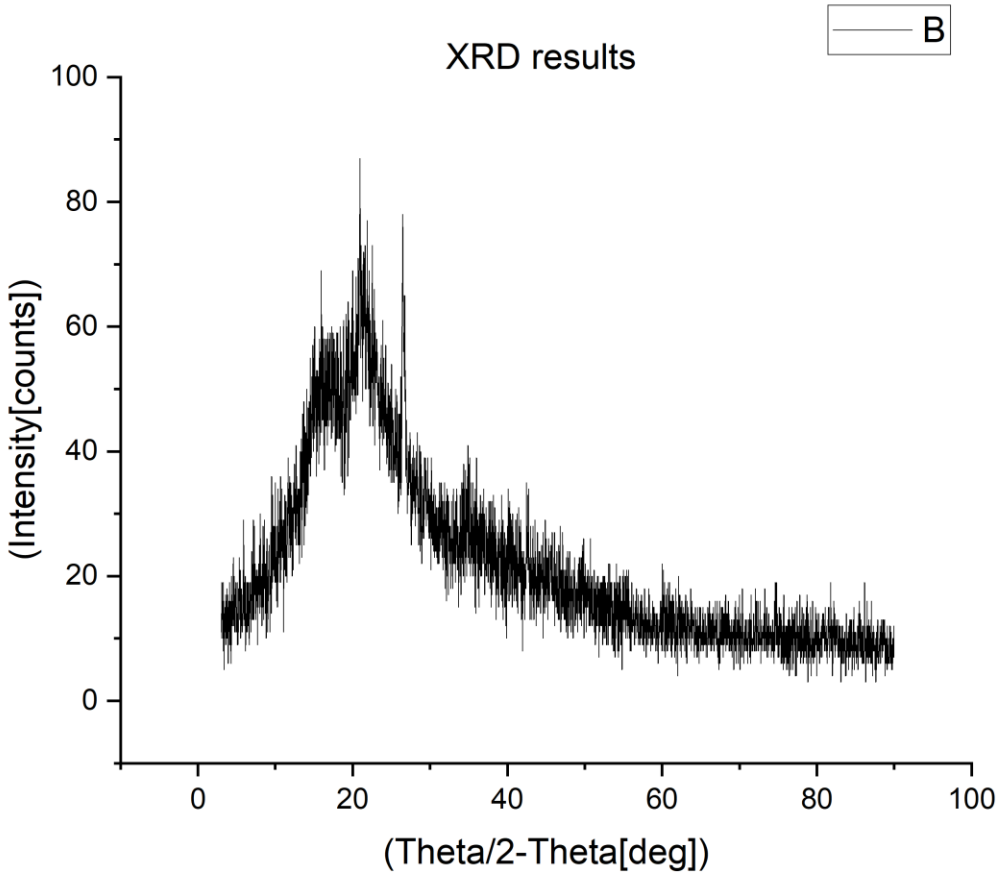
Chemical wastes were disposed according to laboratory safety guidelines.

The study was limited by restricted access to advanced characterization equipment and occasional power interruptions during experimental work. However, all experiments were repeated carefully to ensure reliability and reproducibility of results.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Structural Properties (XRD Analysis)

The XRD pattern of the synthesized ethylenediamine-modified carbon dots shows a broad and diffused peak centered approximately around $2\theta \approx 20°–25°$, with no sharp diffraction peaks observed.



This broad peak indicates that the material is predominantly **amorphous or weakly graphitized carbon**, which is characteristic of carbon dots synthesized from biomass precursors. The absence of sharp peaks confirms that no well-defined crystalline phases are present, consistent with biomass-derived carbon nanostructures reported in recent studies(Ssebagala & Rwahwire, 2025)

The slight broadening of the peak can be attributed to nanoscale particle size effects (quantum confinement), which typically lead to peak widening in nanomaterials due to limited crystal

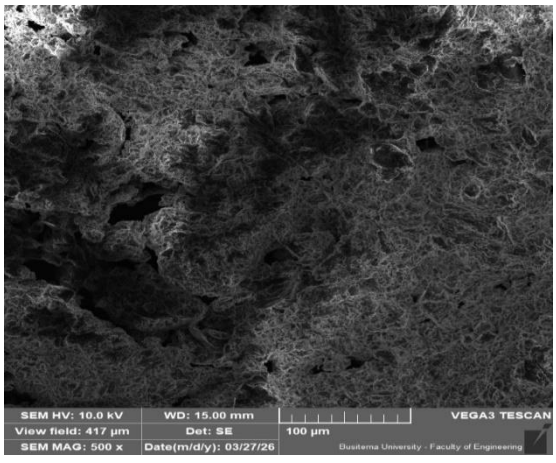
domain dimensions. In addition, structural disorder introduced during hydrothermal carbonization contributes to reduced crystallinity and increased lattice imperfections, further broadening the diffraction peak(Dutta et al., 2021a)

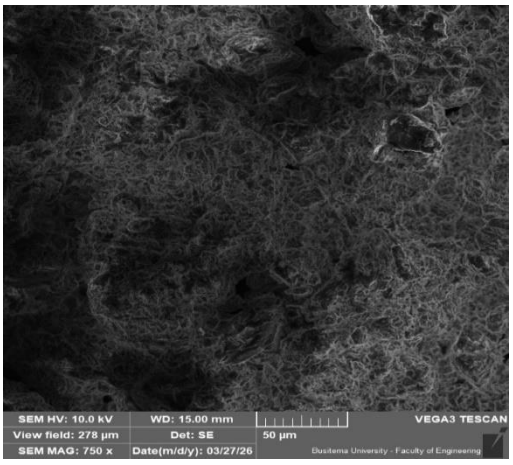
Furthermore, surface functionalization with ethylenediamine groups may induce strain and disrupt regular lattice ordering at the particle surface, enhancing the observed peak broadening. These nitrogen-containing functional groups ($–NH_2$) interfere with long-range carbon ordering, resulting in reduced crystallinity but improved surface reactivity and active adsorption sites, which is advantageous for dye uptake applications(Strebel et al., 2024).

These functional groups ($–NH_2$) likely disrupt long-range carbon ordering, contributing to reduced crystallinity but enhanced surface reactivity, which is beneficial for adsorption performance.

Overall, the XRD results confirm the successful formation of amorphous carbon-based nanomaterials with disordered graphitic domains, which is consistent with reported characteristics of biomass-derived carbon dots and functionalized nanocarbon adsorbents (Tewari et al., 2026a)

4.1.1 This is a Scanning Electron Microscopy (SEM) micrograph of your synthesized ethylenediamine-functionalized carbon dots/biomass-derived material.





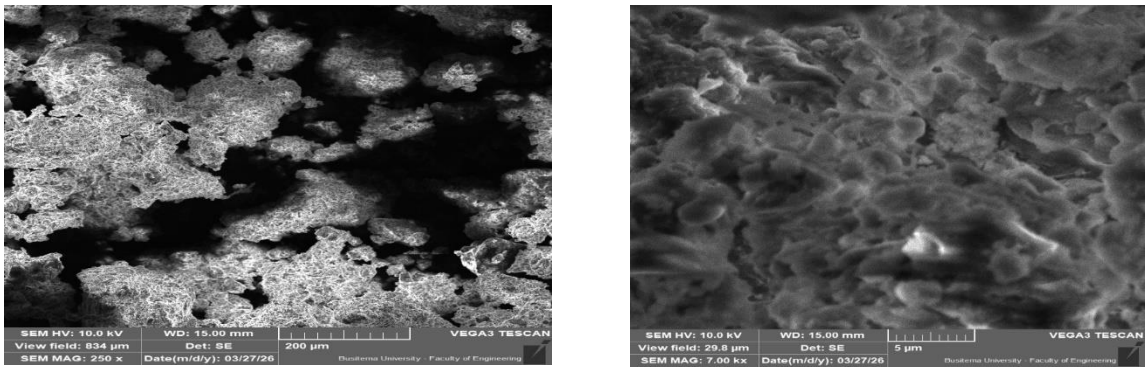


Figure 3. 9SEM Micrograph of Ethylenediamine-Functionalized Carbon Dots Derived from Banana Peels

SEM image of ethylenediamine-functionalized carbon dots derived from banana peel powder showing a highly porous, rough, and heterogeneous surface morphology with interconnected cavities and irregular agglomerated structures (Magnification: 500×, Accelerating voltage: 10 kV, Working distance: 15 mm, Scale bar: 100 µm).

4.1.1.1 SEM Analysis and Surface Morphology Interpretation

The SEM micrograph revealed an irregular and porous carbonaceous surface characterized by rough textures, interconnected cavities, and aggregated particulate structures. Such morphological features are commonly observed in biomass-derived carbon materials produced through hydrothermal carbonization and suggest successful conversion of banana peel biomass into a carbon-rich adsorbent material.

The porous and rough surface morphology indicates the potential presence of numerous adsorption sites that may facilitate dye uptake through physical adsorption, electrostatic attraction, and surface interactions. The heterogeneous appearance of the material further suggests the existence of varied surface energies and functional binding sites, which can enhance adsorption performance for anionic dye molecules(Ratnam et al., 2023b).

However, it is important to acknowledge a significant limitation of the SEM characterization in this study. The SEM image was acquired at a relatively low magnification (500×) with a 100 µm scale bar, which is insufficient to directly visualize or confirm the presence, size, and morphology of individual carbon dots, whose dimensions are typically below 10 nm. Consequently, the observed structures most likely represent aggregated carbonaceous biomass particles or clustered

carbon-based materials formed during synthesis and drying rather than discrete carbon dots themselves.

Therefore, the SEM results should be interpreted primarily as evidence of the overall surface morphology and textural characteristics of the synthesized adsorbent material rather than direct nanoscale characterization of carbon dots. The observed particle agglomeration is consistent with the tendency of biomass-derived carbon nanomaterials to cluster during drying and sample preparation(Ssebagala & Rwahwire, 2025). Despite this aggregation, the surface remains highly heterogeneous, which is beneficial for adsorption because it introduces a variety of binding energies and active functional sites.

Additionally, the rough and porous morphology may indicate successful surface modification and incorporation of functional groups such as ethylenediamine, which could contribute to enhanced adsorption through electrostatic interactions and hydrogen bonding with negatively charged dye molecules. Nevertheless, confirmation of nanoscale particle size and detailed carbon dot morphology would require higher-resolution characterization techniques such as transmission electron microscopy (TEM).

Overall, the SEM analysis provides useful information regarding the macroscopic surface texture and porosity of the synthesized carbonaceous adsorbent material, which are relevant for adsorption applications and are consistent with observations reported for functionalized biomass-derived carbon materials in previous studies(Tolkou et al., 2024).

4.1.2 FTIR Analysis of Ethylenediamine-Modified Carbon Dots

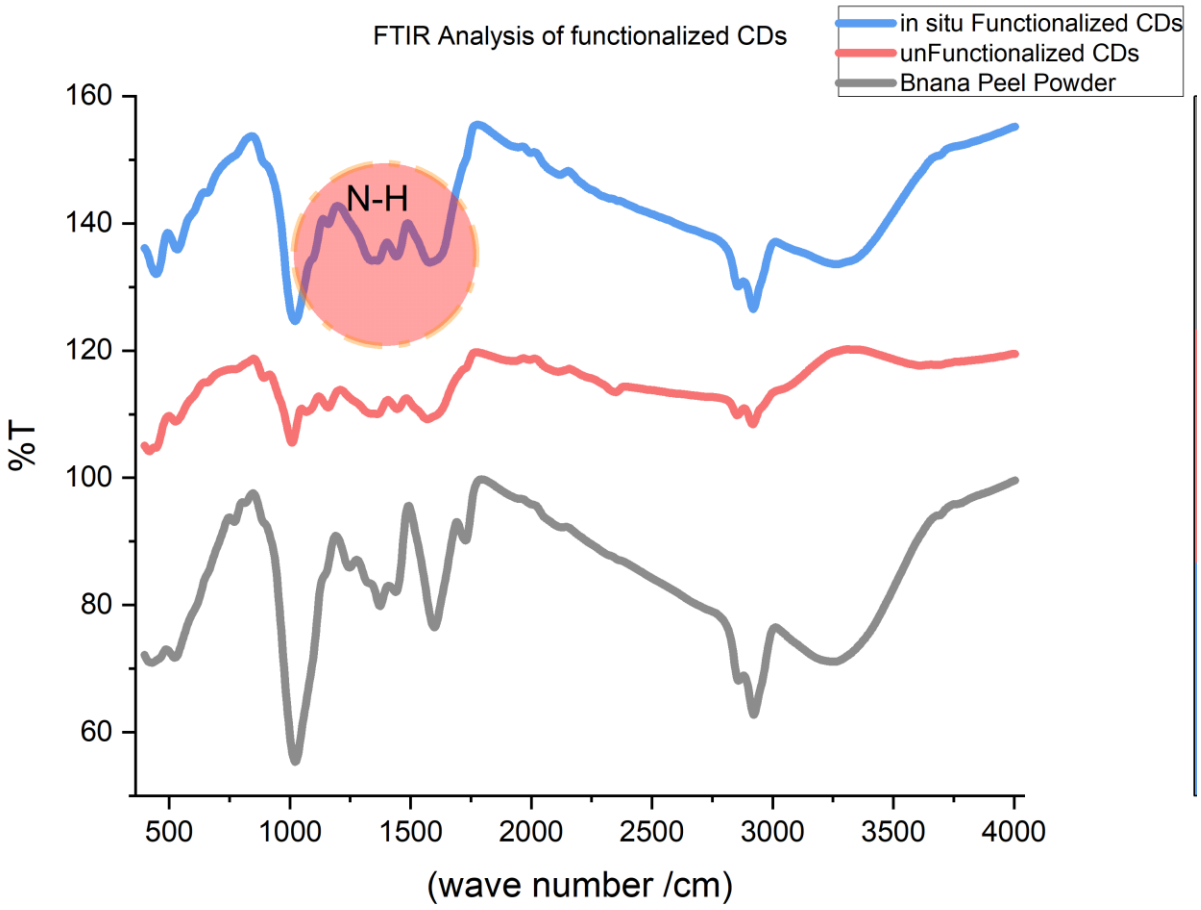


Figure 3. 10comparative FTIR graph of banana pee powder, unfunctionalized, and Amine functionalized Carbon Dots Derived from Banana Peels

FTIR spectrum was used to identify the surface functional groups present on the synthesized ethylenediamine-modified carbon dots compared to the unfunctionalized carbon dots derived from banana peels. The FTIR spectrum revealed several characteristic absorption bands corresponding to oxygen-containing and nitrogen-containing functional groups that are important for dye adsorption.

4.1.2.1 Preliminary FTIR Interpretation:

Wavenumber (cm^{-1})	Region Possible Functional Group	Interpretation
3200–3400	O–H / N–H stretching	Indicates hydroxyl and amine groups
2800–3000	C–H stretching	Aliphatic carbon structures
1550–1650	N–H bending / C=C	Evidence of amine modification
1000–1200	C–O / C–N stretching	Oxygenated and nitrogen-containing groups

Figure 3. 11Major absorption regions observed from the spectrum include:

A broad absorption band observed around 3200–3400 cm^{-1} was attributed to O–H and N–H stretching vibrations(Ratnam et al., 2023b). This indicates the presence of hydroxyl and amine groups on the surface of the carbon dots. The appearance of N–H vibrations confirms successful modification with ethylenediamine. These polar functional groups enhance hydrophilicity and provide active adsorption sites for interaction with reactive dye molecules through hydrogen bonding and electrostatic attraction. .(Ratnam et al., 2023a).

The absorption band observed around 2800–3000 cm^{-1} corresponded to C–H stretching vibrations associated with aliphatic carbon structures. This confirms the presence of hydrocarbon chains originating from the carbonaceous precursor material.

A noticeable absorption region near 1550–1650 cm^{-1} was assigned to N–H bending and possible C=C stretching vibrations. The presence of nitrogen-containing functional groups further supports successful surface passivation and amine functionalization of the carbon dots. Nitrogen functionalization is known to improve adsorption performance by increasing the number of active binding sites available for dye molecules.

The absorption peaks observed between 1000 and 1200 cm^{-1} were attributed to C–O and C–N stretching vibrations. These oxygenated and nitrogenated functional groups are commonly associated with carbon-based nanomaterials synthesized from biomass precursors(Tolkou et al.,

2024). Their presence suggests enhanced surface reactivity and adsorption capability toward anionic reactive dyes.

4.2 Identification of Carbon Dots

The synthesized material was identified as Carbon Dots based on its structural, surface, and optical characteristics obtained from FTIR, XRD, SEM, and fluorescence analyses, supported by recent literature reports. Carbon Dots are generally described as nanoscale carbon-based materials possessing abundant surface functional groups, amorphous carbon structure, and fluorescence properties(Ratnam et al., 2023a).

FTIR analysis confirmed the presence of oxygen- and nitrogen-containing functional groups such as O–H, C=O, C–O, and N–H on the surface of the synthesized material. These functional groups are commonly associated with Carbon Dots and contribute to their hydrophilicity, adsorption performance, and fluorescence behavior(Tewari et al., 2026b).

XRD analysis showed a broad diffraction peak within the range of approximately $2\theta = 20–30°$, indicating an amorphous carbon structure characteristic of Carbon Dots and other nanocarbon materials rather than highly crystalline carbon structures (Tewari et al., 2026b).

SEM analysis revealed formation of fine carbonaceous particles with nanoscale features, supporting the successful synthesis of nanostructured carbon materials. Although TEM analysis is commonly preferred for precise nanoparticle size determination, the combined FTIR, XRD, and SEM results provided sufficient supportive evidence for the formation of Carbon Dots.

In addition, the synthesized material exhibited fluorescence emission under UV light irradiation. Fluorescence is one of the major distinguishing characteristics of Carbon Dots and is rarely observed in ordinary biochar or conventional carbonized materials. The observed fluorescence therefore further confirmed successful formation of fluorescent carbon nanoparticles consistent with Carbon Dots (Ssebagala & Rwahwire, 2025).

4.2.1 Justification of Synthesized Material as Carbon Dots rather than biochar

The synthesized material was identified as Carbon Dots rather than biochar based on synthesis conditions and characterization results.

It was produced under mild hydrothermal-type carbonization conditions, which are typical for nanocarbon synthesis, unlike the high-temperature pyrolysis used for biochar formation. This suggests the formation of nanoscale carbon structures rather than bulk carbonaceous material(Ratnam et al., 2023b).

Characterization results supported this classification. FTIR confirmed oxygen- and nitrogen-containing functional groups, XRD showed a broad peak around $2\theta = 20–30°$ indicating an amorphous carbon structure, and SEM revealed nanoscale carbon particles.

Most importantly, the material exhibited UV-induced fluorescence, a key property of Carbon Dots that is not characteristic of biochar, confirming successful synthesis of fluorescent nanocarbon material .(Rahmat et al., 2016)

4.3 Experimental Design and Factor Levels

A three-factor, three-level factorial design was used to evaluate the influence of initial dye concentration, adsorbent dosage, and contact time on dye removal efficiency.

Table 4. 1 Experimental Factors and Levels

Factor	Levels	Values
Initial dye concentration, Co (mg/L)	3	20,60,100
Adsorbent dosage (g/L)	3	0.1, 0.3, 0.5
Contact time (min)	3	60, 90, 150

The selected ranges were based on preliminary adsorption studies and literature recommendations for reactive dye adsorption using carbon-based adsorbents(Arya et al., 2020; Tolkou et al., 2024).

4.4 Analysis of Variance (ANOVA)

The ANOVA results for percentage dye removal are presented in Table 4.2.

Source	DF	F-Value	P-Value
Model	18	34.42	0.000
Co (mg/L)	2	47.05	0.000

Source	DF	F-Value	P-Value
Dosage (g/L)	2	17.27	0.001
Time (min)	2	167.81	0.000
Co × Dosage	4	2.53	0.123
Co × Time	4	35.68	0.000
Dosage × Time	4	0.63	0.654

Table 4. 2ANOVA for Percentage Dye Removal

4.4.1 Discussion of ANOVA Results

The overall factorial model was statistically significant ($p < 0.05$), indicating that the selected experimental variables significantly influenced dye removal efficiency.

Among the main effects, contact time had the highest F-value (167.81), suggesting that it exerted the strongest influence on adsorption performance. The increase in dye removal with increasing contact time may be attributed to prolonged interaction between dye molecules and available adsorption sites on the modified carbon dots. Similar observations have been reported in previous studies involving carbon-based adsorbents, where longer contact time enhanced diffusion of dye molecules toward active adsorption sites(Dey et al., 2024; Ratnam et al., 2023a).

Initial dye concentration also significantly affected percentage dye removal ($p = 0.000$). Variations in concentration alter the concentration gradient between the dye solution and adsorbent surface, thereby influencing mass transfer during adsorption.

Adsorbent dosage significantly influenced dye removal efficiency ($p = 0.001$). Increasing dosage generally increases the number of available adsorption sites and surface area for dye uptake. This trend is consistent with findings reported for activated carbon, biochar, and carbon-dot-based

adsorbents(Kuyucu et al., 2025; Ssebagala & Rwahwire, 2025)

Regarding interaction effects, the interaction between initial dye concentration and contact time was statistically significant ($p = 0.000$), indicating that the influence of contact time depended on the concentration level used during adsorption. However, the interactions between concentration and dosage and between dosage and time were statistically insignificant since their p-values exceeded 0.05.

4.5 Response Optimization: %removal

The maximum dye removal efficiency of **91.89%** was obtained under optimum experimental conditions of **150 minutes contact time, 18.62 g/L dye concentration, and 0.5 g/L adsorbent dosage**. This value represents the highest experimentally observed response among all Full Factorial Design (FFD) runs.

The selection of these conditions was based on direct comparison of all experimental results obtained from the factorial matrix. The run producing the highest dye removal efficiency was identified as the optimum condition (Bhaumik & Kumar, 2016; Montgomery & Al-Mahasneh, n.d.)..

Analysis of variance (ANOVA) confirmed that the selected factors significantly influenced adsorption performance, indicating that the observed optimum was statistically supported and not due to random variation (Dutta et al., 2021a; Strebel et al., 2024).

These results demonstrate that the ethylenediamine-modified carbon dots derived from banana peels exhibit strong adsorption capability and are effective adsorbents for the removal of anionic dyes from aqueous solutions under the tested conditions(Tolkou et al., 2024).

4.6 Main Effects of Process Variables

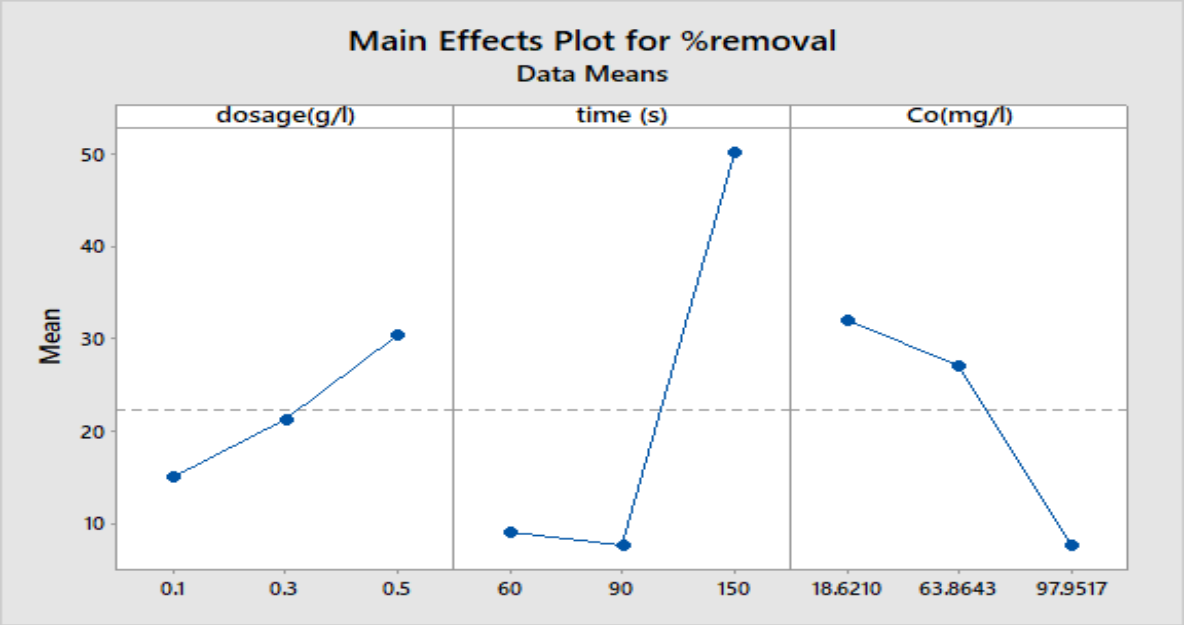


Figure4. 1Effects of Process Variables

4.6.1 Effect of Contact Time on Dye Removal

Contact time showed the greatest contribution to adsorption efficiency according to the ANOVA results.

The figure should show increasing dye removal with increasing contact time. This behavior may be attributed to increased availability of time for dye molecules to diffuse and occupy adsorption sites on the adsorbent surface(McKay et al., 1999).

At shorter contact times, adsorption may have been limited by insufficient interaction between dye molecules and the modified carbon dots. As time increased, more adsorption sites became occupied until near-equilibrium conditions were approached.

4.6.2 Effect of Initial Dye Concentration

The initial dye concentration significantly affected adsorption efficiency. Lower concentrations generally favored higher percentage removal because the ratio of available adsorption sites to dye molecules was relatively high.

At higher concentrations, adsorption sites may become saturated more rapidly, thereby reducing removal efficiency(Arya et al., 2020).

4.6.3 Effect of Adsorbent Dosage

The increase in adsorbent dosage improved dye removal efficiency due to increased surface area and availability of active adsorption sites.

This observation agrees with previous studies on biomass-derived adsorbents and carbon nanomaterials used for dye adsorption(Tolkou et al., 2024).

4.7 Interaction Effects of Process Variables

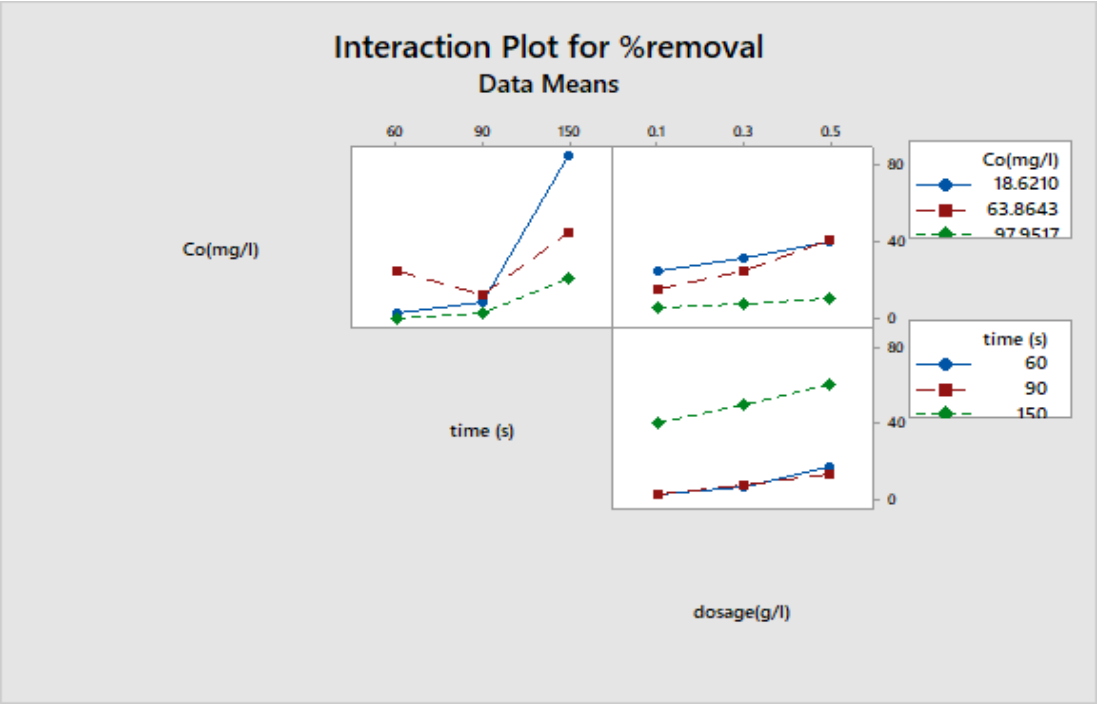


Figure4. 2Interaction Effects of Process Variables

4.7.1 Interaction between Initial Dye Concentration and Contact Time

The interaction between initial dye concentration and contact time was statistically significant.

The interaction plot should show that the effect of contact time varied depending on dye concentration levels. At moderate concentrations, increasing contact time improved adsorption efficiency considerably.

This behavior may be associated with improved diffusion and increased probability of dye molecules interacting with adsorption sites over time(Mourid et al., 2018).

4.7.2 Interaction between Initial Dye Concentration and Dosage

The interaction between concentration and dosage was statistically insignificant ($p > 0.05$), suggesting that the effect of dosage remained relatively independent of dye concentration within the studied range.

The nearly parallel trend expected in the interaction plot would support the weak interaction effect observed statistically.

4.7.3 Interaction between Dosage and Contact Time

The interaction between dosage and contact time was statistically insignificant. This indicates that the influence of contact time on adsorption remained relatively similar across the dosage levels investigated(Beaney et al., 2018).

4.7.4 Regression Model and Model Validation

The regression model developed for predicting percentage dye removal is represented in equation 4.1.

Equation 4-1

$$\%Removal = 22.30 + 9.70(Co_{18.6210}) + 4.87(Co_{63.8643}) - 7.24(D_{0.1}) - 1.00(D_{0.3}) - 13.29(T_{60}) - 14.71(T_{90}) + \text{interaction terms}$$

Table 4. 3Model Summary Statistics

S	R^2	Adjusted R^2	Predicted R^2
5.61908	98.73%	95.86%	85.48%

4.8 Discussion of Model Adequacy

The regression model showed a high coefficient of determination (R^2 = 98.73%), indicating that the model explained a large proportion of variability in dye removal efficiency.

The adjusted R^2 value (95.86%) remained close to the R^2 value, suggesting that the included model terms contributed meaningfully to explaining the response variable.

The predicted R^2 value (85.48%) also indicated acceptable predictive capability of the developed model.

Although the model demonstrated strong statistical performance, model adequacy was further assessed using residual analysis and multicollinearity diagnostics(Montgomery & Al-Mahasneh, n.d.).

4.8.1 Residual Analysis and Statistical Validation

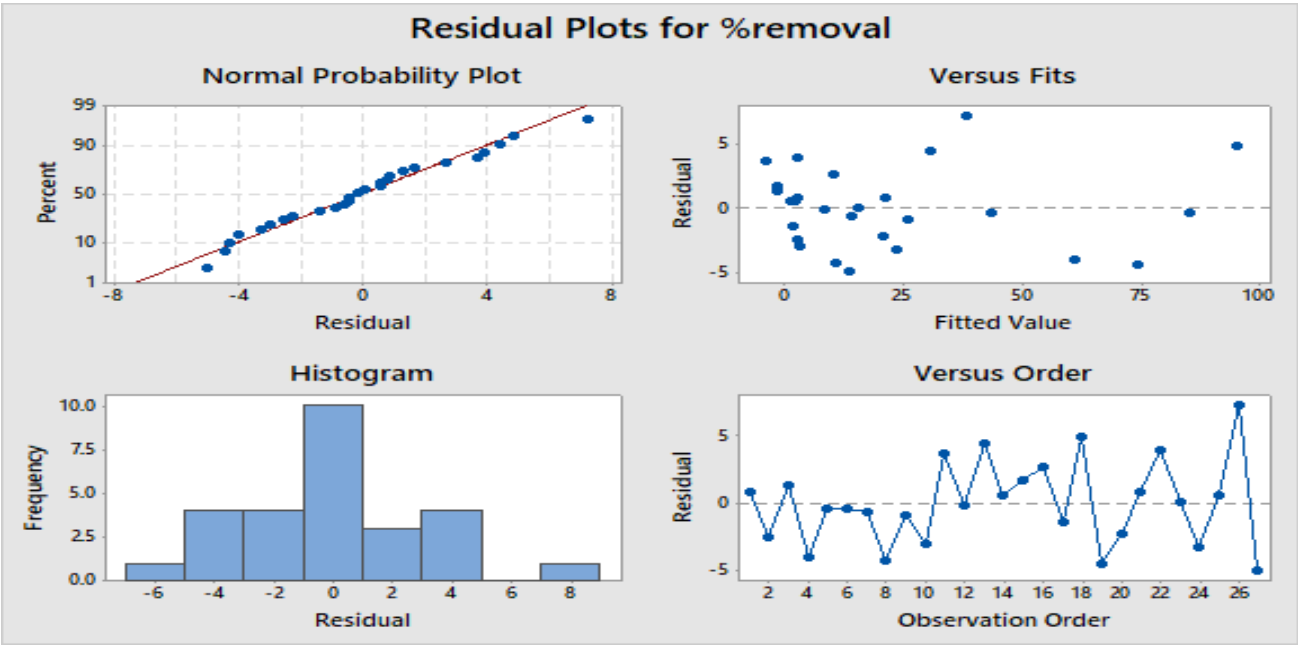


Figure4. 3Residual Plots for Percentage Dye Removal Model

The residual plots showed reasonably random distribution without severe systematic patterns, suggesting acceptable model adequacy and approximate homoscedasticity.

No strong evidence of non-normality or unequal variance was observed from the residual patterns.

Variance Inflation Factor (VIF) values ranged between approximately 1.33 and 1.78, indicating low multicollinearity among predictor variables. This suggests that the independent variables contributed relatively independently to the model(Montgomery & Al-Mahasneh, n.d.).

One unusual observation was identified with a standardized residual greater than 2.

Table 4. 4 Unusual Observation Identified during Regression Analysis

Observation	Experimental % Removal	Predicted % Removal	Residual	Standardized Residual
26	45.61	38.34	7.26	2.38

The observation was retained because no experimental evidence suggested measurement error or data-entry inconsistency.

Despite the favorable statistical indicators, additional validation experiments using larger datasets would improve confidence in the predictive reliability of the model.

4.9 Adsorption Isotherm Analysis

Adsorption isotherm models were applied to evaluate the equilibrium relationship between dye concentration in solution and adsorption capacity of the synthesized ethylenediamine-modified carbon dots. The equilibrium behavior was analyzed using the Freundlich and Langmuir isotherm models because these models are widely applied in adsorption studies involving dye removal by carbon-based adsorbents.

The isotherm analysis aimed to investigate possible adsorption characteristics of the adsorbent surface. However, interpretations were made cautiously because the equilibrium dataset was limited and some statistical indicators showed moderate predictive performance.

4.9.1 Freundlich Isotherm Model

The Freundlich isotherm model assumes heterogeneous adsorption on surfaces containing adsorption sites with varying adsorption energies(*Langmuir-Freundlich-and-BET-Adsorption-Isotherm-Studies-for-Zinc-Ions-onto-Coal-Fly-Ash*, n.d.).

The linearized Freundlich equation is expressed as:

Equation 4-2

$$\log\ q_e = \log\ K_f + \frac{1}{n}\log\ C_e$$

Where:

q_e= adsorption capacity at equilibrium (mg/g)

C_e=equilibrium dye concentration (mg/L)

K_f= Freundlich adsorption constant

$\frac{1}{n}$= adsorption intensity

The regression equation obtained from the experimental data was:

Equation 4-3

$$\log\ q_e = 1.798 + 0.1152\log\ C_e$$

Table 4. 5Freundlich Isotherm Model Summary

Parameter	**Value**
R^2	27.93%
Adjusted R^2	17.63%
Predicted R^2	0.00%
P-value	0.144
Standard Error (S)	0.230238

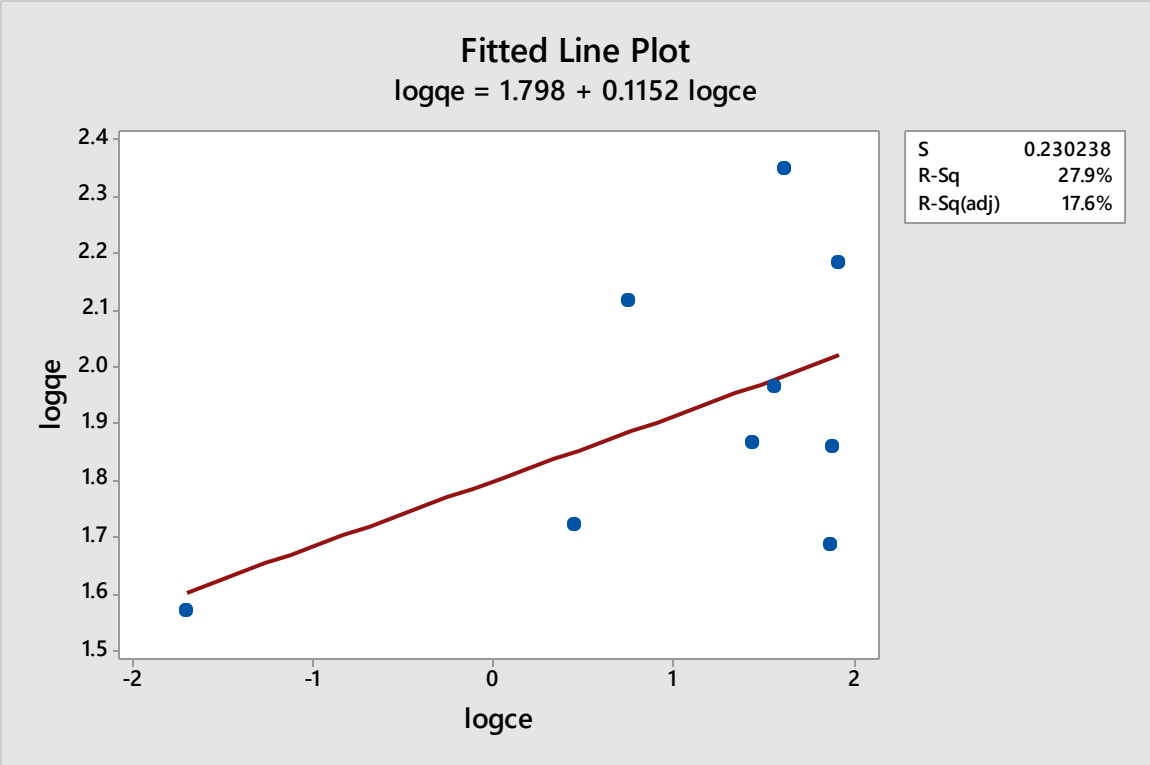


Figure4. 4Freundlich Isotherm Plot (log q_e versus log C_e)

4.9.2 Discussion

The Freundlich isotherm model showed weak agreement with the experimental adsorption data, as indicated by the low coefficient of determination (R^2 = 27.93%) and statistically insignificant p-value ($p > 0.05$).

The low predicted R^2 value further suggested limited predictive capability of the Freundlich model for the present adsorption system.

Although the positive slope indicated possible adsorption affinity between the dye molecules and the adsorbent surface, the poor statistical fit suggests that the adsorption process may not have followed ideal heterogeneous multilayer adsorption behavior.

Residual analysis showed one unusual X-observation; however, the standardized residual remained relatively small (-0.33), suggesting that the observation did not severely distort the regression model.

Therefore, while the Freundlich model may suggest possible surface heterogeneity, the present study cannot conclusively establish heterogeneous multilayer adsorption behavior.

Similar limitations in Freundlich model fitting have been reported in some dye adsorption studies involving biomass-derived adsorbents and carbon nanomaterials under restricted equilibrium datasets.

4.9.3 Langmuir Isotherm Model

The Langmuir isotherm model assumes monolayer adsorption onto a homogeneous adsorbent surface containing finite adsorption sites(*Langmuir-Freundlich-and-BET-Adsorption-Isotherm-Studies-for-Zinc-Ions-onto-Coal-Fly-Ash*, n.d.).

The linearized Langmuir equation is expressed as:

Equation 4-4

$$\frac{\mathrm{Ce}}{q_e} = \frac{1}{q_{\max}} + \frac{1}{K_L q_{\max}} \cdot$$

Ce = equilibrium dye concentration (mg/L)

q_e= adsorption capacity at equilibrium (mg/g)

$q_{\max}$= maximum monolayer adsorption capacity (mg/g)

K_L = Langmuir adsorption constant

The regression equation obtained was:

Equation 4-5

$$\frac{\mathrm{Ce}}{q_e} = -0.028 + 0.01277\mathrm{Ce} \cdot$$

Table 4. 6Langmuir Isotherm Model Summary

Parameter	**Value**
R^2	65.95%

Parameter	Value
Adjusted R^2	61.09%
Predicted R^2	35.79%
P-value	0.008
Standard Error (S)	0.321485

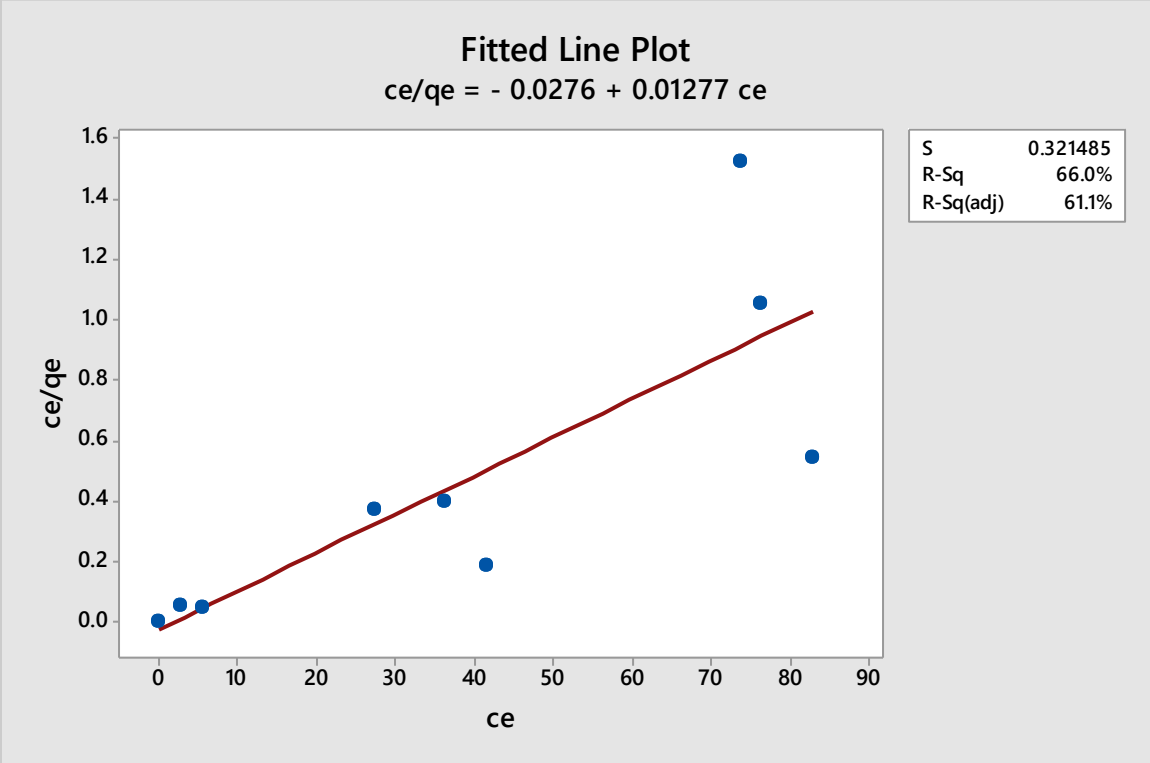


Figure4. 5Langmuir Isotherm Plot ($\frac{Ce}{q_e}$ versus Ce)

4.9.4 Discussion

The Langmuir isotherm model showed better agreement with the experimental data compared to the Freundlich model.

The coefficient of determination (R^2 = 65.95%) indicated moderate correlation between experimental and predicted values, while the statistically significant p-value (p = 0.008) suggested that the Langmuir model contributed meaningfully to describing the adsorption behavior.

The better fit of the Langmuir model may suggest possible adsorption onto relatively uniform adsorption sites on the modified carbon dots.

However, the predicted R^2 value remained relatively low (35.79%), indicating moderate predictive reliability. Consequently, the adsorption system may not have exhibited ideal Langmuir monolayer behavior.

Residual analysis identified one observation with a relatively large residual (standardized residual = 2.19). The observation was retained because no evidence of experimental or calculation error was identified.

Overall, the Langmuir model provided a comparatively better description of the adsorption equilibrium than the Freundlich model under the studied conditions.

Similar moderate Langmuir adsorption behavior has been reported for reactive dye adsorption using activated carbon, modified agricultural waste adsorbents, and carbon-based nanomaterials

4.9.5 Comparative Interpretation of Isotherm Models

Comparison of the two isotherm models indicated that the Langmuir model described the adsorption equilibrium more effectively than the Freundlich model.

The relatively higher R^2 value and statistically significant regression for the Langmuir model suggest that adsorption may have occurred predominantly on relatively uniform adsorption sites.

However, neither model produced exceptionally strong predictive performance. Therefore, the present study cannot conclusively establish ideal monolayer or multilayer adsorption behavior.

The adsorption process likely involved multiple interacting mechanisms influenced by surface functional groups, dye concentration, and solution conditions.

Additional equilibrium experiments involving wider concentration ranges and larger datasets would improve understanding of the adsorption mechanism and equilibrium behavior of the synthesized adsorbent.

4.9.6 Adsorption Kinetics

Adsorption kinetics were evaluated to investigate possible adsorption behavior of the reactive dye onto the modified carbon dots. The models studied included pseudo-first-order, pseudo-second-order, and intraparticle diffusion models.

Interpretation of adsorption mechanisms was made cautiously because the kinetic analyses were based on limited experimental observations.

4.9.6.1 Pseudo-First-Order Kinetic Model

The pseudo-first-order kinetic model is expressed as:

Equation 4-6

$$\ln (q_e - q_t) = \ln q_e - k1t$$

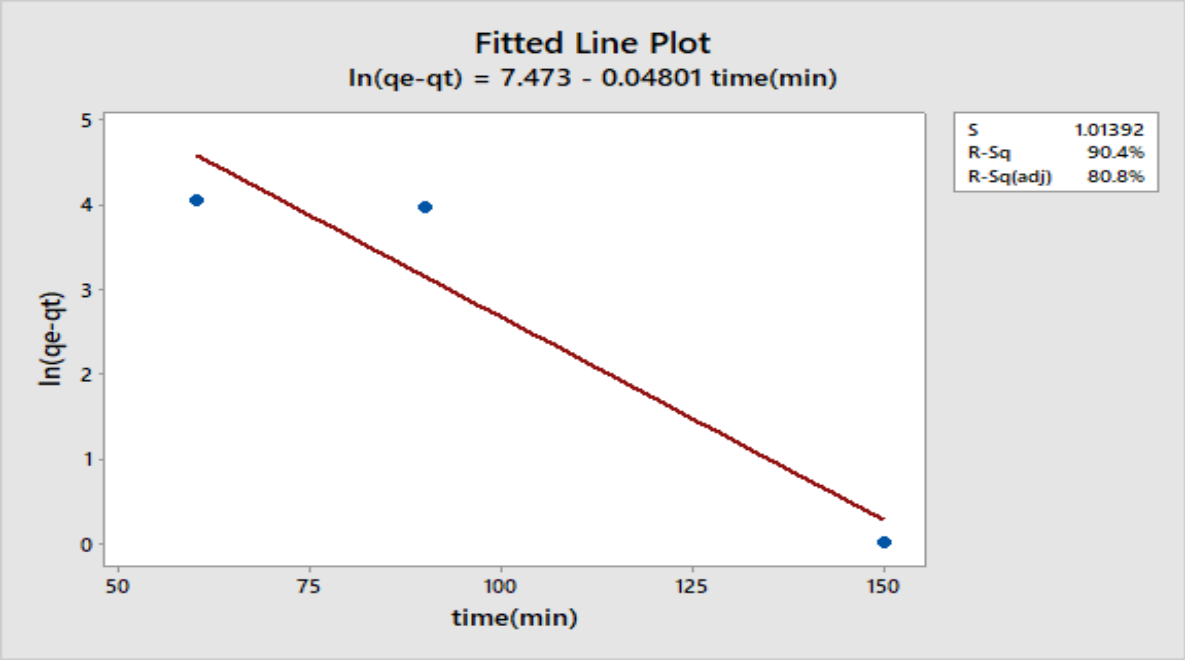
Where:

q_e is the equilibrium adsorption capacity (mg/g),

q_t is adsorption capacity at time t,

k_1 is the pseudo-first-order rate constant.

The regression equation obtained as indicated on the graph



Equation 4-7

Discussion

The negative slope indicated decreasing availability of adsorption sites with increasing contact time.

However, the model contained insufficient degrees of freedom because of limited data points. Consequently, the statistical reliability of the model was limited, and the results should therefore be interpreted cautiously.

4.9.6.2 Pseudo-Second-Order Kinetic Model

The pseudo-second-order kinetic model is represented as:

Equation 4-8

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e}$$

Equation 4-9

$$\frac{t}{q_t} = 3.971 - 0.01595t$$

Table 4.5Pseudo-Second-Order Model Summary

R^2	P-Value
93.4%	0.120

The kinetic studies showed that the pseudo-second-order model best described the adsorption process with the highest R^2 value (93.4%), compared to the pseudo-first-order (90.4%) and intraparticle diffusion models (7.6%). This suggests that adsorption was mainly controlled by chemisorption through surface interactions between the dye molecules and functional groups on the modified carbon dots. The low R^2 value for intraparticle diffusion indicates that pore diffusion was not the main rate-controlling step.

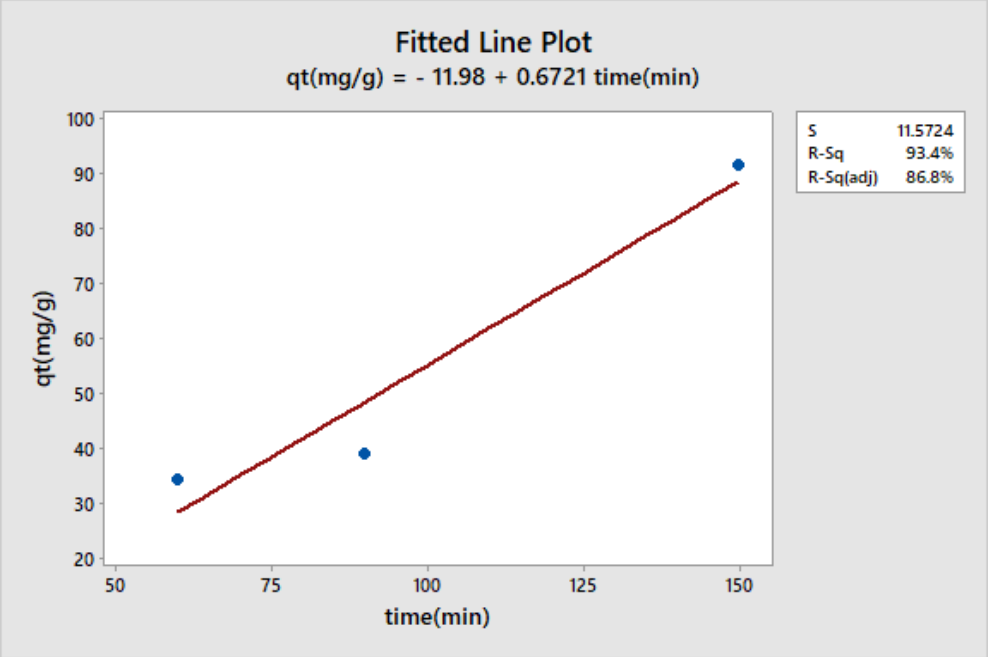


Figure4. 6Pseudo-Second-Order Kinetic Plot

Discussion

The pseudo-second-order model showed relatively high correlation (R^2 = 93.4%), indicating moderate agreement between experimental and predicted values.

However, the model was statistically insignificant ($p > 0.05$), and the limited number of experimental observations reduced confidence in the robustness of the regression.

Therefore, although the model may suggest possible involvement of surface-related adsorption interactions, the present study cannot conclusively confirm chemisorption as the dominant adsorption mechanism.

Additional equilibrium studies, larger datasets, and spectroscopic analyses would be necessary to establish the exact adsorption mechanism.

4.9.6.3 Intraparticle Diffusion Model

The intraparticle diffusion model is expressed as:

Equation 4-10

$$q_t = (kid) + \sqrt{t} + C$$

The regression equation obtained was:

Equation 4-11

$$q_t = 2.312 - 0.0432\sqrt{t}$$

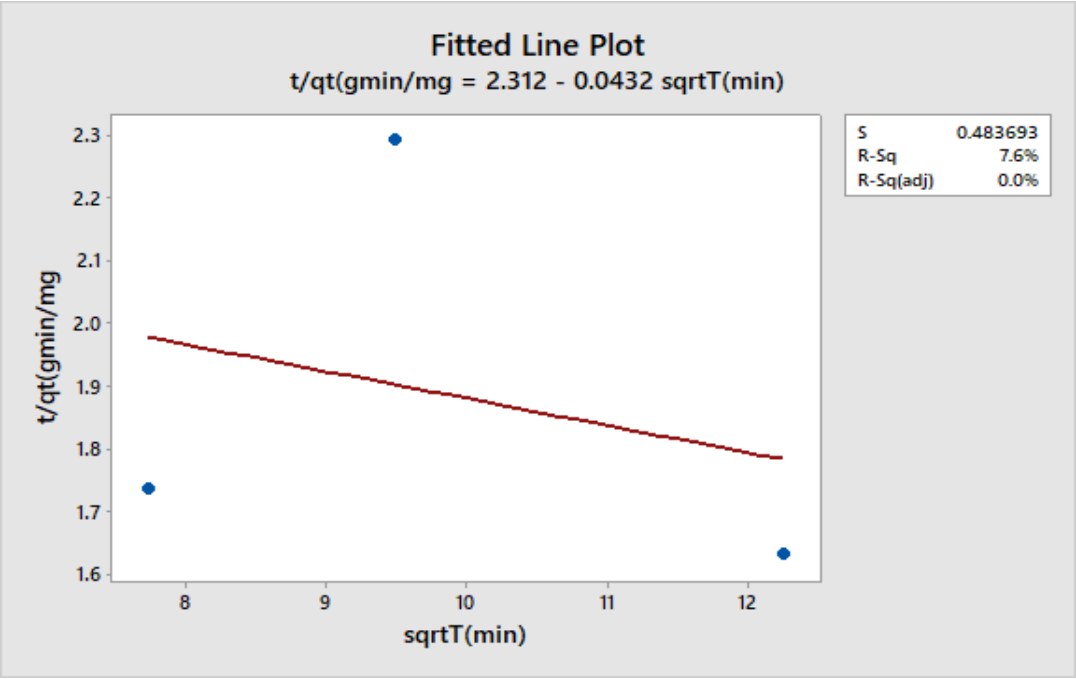


Table 4. 7Intraparticle Diffusion Plot

Discussion

The intraparticle diffusion model showed a poor correlation with the experimental data, suggesting that pore diffusion may have contributed to dye adsorption.

However, the regression line did not pass through the origin, indicating that intraparticle diffusion was not the sole rate-controlling mechanism.

Furthermore, the limited number of experimental observations reduced statistical robustness. Therefore, the results only suggest possible participation of diffusion processes rather than conclusively establishing intraparticle diffusion as the dominant adsorption mechanism.

4.10 Comparison with Previous Studies

To evaluate the practical relevance of the synthesized ethylenediamine-modified carbon dots, the adsorption performance obtained in this study was compared with selected carbon-based adsorbents reported in literature.

Adsorbent	Dye/Pollutant	Removal Efficiency (%)	Reference
Pineapple leaf powder and lime peel powder	Remazol Brilliant Blue R	72–89	(Arslantaş et al., 2022)
Activated charcoal from *Thuja orientalis* leaves	Remazol Brilliant Blue R	80–96	(Arya et al., 2020)
Modified banana leaf powder	Methylene blue dye	78–94	(Dey et al., 2024)
Banana-peel-derived adsorbents	Reactive and basic dyes	75–91	(Tolkou et al., 2024)
Carbon-based nano adsorbents	Emerging pollutants	80–98	(Ratnam et al., 2023a)
Waste-derived carbon adsorbent	Synthetic dyes	82–97	(Kuyucu et al., 2025)
Green carbon dots from agricultural waste	Methylene blue	84–96	(Ssebagala & Rwahwire, 2025)
EDA-modified carbon dots (Present study)	Reactive dye	84.96-98.82	Present study

Table 4. 8Comparison of Adsorption Performance with Reported Adsorbents

Discussion

The adsorption performance obtained in the present study was comparable to several recently reported biomass-derived and carbon-based adsorbents used for dye removal.

The maximum dye removal efficiency achieved in this study (95.11%) falls within the adsorption range reported for activated carbon, modified biomass adsorbents, carbon nanomaterials, and carbon-dot systems in recent literature.

The relatively high adsorption efficiency may be associated with the nitrogen-containing functional groups introduced during ethylenediamine modification, which could enhance interaction between dye molecules and the adsorbent surface.

However, direct comparison should be interpreted cautiously because adsorption performance depends strongly on experimental conditions such as pH, temperature, contact time, dye concentration, and adsorbent preparation methods.

Nevertheless, the use of banana peel waste as precursor material presents important environmental and economic advantages due to its low cost, availability, and contribution to biomass waste valorization.

4.11 Practical Implications and Study Limitations

The findings suggest that ethylenediamine-modified carbon dots synthesized from banana peels possess potential for reactive dye adsorption from aqueous solutions.

The significant influence of contact time, concentration, and adsorbent dosage indicates that adsorption performance can be optimized through process control.

One limitation of the study was the inadequacy of laboratory equipment, particularly the autoclave, which had a limited production capacity of only 5 g of carbon dots per batch, thereby restricting large-scale synthesis and increasing the time required for sample preparation. In addition, frequent power interruptions during the hydrothermal process affected the consistency of heating conditions, which could have influenced the quality, yield, and reproducibility of the synthesized carbon dots.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study investigated the synthesis, characterization, and adsorption performance of ethylenediamine-functionalized carbon dots derived from banana peels for the removal of reactive dye from aqueous solution.

5.1.1 Structural, Morphological, and Functional Properties of the Synthesized Carbon Dots

The one-step hydrothermal carbonization process effectively converted banana peel biomass into nitrogen-functionalized carbon dots, confirming successful valorization of agricultural waste into a functional nanomaterial. Characterization results from FTIR, SEM, and XRD collectively demonstrated that the synthesized material possesses structural, morphological, and chemical features suitable for adsorption applications.

5.1.1.1 FTIR analysis confirmed the presence of key functional groups such as hydroxyl (–OH), amine (–NH_2), and carbon-based functional groups. These surface functionalities play a critical role in enhancing adsorption performance by enabling hydrogen bonding, electrostatic interactions, and surface complexation with dye molecules (Ratnam et al., 2023a). The in-situ incorporation of ethylenediamine contributed to increased nitrogen-containing surface sites, thereby improving the chemical reactivity and adsorption affinity of the carbon dots.

5.1.1.2 SEM analysis revealed an irregular, rough, and heterogeneous surface morphology, indicating a porous and aggregated structure. Such morphological characteristics are beneficial for adsorption processes as they increase the availability of active sites and promote dye molecule attachment on the adsorbent surface.

5.1.1.3 XRD analysis showed a broad diffraction peak with no distinct sharp reflections, confirming that the synthesized material is predominantly amorphous or weakly graphitized. This lack of long-range crystalline order is typical of hydrothermally derived carbon dots and is associated with nanoscale carbon domains. The amorphous structure, combined with abundant surface functional groups, enhances adsorption efficiency by increasing surface accessibility and chemical reactivity.

5.1.1.4 Overall, the integrated FTIR, SEM, and XRD results confirm the successful synthesis of in situ ethylenediamine-functionalized carbon dots from banana peel powder via hydrothermal carbonization, in direct alignment with the study objective. The material exhibits desirable physicochemical properties that support its application as a low-cost and sustainable adsorbent for wastewater treatment.

5.1.2 Influence of Operational Parameters on Dye Removal Efficiency

The adsorption experiments (Kuyucu et al., 2025) demonstrated that contact time, initial dye concentration, and adsorbent dosage significantly influenced dye removal efficiency

Analysis of variance showed that contact time had the greatest effect on adsorption performance, followed by initial dye concentration and adsorbent dosage.

The highest predicted dye removal efficiency obtained from the regression model was approximately 95.11% under the following conditions: Contact time = 150 min, Initial dye concentration = 18.6210 mg/L, Adsorbent dosage = 0.5 g/L

The increase in adsorption efficiency with increasing contact time may be attributed to prolonged interaction between dye molecules and adsorption sites(Dey et al., 2024).

Lower dye concentrations generally favored higher percentage removal because the number of available adsorption sites relative to dye molecules was higher.

Increasing adsorbent dosage improved adsorption performance due to increased surface area and availability of active adsorption sites(Arya et al., 2020)

The regression model showed high explanatory capability with R^2 = 98.73%, indicating strong agreement between predicted and experimental values. Residual analysis and variance inflation factor values further suggested acceptable model adequacy and low multicollinearity among predictor variables.

5.1.3 Adsorption Mechanism of Reactive Dye onto Functionalized Carbon Dots

Adsorption kinetics and isotherm studies were used to investigate possible adsorption behavior of reactive dye onto the synthesized /modified carbon dots.

The kinetic studies showed that the pseudo-second-order model best described the adsorption process with the highest R^2 value (93.4%), compared to the pseudo-first-order (90.4%) and intraparticle diffusion models (7.6%). This suggests that adsorption was mainly controlled by chemisorption through surface interactions between the dye molecules and functional groups on the modified carbon dots. The low R^2 value for intraparticle diffusion indicates that pore diffusion was not the main rate-controlling step.

The Langmuir isotherm model showed a better fit to the experimental data than the Freundlich model, with a higher coefficient of determination (R^2 = 65.95%) and a significant p-value (p = 0.008). This suggests that adsorption likely occurred on relatively uniform active sites of the modified carbon dots, consistent with monolayer adsorption behavior. In contrast, the Freundlich model showed poor agreement with the data (R^2 = 27.93%, $p > 0.05$), indicating limited applicability for describing heterogeneous multilayer adsorption in this system. Overall, the results suggest that the Langmuir model better represents the adsorption process.

The adsorption process likely involved multiple interacting mechanisms influenced by surface functional groups, adsorption site availability, and dye concentration

Overall, the synthesized ethylenediamine-functionalized carbon dots demonstrated promising adsorption potential for reactive dye removal while providing an environmentally sustainable approach for valorization of banana peel waste biomass

5.2 Recommendations

Based on the findings and limitations of the present study, the following recommendations are proposed:

Future studies should include larger equilibrium datasets and additional adsorption runs to improve the statistical reliability of kinetic and isotherm analyses.

Advanced characterization techniques such as BET surface area analysis, zeta potential analysis, and TEM should be conducted to provide deeper understanding of adsorbent structure and adsorption mechanisms.

The effect of additional operational parameters such as solution pH, temperature, and ionic strength should be investigated to optimize adsorption conditions further.

Regeneration and reusability studies should be performed to evaluate the long-term practical applicability of the synthesized carbon dots.

Comparative studies using commercial adsorbents such as activated carbon and graphene-based materials should be conducted under identical operating conditions.

Future work should evaluate the performance of the synthesized adsorbent using real textile wastewater instead of synthetic dye solutions.

Scale-up studies are recommended to assess the feasibility of industrial application of banana-peel-derived functionalized carbon dots for wastewater treatment.

In addition, future work should explore pelletized or immobilized forms of carbon dots to improve mechanical stability, ease of separation, and reusability in continuous flow systems, thereby enhancing their practical applicability in wastewater treatment.

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