Sustainable Wastewater Treatment: Using Mahogany and Tamarind-Based Bio-Coagulants and Biochar

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It is hereby declared that this thesis/project report, in whole part, has not heen submitted elsewhere for the award of any Degree or Diploma.

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Dedication

To our loving family members and beloved teachers

for

the support, patience and most of all, faith they have shown in us.

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"In the name of Allah, Most Gracious, Most Merciful"

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Table of Contents

CHAPTER 1: INTRODUCTION **1**

1.1 GENERAL 1
1.2 PROBLEM STATEMENT 3
1.3 OBJECTIVES OF THE STUDY 3
1.4 SCOPE AND LIMITATIONS OF THE STUDY 4
1.5 LAYOUT OF THE THESIS 5

CHAPTER 2: LITERATURE REVIEW **7**

2.1 INTRODUCTION 7
2.2 GLOBAL PERSPECTIVE ON WASTEWATER GENERATION AND TREATMENT 7
2.3 WASTEWATER TREATMENT SCENARIO IN BANGLADESH 10
2.4 CONVENTIONAL COAGULANTS AND THEIR DRAWBACKS 14
2.5 NATURAL AND BIO-BASED COAGULANTS 17
2.6 MAHOGANY AND TAMARIND AS BIO-COAGULANTS 19
2.7 BIOCHAR FOR WASTEWATER TREATMENT 23
2.8 MAHOGANY AND TAMARIND-BASED BIOCHAR 28
2.9 ADSORPTION ISOTHERM MODELS FOR BIOCHAR-BASED TREATMENT 31
2.10 EVALUATION OF BIOCHAR PERFORMANCE UNDER CONTINUOUS FLOW CONDITIONS 34

CHAPTER 3: MATERIALS & METHODOLOGY **36**

3.1 WASTEWATER SAMPLE COLLECTION 36
3.2 PHYSICOCHEMICAL PARAMETER ANALYSIS 36
3.3 EXPERIMENTAL METHOD OVERVIEW 38
3.3.1 Batch Experiments 38
3.3.2 Adsorption Isotherm Models 50
3.3.3 Continuous Column Adsorption 52
3.3.4 Analysis 53

CHAPTER 4: RESULT & DISCUSSION **55**

4.1 GENERAL 55
4.2 WATER PARAMETER TEST 56
4.3 BATCH EXPERIMENT 57
4.3.1 Batch Experiment by Bio-coagulants 58
4.3.2 Batch Experiment by Chemical Coagulants 63

4.3.3 Batch Experiment by Bio-coagulants and Chemical Coagulants 66
4.3.4 Batch Experiment by Biochar....73
4.4 Column Test 80
4.5 Result Summary 82
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS.... 84
5.1 Conclusion....84
5.2 Future Scopes....87
CHAPTER 6: REFERENCES.... 89
CHAPTER 7: APPENDIX XIII
7.1 APPENDIX 1: Continuous Column Test Data....xiii

List of Tables

Table 2.1 Global Wastewater Generation and Treatment Coverage 9

Table 2.2 Wastewater Generation, Treatment, and Chemical Use in Bangladesh 11

Table 2.3 Key Wastewater Treatment Strategies in Bangladesh..................................... 13

Table 2.4 Comparison of Common Conventional Coagulants 16

Table 2.5 Comparative characteristics and performance of Tamarind and Mahogany-based bio-coagulants 21

Table 2.6 Summary of Biochar and Natural Adsorbents for Wastewater Treatment....... 25

Table 2.7 Summary of key characteristics and performance of Mahogany and Tamarind-based biochars 29

Table 2.8 Summary of Adsorption Isotherm and Kinetic Models for Tamarind and Mahogany-Based Adsorbents 33

Table 3.1 Comparison of Physicochemical Parameters of Wastewater Samples with WHO, US EPA and ECR Guideline Values 37

Table 3.2 Bio-coagulant Dosage.. 41

Table 3.3 Individual Chemical Coagulant Dosage 44

Table 3.4 Combined Application Ratios of Chemical Coagulants and Bio-coagluants... 45

Table 3.5 Biochar Dosage.. 49

Table 3.6 Adsorption Isotherm Models 51

Table 4.1 Turbidity and Color Removal Efficiency by Combined Bio-coagulants and Chemical Coagulants 70

Table 7.1: Turbidity removal through column test by mahogany biochar xiii

Table 7.2: Turbidity removal through column test by tamarind biochar......................... xiv

Table 7.3: Color removal through column test by mahogany biochar xv

Table 7.4: Color removal through column test by tamarind biochar.............................. xvi

List of Figures

Figure 2.1 Wastewater Treatment Coverage and Technology Adoption in Bangladesh.. 14

Figure 3.1 Experimental Setup of Batch Experiments with Bio-coagulants 39

Figure 3.2 Experimental Setup of Batch Experiments with Chemical Coagulants and Combined Application of Chemical Coagulants and Bio-coagulants 43

Figure 3.3 Experimental Setup of Batch Experiments with Biochars Prepared from Mahogany and Tamarind Powders 47

Figure 3.4 Continuous Column Test of Biochar Adsorption... 52

Figure 4.1 Turbidity Removal by Bio-coagulants 61

Figure 4.2 Color Removal by Bio-coagulants 61

Figure 4.3 Turbidity Removal by Chemical Coagulants 65

Figure 4.4 Color Removal by Chemical Coagulants 65

Figure 4.5 Turbidity and Color Removal by Mahogany and Chemical Coagulants 69

Figure 4.6 Turbidity and Color Removal by Tamarind and Chemical Coagulants.......... 69

Figure 4.7 Turbidity and Color Removal by Combined Bio-coagulants and Chemical... 71

Figure 5.1 Wastewater (left) and treated water (right) 86

ABSTRACT

Over the past several decades, ensuring an adequate supply of usable water has been a great challenge due to pollution, rapid population growth, overuse, declining resources and the impacts of climate change. While water purification can be a solution, conventional water treatment methods are often expensive and chemical-intensive, particularly in a developing country like Bangladesh. This study investigates the use of two locally available, low-cost agricultural byproducts - mahogany (*Swietenia macrophylla*) fruit shell powder and tamarind (*Tamarindus indica*) seed powder, for their individual and combined application as bio-coagulants at varying dosages; and their performance when paired with conventional chemical coagulants (Alum and $FeCl_3$) in order to treat a mixed source of domestic and industrial wastewater. In addition, biochars prepared from the same materials were tested for adsorption efficiency under both batch and continuous flow conditions. The research focuses on turbidity and color removal, two key indicators of organic and industrial pollution in effluents.

Batch experiments were conducted under constant operational conditions to determine the optimal dosage for the highest removal efficiency. The optimal dosages were found to be 10 mg/L for mahogany, 50 mg/L for tamarind and 25 mg/L for the combined dosage. Under identical conditions, turbidity removal efficiencies were 63.67%, 90.34% and 91.19%, respectively, while color removal efficiencies were 53.13%, 88.96% and 85.42%. The results indicate that both the materials and their combined usage exhibited noticeable removal efficiency, with tamarind seed powder showing the most effective overall performance among the bio-coagulants. To obtain a comprehensive comparison, the bio-coagulants were also applied in combination with conventional chemical coagulants such as alum and ferric chloride ($FeCl_3$) at optimized ratios. These hybrid systems showed improved removal efficiencies, with turbidity removal reaching up to 89.43% for the combined (bio-coagulant + alum) treatment and 88.15% for the (bio-coagulant + $FeCl_3$) treatment at 70:30 and 80:20 ratios, respectively. Color removal efficiencies also improved moderately for these combinations. Overall, these experimental results highlight the potential of using natural materials in wastewater treatment, offering a sustainable alternative that can reduce reliance on chemicals. In addition, biochar prepared from mahogany and tamarind was applied in adsorption studies to evaluate turbidity and color removal under both batch and continuous flow column conditions. Biochar batch adsorption exhibited high removal efficiencies for both turbidity and color. The biochars were able to remove upto 92% of turbidity and 73% of color, with equilibrium data best fitting the Freundlich isotherm model, indicating multilayer adsorption on heterogeneous surfaces. Continuous column experiments using these biochars further confirmed the reliability and stability of adsorption over time, demonstrating consistent reduction of turbidity and color under continuous flow and achieving 99% turbidity and 94-98% color removal of the effluent after 3 hours of operation. However, even after 12 hours of continuous operation, the adsorption performance of the biochars remained highly efficient, thus no breakthrough point was observed during the experiment.

Overall, the findings suggest that the application of these bio-coagulants and biochars can significantly reduce reliance on chemical treatments and imported reagents. Their utilization offers a cost-effective, environment-friendly and sustainable approach to wastewater purification, particularly suitable for a developing country like Bangladesh, abundant with natural resources. Moreover, this study highlights the potential of transforming agricultural byproducts into valuable treatment materials, thereby contributing to circular resource management and sustainable water treatment development in Bangladesh.

CHAPTER 1: INTRODUCTION

1.1 General

Water is one of the most vital natural resources for all forms of life, yet ensuring an adequate supply of clean and usable water has become one of the most critical global challenges. Rapid population growth, urbanization and industrial expansion have significantly increased water demand and wastewater generation, often surpassing the capacity of existing treatment systems. In many developing countries, this has led to widespread discharge of untreated or inadequately treated wastewater into natural water bodies. The resulting deterioration of water quality not only threatens aquatic ecosystems but also poses serious public health risks through contamination of surface and groundwater resources. According to the United Nations World Water Development Report (UNESCO, 2023), more than 80% of wastewater globally is released into the environment without sufficient treatment, particularly in low- and middle-income countries.

In the context of Bangladesh, the situation is particularly concerning. Major urban and industrial areas, including Dhaka, Gazipur and Narayanganj, generate large volumes of domestic and industrial wastewater daily. Bangladesh has experienced rapid urban growth, with the urban population increasing by more than 7% in the last decade (UN, 2019). This growth has led to higher volumes of domestic and industrial wastewater, putting considerable pressure on the existing treatment systems. Textile dyeing, tanneries and food-processing industries are among the leading contributors to wastewater pollution, producing highly colored and turbid effluents. Most of these effluents are discharged into nearby rivers such as the Buriganga, Turag and Shitalakhya without proper treatment. This pollution severely affects aquatic life, agricultural productivity and public health, as many communities rely on these water sources for domestic and agricultural use. Similar challenges are observed across other developing countries, where untreated or partially treated wastewater is discharged into rivers and canals, causing environmental degradation and public health issues (Ahmed et al., 2020). Despite some recent improvements, wastewater treatment coverage in Bangladesh remains low, with the majority of small and medium industries lacking efficient treatment facilities due to high operational and maintenance costs.

Conventional wastewater treatment methods often depend heavily on chemical coagulants such as aluminum sulfate (alum) and ferric chloride ($FeCl_3$) to remove turbidity, color and suspended solids. Although effective, their excessive use creates several challenges, including the generation of large quantities of non-biodegradable sludge, increased chemical costs and potential secondary pollution due to residual aluminum or iron ions. Moreover, in developing countries where treatment facilities operate under tight budgets, the continuous use of imported coagulants may not be economically sustainable. There is also growing concern over the environmental footprint associated with chemical-based treatment methods and the need for safer, eco-friendly alternatives that can ensure long-term sustainability.

In response to these challenges, increasing attention has been directed toward the use of natural coagulants and adsorbents derived from plants, seeds, fruit shells and other agricultural byproducts. These bio-based materials are locally available, renewable, biodegradable and less harmful to the environment. Materials such as Moringa oleifera, banana peel, rice husk and tamarind seed powder have shown promising results in removing turbidity and color from various types of wastewater. Similarly, the conversion of agricultural residues into biochar through pyrolysis has emerged as a potential method to enhance adsorption performance and improve pollutant removal efficiency. Studies in Asia and Africa have demonstrated that natural coagulants and biochars can effectively remove turbidity, color and organic pollutants through mechanisms such as charge neutralization, flocculation and multilayer adsorption (Ali et al., 2019; Rahman et al., 2019). Using such low-cost natural materials not only promotes waste valorization but also contributes to the circular economy and supports sustainable development goals (SDG 6 - Clean Water and Sanitation).

The exploration of these natural materials represents a promising step toward developing sustainable wastewater treatment systems, especially for countries like Bangladesh, where financial and technological constraints often limit large-scale implementation of conventional treatment plants. By utilizing locally sourced, low-cost bio-coagulants and biochar, it becomes possible to design effective, environment-friendly and economically feasible treatment processes that can complement or partially replace traditional chemical methods. Such approaches not only reduce dependency on chemicals but also minimize the environmental impacts associated with sludge disposal and secondary pollution, ultimately supporting cleaner and more resilient water management systems.

1.2 Problem Statement

Bangladesh continues to face critical challenges in managing and treating wastewater due to rapid industrialization, urban expansion and insufficient treatment infrastructure. The excessive use of chemical coagulants such as alum and ferric chloride in conventional treatment plants leads to high operational costs, chemical sludge generation and potential secondary pollution. Despite these drawbacks, dependence on chemical treatment remains widespread.

At the same time, large quantities of agricultural byproducts such as mahogany fruit shells and tamarind seeds are readily available but remain underutilized. These natural materials have the potential to serve as cost-effective and eco-friendly coagulants or adsorbents in wastewater treatment. However, comprehensive studies examining their efficiency, dosage optimization, adsorption behavior and performance under continuous flow conditions are still limited. Addressing these gaps is essential for identifying sustainable alternatives that can reduce reliance on chemicals and promote environmentally responsible treatment practices in Bangladesh.

1.3 Objectives of the Study

The main objective of this study is to explore the potential of mahogany and tamarind-based materials as natural coagulants and biochars for turbidity and color removal from wastewater.

The specific objectives are:

- To determine turbidity and color removal efficiency of mahogany and tamarind-based bio-coagulants and biochar through batch experiments.
- To identify the optimum dosage of bio-coagulants and biochar for maximum removal performance.
- To evaluate the adsorption performance of biochar and determine the best-fit isotherm model.
- To assess turbidity and color removal efficiency of biochar under continuous flow conditions.
- To compare different treatment methods to identify the most sustainable and efficient approach for wastewater purification in the local context.

1.4 Scope and Limitations of the Study

Very few studies have directly compared mahogany and tamarind-based bio-coagulants under identical experimental conditions. Research papers exploring their combined application or integration with chemical coagulants, which could reduce costs and chemical use, are also very limited. Similarly, the adsorption efficiency of biochars prepared from these materials, particularly using locally sourced agricultural residues, need further extensive study. Comparative evaluations of bio-coagulants, chemical coagulants and biochars to determine the most sustainable wastewater treatment method are also not well-explored.

This study addresses these research gaps by evaluating turbidity and color removal efficiencies of mahogany and tamarind bio-coagulants, their combined applications and their integration with chemical coagulants. Additionally, the study investigates biochar adsorption performance under both batch and continuous flow conditions and identifies optimal dosages and application strategies to maximize treatment efficiency. By doing so, it provides practical insights into sustainable, cost-effective and locally adaptable wastewater treatment approaches.

However, the availability of mahogany fruit shells and tamarind seeds is seasonal, which may restrict continuous production of bio-coagulants or biochar. However, the prepared coagulants and biochars can be stored under controlled conditions for later use, partially mitigating this limitation. Other factors such as temperature fluctuations, quality of raw materials and operational conditions in real-scale applications could also influence results. In addition, laboratory-scale findings may differ when scaled up and long-term stability of bio-coagulant solutions and continuous flow column performance require further investigation.

1.5 Layout of the Thesis

This thesis is organized into five comprehensive chapters, along with a full list of references and appendices. Each chapter builds upon the previous to provide a complete understanding of the study.

Chapter 1 introduces the background of wastewater treatment challenges, highlighting the problem of chemical dependence, rising pollution loads and the potential of natural alternatives. It also outlines the research gaps, objectives and the overall purpose of the study.

Chapter 2 provides an extensive literature review on wastewater treatment practices worldwide and in Bangladesh. It discusses conventional chemical coagulants, natural bio-coagulants, biochar adsorption and hybrid treatment approaches. Previous studies on removal of turbidity and color, adsorption mechanisms and isotherm modeling are critically analyzed to contextualize the current research.

Chapter 3 details the methodology of the study. It describes the preparation of bio-coagulants and biochars, batch jar experiments, continuous flow column tests and the analytical procedures for turbidity and color measurements. Standard protocols, experimental setups, sample collection and data recording procedures are thoroughly explained.

Chapter 4 presents the results and discussion of the experiments. Batch study findings for mahogany and tamarind bio-coagulants, chemical coagulants, their combined applications and biochars are reported. Continuous column performance and adsorption efficiency data are analyzed. The optimum dosages, removal efficiencies and isotherm model fits are discussed and the results are interpreted in the context of previous studies and sustainability considerations.

Chapter 5 summarizes key findings on the performance of bio-coagulants, chemical coagulants, their combinations and biochars. Provides recommendations for practical applications, sustainability and future research, including scaling up natural treatments and integrating them with conventional systems.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Wastewater treatment is a critical area of research due to increasing water demand and pollution. While chemical coagulants are widely used, their high cost, sludge production, and potential health risks have motivated the search for alternatives. Natural coagulants and biochars, derived from plant-based wastes, offer low-cost, sustainable options, removing turbidity and contaminants through flocculation and adsorption.

This chapter reviews global research on wastewater treatment, focusing on plant-derived coagulants and biochars, highlighting key findings, preparation methods, and research gaps relevant to sustainable solutions.

2.2 Global Perspective on Wastewater Generation and Treatment

The global rise in population, industrialization, and urbanization has drastically increased wastewater generation, posing serious environmental and public health challenges. It is estimated that over 80% of global wastewater is discharged untreated into natural ecosystems, contaminating both surface and groundwater sources (WWAP, 2017). Such discharges threaten aquatic biodiversity, compromise food security, and undermine the achievement of Sustainable Development Goal 6 (Clean Water and Sanitation).

In developed countries, advanced wastewater infrastructure has significantly reduced untreated discharges. However, these systems increasingly struggle to remove emerging pollutants such as pharmaceuticals, endocrine-disrupting compounds, and microplastics (Sato et al., 2013; Jiang et al., 2013). In contrast, developing nations, particularly in Asia and Africa, face acute challenges due to inadequate collection networks, insufficient treatment capacity, and weak enforcement of discharge regulations (Tella et al., 2023; Kjellén & M., 2018; Ingole et al., 2012). As a result, untreated wastewater remains a major source of pollution, leading to the degradation of rivers, lakes, and wetlands, and contributing to the spread of waterborne diseases such as cholera, dysentery, and typhoid (Breach et al., 2018; Sonune & Ghate, 2004).

Traditional treatment technologies, such as coagulation-flocculation, sedimentation, filtration, and activated sludge, are widely used but suffer from economic and performance limitations. While these methods effectively remove suspended solids and biodegradable organic matter, they remain inefficient against persistent contaminants, including dyes, heavy metals, and complex industrial compounds (Owhonka et al., 2021; Ingole et al., 2012; Sonune & Ghate, 2004). Additionally, these systems generate large volumes of chemical sludge, require continuous energy input, and demand high operational and maintenance costs, particularly in resource-limited settings (Ingole et al., 2012; Tella et al., 2023).

In response, recent decades have seen a paradigm shift toward advanced and hybrid wastewater treatment systems that integrate biological, physicochemical, and membrane-based processes. Membrane bioreactors (MBRs) and nanofiltration systems have demonstrated high efficiency in pathogen and nutrient removal, enabling the reuse of treated wastewater for irrigation and industrial purposes (Sonune & Ghate, 2004; WWAP, 2017). Similarly, advanced oxidation processes (AOPs), including photocatalysis, ozonation, and electrochemical oxidation, can degrade complex organic pollutants beyond the reach of conventional treatments (Jiang et al., 2013; Sonune & Ghate, 2004). However, their high capital investment and energy-intensive operation limit large-scale implementation in developing regions (Ingole et al., 2012).

The following table summarizes global wastewater generation, collection, and treatment coverage, highlighting stark disparities between high-income and low-income regions in both technological capacity and sustainability focus.

Table 2.1 Global Wastewater Generation and Treatment Coverage

Region	Wastewater Generated (km^3/year)	Collected (%)	Treated (%)	Untreated Discharge (%)	Typical Treatment Technologies
North America	85	90	76	24	Activated sludge, MBRs, AOPs
Europe	70	95	85	15	Biological treatment, membrane filtration
Asia-Pacific	160	60	25	75	Coagulation, lagoon systems, biochar adsorption
Latin America	45	70	35	65	Conventional biological and natural treatment systems
Africa	20	30	10	90	Decentralized, low-cost natural and coagulant systems
Global Average	380	56	20	80	Conventional + emerging eco-friendly hybrid approaches

References: (Kjellén, 2018; Sonune & Ghate, 2004; Tella et al., 2023; WWAP, 2017)

Globally, the focus of wastewater management has evolved from mere disposal toward resource recovery and water reuse, particularly within the framework of circular economy models (Kjellén, 2018; WWAP, 2017). Developed countries are advancing closed-loop systems that recover nutrients, energy, and water, while developing regions emphasize low-cost, locally available, and nature-based treatment options such as bioadsorbents and plant-derived coagulants to enhance affordability and sustainability (Ingole et al., 2012; Owhonka et al., 2021; Tella et al., 2023).

Achieving global water security will require not only technological innovation but also stronger financial mechanisms and governance frameworks. Future strategies should integrate eco-efficient technologies with inclusive policies, ensuring equitable access to safe water and effective wastewater treatment across all regions.

2.3 Wastewater Treatment Scenario in Bangladesh

Bangladesh faces growing challenges in wastewater management due to rapid urbanization, industrial expansion, and limited treatment infrastructure. The country generates approximately 5,326 million m^3 of wastewater annually from domestic and industrial sources combined (Islam, 2023). Despite this large volume, treatment coverage remains low. In urban centers such as Dhaka and Chattogram, the existing systems are inadequate to meet the increasing demand. The Pagla Sewage Treatment Plant, designed decades ago, operates below capacity (Dey & Islam, 2015), while the newly commissioned Dasherkandi STP (2023), South Asia's largest with 500 million L/day capacity, treats only part of the sewage load, leaving the rest to pollute rivers like the Buriganga (Hossain et al., 2018; Sharmin & Ayesha, 2016).

Industrial wastewater further aggravates environmental stress. The leather tanning industry in Hazaribagh, Dhaka, discharges roughly 21,000 m^3/day of untreated effluent containing chromium, acids, and dyes, posing risks to aquatic ecosystems and public health (Gulfam-E-Jannat et al., 2023; Haque, 2020). Similarly, the textile sector is both water- and chemical-intensive. On average, factories consume 164 L of groundwater and 136 L of dyehouse water per kg of fabric, generating about 119 L of wastewater and using roughly 449 g of chemicals per kg of textiles (Shefa et al., 2023). High dye and salt usage, especially in deep-shade dyeing, leads to up to 40 % residual dyes in effluents, creating heavy coloration and chemical contamination (Shefa et al., 2023).

Table 2.2 Wastewater Generation, Treatment, and Chemical Use in Bangladesh

Sector	Avg Water Consumption (L/kg)	Wastewater Generated (L/kg)	Chemical Use (g/kg)	Treatment Technology
Textile (all types)	164 (groundwater), 136 (dyehouse)	119	449 (range 152-705)	Biological, Physico-Chemical, MBR
Leather Tanning	N/A	21,000 m^3/day untreated	N/A	Minimal / Basic ETP
Domestic Urban	N/A	5,326 million m^3/year total	N/A	Limited centralized STPs, Dasherkandi Plant (500 m^3/day)

References: (daiki-axisbd.com, 2025; Time, 2015; Uddin et al., 2023; Water Technologies, 2025; Wikipedia, 2025; Wired, 2017)

Although conventional methods such as coagulation-flocculation, sedimentation, and chlorination are well known, they remain under-implemented due to high operating costs and dependence on imported chemical coagulants like alum and ferric salts (Sarker & Sarkar, 2018). These chemicals not only increase treatment expenses but also generate toxic sludge and metal residues harmful to aquatic life and human health (Sarker & Sarkar, 2018). Consequently, a shift toward eco-friendly and low-cost alternatives is gaining momentum.

A feasibility study on Common Effluent Treatment Plants (CETPs) for the textile sector revealed that zero-liquid-discharge (ZLD) systems can recover 90-95% of water and cut treatment costs by 18.7% (Ihekweme et al., 2020). However, small- and medium-scale industries still struggle to afford such systems without collective investment or policy incentives (Ihekweme et al., 2020). Innovative technologies, such as non-thermal plasma treatment, have emerged as cost-effective options for domestic and agricultural water purification, enhancing physicochemical and microbiological quality while avoiding harmful chemical residues (Sarker & Sarkar, 2018).

In rural and peri-urban regions, biological and natural treatments are gaining traction. Studies demonstrated that combining Moringa seed powder and scallop powder, followed by bio-sand filtration, yields water meeting US EPA standards (6W Research, 2024). Similarly, natural adsorbents like clay, activated carbon, zeolites, rice husk, chitosan, hydroxyapatite, and modified expanded clay aggregates have shown strong potential to remove microbial, organic, and inorganic contaminants (Begum et al., 2025). These natural coagulants are not only cost-efficient but also environmentally benign, minimizing toxic by-products associated with chemical treatments.

Despite such advances, wastewater treatment coverage remains critically low. According to the Department of Environment (DoE), less than 10 % of total wastewater in Bangladesh is treated before disposal (Dey & Islam, 2015; daiki-axisbd.com, 2025). The figure below illustrates the disparity in treatment coverage across sectors, while the table summarizes major wastewater management strategies currently applied in Bangladesh.

Table 2.3 Key Wastewater Treatment Strategies in Bangladesh

Sector	Treatment Method	Key Challenges	Cost Level	Sustainability
Domestic (Urban)	Centralized STPs (e.g., Pagla, Dasherkandi)	Aging infrastructure, high O&M cost	High	Moderate
Domestic (Rural)	Natural filters, lagoons	Land requirement	Low	Moderate
Textile Industry	CETP, ZLD, MBR	High capital + maintenance cost	High	High
Leather Tanning	Basic ETPs / Minimal Treatment	Toxic effluent, weak enforcement	Moderate	Low
Food & Agro	Biological + Natural Coagulants	Sludge management	Moderate	High
Research & Innovation	Plasma, Moringa, Biochar approaches	Limited scalability	Low-Moderate	High

References: (Gulfam-E-Jannat et al., 2023; Haque, 2020; Islam, 2023; Sarker & Sarkar, 2018; Sharmin & Ayesha, 2016; Shefa et al., 2023)

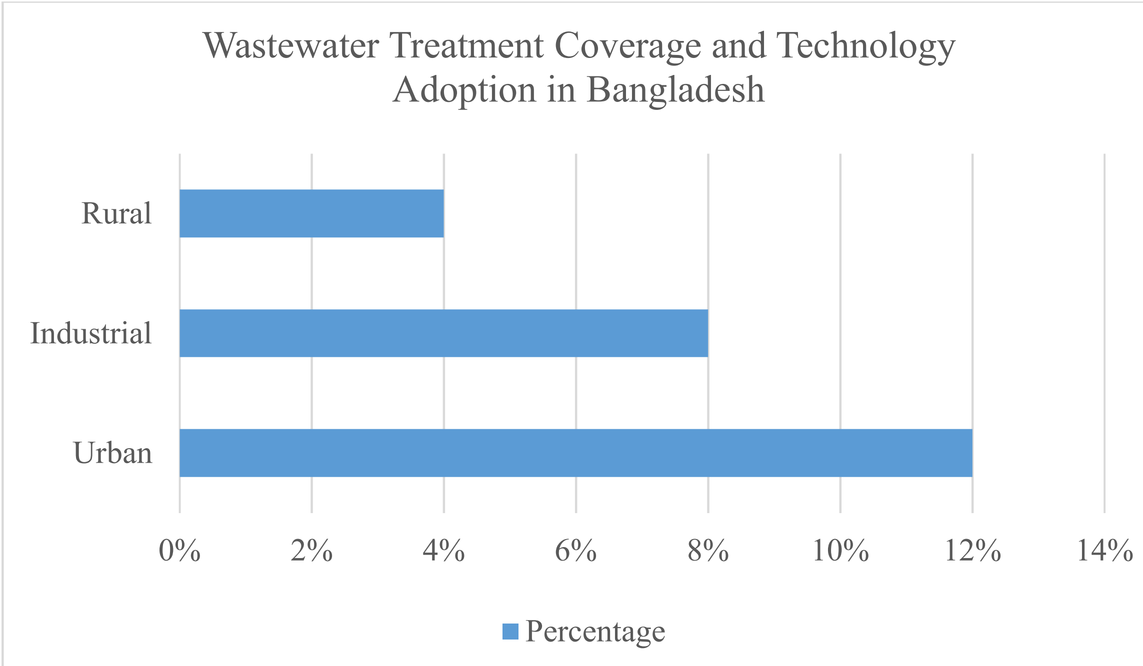


Figure 2.1 Wastewater Treatment Coverage and Technology Adoption in Bangladesh

References: (Gulfam-E-Jannat et al., 2023; Islam, 2023; Shefa et al., 2023)

Overall, Bangladesh is gradually transitioning from chemical-based to bio-based and physical treatment systems, reducing reliance on costly imports and promoting circular-economy practices through reuse of agricultural waste materials as coagulants or adsorbents. Sustainable wastewater management, supported by policy reforms, public-private partnerships, and technological adaptation, is vital for achieving long-term water security and environmental resilience.

2.4 Conventional Coagulants and Their Drawbacks

Conventional coagulation-flocculation remains one of the most widely used water and wastewater treatment processes due to its proven efficiency, ease of operation, and ability to rapidly reduce turbidity and color from raw water. Commonly applied coagulants include aluminum sulfate (alum), ferric chloride, and polyaluminum chloride (PACl), which destabilize suspended colloids through charge neutralization and enmeshment within flocs (Diver et al., 2023). These materials typically achieve high removal efficiencies for turbidity (80-99 %) and color (70-95 %) across a broad range of pH and particle loads (Diver et al., 2023). Despite these advantages, the application of metal-based coagulants introduces several environmental, economic, and health-related limitations that are increasingly drawing global concern.

From an operational perspective, chemical coagulants require precise pH control, continuous dosing, and post-treatment sludge handling, all of which contribute to higher operational costs (Sinha et al., 2004). Studies comparing electrochemical and conventional coagulation indicate that although both achieve comparable removal efficiencies, traditional coagulants generate large volumes of metal-rich sludge that demand energy-intensive dewatering and disposal (Bahrodin et al., 2021). The disposal of this sludge often leads to secondary pollution when landfilled or discharged into surface waters, as aluminum and iron ions may leach into the environment.

Health implications of aluminum accumulation in the human body have also been widely documented. Long-term exposure through drinking water has been correlated with neurological disorders such as Alzheimer's disease (Salem et al., 2021). Similarly, ferric-based coagulants, though less neurotoxic, can increase residual iron concentration in treated water, causing aesthetic and taste issues, pipe corrosion, and potential microbial regrowth (Mishra et al., 2019). These risks, coupled with the rising cost of chemical reagents, have motivated extensive research into low-cost and safer alternatives.

Furthermore, chemical coagulants are energy-intensive to produce, contributing indirectly to greenhouse gas emissions. The production of alum, for instance, involves bauxite mining and sulfuric acid treatment, both environmentally degrading processes (Alexander et al., 2012). In developing regions, especially where water treatment facilities operate with limited budgets and technical capacity, the dependence on such imported and chemical-intensive agents challenges the sustainability of water treatment systems (Salem et al., 2021).

The table here summarizes the characteristics and drawbacks of the most commonly used conventional coagulants.

Table 2.4 Comparison of Common Conventional Coagulants

Coagulant	Main Mechanism	Typical Turbidity Removal (%)	Key Advantages	Major Drawbacks
Aluminum sulfate (Alum)	Charge neutralization and sweep flocculation	80-99	Highly effective, widely available	Produces large sludge volumes; residual Al linked to Alzheimer's disease; narrow optimal pH range
Ferric chloride	Hydrolysis and adsorption of colloids	75-95	Effective across wide pH range; strong color removal	Corrosive; may impart color and taste; residual Fe may exceed standards
Polyaluminum chloride (PACl)	Pre-hydrolyzed polymeric species enhance bridging	85-98	Works efficiently at lower dosages; faster floc formation	Costly; still yields metal-rich sludge; environmental persistence

References: (Diver et al., 2023; Mishra et al., 2019; Salem et al., 2021; Sinha et al., 2004)

In light of these challenges, there is growing interest in the development of eco-friendly, biodegradable coagulants derived from plants, microbes, and agricultural by-products that can replace or supplement metal salts (Bahrodin et al., 2021). These natural and bio-based materials aim to reduce toxicity, minimize sludge generation, and provide cost-effective treatment compatible with local resources.

2.5 Natural and Bio-Based Coagulants

Natural and bio-based coagulants have emerged as promising alternatives to conventional chemical coagulants for wastewater treatment due to their biodegradability, lower cost, and reduced environmental impact. These coagulants are generally derived from plants, animals, or microorganisms and have demonstrated efficiency in removing turbidity, color, organic matter, heavy metals, and pathogenic microorganisms (Kurniawan et al., 2023). Plant-based coagulants are typically extracted from seeds, fruit peels, leaves, or bark, containing cationic proteins, polysaccharides, and polyphenols that facilitate coagulation-flocculation (Benalia et al., 2024; Kurniawan et al., 2023; Radovic et al., 2023). Moringa oleifera seeds, for example, are rich in cationic proteins that neutralize negatively charged colloids, while Cicer arietinum (chickpea) and Strychnos potatorum seeds have proteins that form flocs by bridging suspended particles (Deepa et al., 2022).

The extraction methods, such as solvent extraction, ultrasonic-assisted extraction, and microwave-assisted grafting copolymerization, can significantly enhance the physicochemical properties and stability of plant-based natural coagulants (PBNCs). Optimizing these processes using response surface methodology and carefully designed extraction protocols improves coagulation efficiency, grafting yield, and practical applicability (Benalia et al., 2024; Usman et al., 2023). However, challenges with PBNCs include instability during storage due to biological degradation, variability in composition depending on plant species, season, and cultivation conditions, and competition with food sources when edible plants are used. Additionally, large-scale application is limited by the lack of standardization (Benalia et al., 2024; Usman et al., 2023). Despite these limitations, modified PBNCs have demonstrated treatment efficiencies comparable to chemical coagulants and hold significant promise for sustainable wastewater management.

Animal-based coagulants, such as chitosan derived from crustacean shells, provide high coagulation efficiency and antimicrobial properties but are limited by cost and ethical concerns. Microorganism-derived coagulants, including bioflocculants, are environmentally friendly and can produce value-added products, yet their production is more complex and scaling remains a challenge (Badawi et al., 2023; Kurniawan et al., 2023). Recent advancements have incorporated magnetic nanoparticles into natural coagulants, creating magnetic natural coagulants/flocculants (MN-CFs) that enable easy separation and recovery from treated wastewater. Large-scale proposed systems include magnetic chitosan nanoparticles, magnetic Moringa seeds, magnetic starch-based flocculants, magnetic tannin-based coagulants, and magnetic cellulose-based flocculants. These MN-CFs provide cost-effective, sustainable, and easily recoverable treatment options, particularly suitable for developing countries with limited access to clean water (Kurniawan et al., 2023).

Experimental studies on dairy wastewater demonstrate the practical effectiveness of plant-based coagulants. Deepa et al. (2022) compared Strychnos potatorum, Cicer arietinum, and Moringa oleifera with chemical coagulants, showing high turbidity and BOD removal: Strychnos potatorum achieved 75.62% turbidity removal and 72.1% BOD reduction, Cicer arietinum showed 74.23% turbidity removal and 63.2% BOD reduction, and Moringa oleifera achieved 65.6% turbidity removal and 70.9% BOD reduction. These results demonstrate that plant-based coagulants can achieve 65-76% turbidity removal and 63-72% BOD reduction, which is competitive with conventional chemical coagulants. Furthermore, PBNCs generate less sludge, are biodegradable, and reduce environmental risks, making them sustainable alternatives (Deepa et al., 2022; Kurniawan et al., 2023; Radovic et al., 2023; Usman et al., 2023).

The sustainability of natural coagulants, including PBNCs, MN-CFs, and animal/microbial coagulants, can be evaluated across environmental, technical, and economic dimensions. Environmentally, they reduce sludge volume, are less toxic, and residuals can be reused in agriculture or construction (Benalia et al., 2024; Kurniawan et al., 2023). Technically, they provide reliable performance, compatibility with other water treatment steps, and potential for large-scale application, especially when functionalized with magnetic nanoparticles (Badawi et al., 2023; Kurniawan et al., 2023). Economically, natural coagulants can lower costs, particularly when derived from local, non-edible plant sources (Benalia et al., 2024; Radovic et al., 2023; Usman et al., 2023). Future research should focus on enhancing stability, standardizing production protocols, optimizing extraction and modification methods, and integrating natural coagulants into hybrid treatment systems to maximize efficiency and commercialization potential (Benalia et al., 2024; Kurniawan et al., 2023; Radovic et al., 2023; Usman et al., 2023). Overall, plant-based and bio-based coagulants offer a promising, environmentally friendly, and cost-effective alternative to traditional chemical coagulants, with growing evidence supporting their application in industrial, municipal, and food processing wastewater treatment (Deepa et al., 2022).

2.6 Mahogany and Tamarind as Bio-Coagulants

Mahogany (Swietenia macrophylla) and tamarind (Tamarindus indica) are emerging as highly promising natural coagulants for water and wastewater treatment, offering sustainable alternatives to conventional chemical coagulants such as aluminum sulfate and ferric chloride. Both species are abundantly available in tropical regions, and their by-products, such as fruit shells and seeds, are typically discarded as agricultural waste, making them ideal candidates for low-cost and eco-friendly water purification applications (Akhtar et al., 2015; Adeogun et al., 2019; Choy et al., 2016).

Recent studies have demonstrated that the seed and shell powders of these plants possess functional groups, including hydroxyl, carbonyl, and carboxyl groups, which actively participate in the coagulation-flocculation process through charge neutralization and polymer bridging (Gunatilake, 2017; Saleem & Bachmann, 2019; Zainol & Fadli, 2020). These biopolymers enhance floc formation and settling efficiency, effectively reducing turbidity, suspended solids, color, and even heavy metals. For instance, tamarind seed extracts have shown removal efficiencies exceeding 99% for turbidity and 77% for COD at optimal dosages of 30 mg/L and pH 5 (Adeogun et al., 2019), while mahogany fruit shell and biochar have exhibited strong adsorptive and flocculating properties against both organic and inorganic contaminants (Idris et al., 2018).

In addition to pollutant removal, both materials generate biodegradable, non-toxic sludge, offering an added advantage over chemical coagulants that produce hazardous residues (Hasan et al., 2022; Pathak et al., 2021). Their application aligns with circular economy principles, where the waste from one system serves as a resource in another, contributing to sustainable environmental management and agricultural productivity. Furthermore, the polysaccharides and proteins in tamarind and the lignocellulosic components in mahogany enhance their cationic activity, enabling effective interaction with negatively charged colloids and fine particulates (Saleem & Bachmann, 2019; Zainol & Fadli, 2020).

The future potential of mahogany and tamarind as bio-coagulants lies in their wide adaptability, cost-effectiveness, and environmental compatibility. Tamarind, being a common kitchen waste, can be easily sourced, processed, and utilized even in rural settings with minimal technology (Akhtar et al., 2015). Meanwhile, mahogany, often used for timber production, generates large volumes of shells and husks that can be valorized for water purification instead of disposal. With advances in biochar modification, extraction methods, and surface activation, these materials can be further optimized to enhance removal efficiency for dyes, heavy metals, and industrial effluents (Gunatilake, 2017; Ojha et al., 2020).

In the context of Bangladesh and other developing nations, where treatment facilities are limited, these bio-coagulants represent a green and affordable solution for addressing both domestic and industrial water quality challenges. The integration of tamarind and mahogany-based materials into existing treatment frameworks can significantly reduce chemical dependency, operational costs, and secondary pollution. Moreover, their demonstrated performance in removing contaminants such as turbidity, COD, TDS, and fluoride positions them as viable candidates for large-scale sustainable wastewater treatment (Banu et al., 2017; Ojha et al., 2020; Saleem & Bachmann, 2019).

Table 2.5 Comparative characteristics and performance of Tamarind and Mahogany-based bio-coagulants

Parameter	Tamarind Seed	Mahogany Fruit Shell	References
Botanical Name	*Tamarindus indica*	*Swietenia macrophylla*	*Wikipedia*
Main Active Compounds	Polysaccharides, proteins, tannins	Lignin, cellulose, polyphenols	(Akhtar et al., 2015; Aboagye et al., 2021)
Mechanism of Coagulation	Charge neutralization and inter-particle bridging	Protein-mediated charge neutralization and polymer bridging	(Wasj, 2017; Zainol & Fadli, 2020)
Optimum pH Range	3.0-6.0	5.0-8.0	(Idris et al., 2018; Ochoa-Fajardo et al., 2020)
Optimum Dosage	30-40 mg/L (distilled water extraction)	0.4-1.0 g/L (powder form)	(Ojha et al., 2020; Wasj, 2017)
Turbidity Removal Efficiency	86-99%	80-95%	(Wasj, 2017; Zainol & Fadli, 2020)
COD/BOD Reduction	68-77%	65-90%	(Idris et al., 2018; Idris, Karamba, & Ayoubi, 2018)

Heavy Metal Removal	Cu^{2+}: 89% [4]	Pb^{2+}, Cd^{2+}: 80-92% [10]	(Gunatilake, 2017; Ojha et al., 2020)
Functional Groups	-OH, -COOH, $-NH_2$ (FTIR)	-OH, -C=O, -COOH (FTIR)	(Jaganathan et al., 2023)
Sludge Property	Biodegradable, non-toxic	Biodegradable, fibrous structure	(Kaur et al., 2021; Pathak et al., 2021)
Source	Agricultural seed waste	Timber by-product waste	(Jaganathan et al., 2023)
Best Reported Performance	99% turbidity removal at 30 mg/L [3]	High adsorption with modified biochar [7]	(Vijayaraghavan et al., 2018; Zainol & Fadli, 2020)
Environmental Benefit	Reduces chemical coagulant use, thus, lower sludge toxicity	Eco-friendly, supports circular reuse of agricultural waste	(Sharma et al., 2020; Vijayaraghavan et al., 2018)
Research Gaps	Limited hybrid (bio + chemical) studies ; scaling methods	Few comparative and long-term performance studies	(Sharma et al., 2020)

As shown in the above table, both mahogany and tamarind seeds exhibit promising characteristics as sustainable bio-coagulants for water and wastewater treatment. Their natural composition, rich in proteins, polyphenols, and polysaccharides, contributes to effective pollutant removal through charge neutralization and polymer bridging. Tamarind seed extracts demonstrate particularly high turbidity and COD removal efficiencies at relatively low dosages, while mahogany's fibrous lignocellulosic structure enhances floc formation and sedimentation. Both materials yield biodegradable sludge, minimizing secondary pollution and offering potential reuse in agriculture. These findings collectively underscore the growing viability of agricultural by-products as low-cost, eco-friendly coagulants, aligning with global efforts toward sustainable water treatment technologies.

2.7 Biochar for Wastewater Treatment

Recent research highlights the growing significance of biochar and natural adsorbents as sustainable alternatives to conventional activated carbon in wastewater treatment. Thompson et al. (2020) demonstrated that moderate capacity wood biochar can outperform coal-based powdered activated carbon (PAC) in removing micropollutants from wastewater, offering environmental benefits in smog, global warming, respiratory effects, and noncarcinogenic impacts, while also aiding carbon sequestration. However, biochar production conditions and adsorption capacity critically influence overall environmental performance, with low-capacity wood biochar requiring larger dosages and biosolids biochar showing poorer outcomes (Environ. Sci. Technol., 2016).

The development of magnetic biochar (MBC) offers enhanced practicality for wastewater remediation due to its magnetic separability, allowing repeated application and mitigating secondary pollution risks. Kang et al. (2023) highlighted trends in synthesizing MBC using Fe or Mn to improve adsorption efficiency, with hydrothermal synthesis gaining attention for its mild reaction conditions. Challenges remain regarding adsorption capacity, techno-economic feasibility, and life-cycle environmental impacts, emphasizing the need for future studies on real wastewater applications (Kang et al., 2023).

Comparative studies of granular biochar versus granular activated carbon (GAC) indicate that biochar can be an effective, low-cost alternative for high-strength wastewater treatment and nutrient recovery. Huggins et al. (2016) found that macroporous biochar exhibits greater adsorption capacity for COD, PO_4, and NH_4 at high concentrations, while also retaining beneficial macronutrients and showing reduced fouling compared to microporous GAC. This structural advantage enhances both treatment efficiency and the potential for resource recovery (Huggins et al., 2016).

From a circular economy perspective, biomass-derived biochar provides additional environmental and economic benefits. Olunusi et al. (2023) emphasized that biochar can treat a variety of contaminants, organic, inorganic, heavy metals, and nutrients, while promoting reuse in agriculture, construction, and industrial applications. Integration with machine learning approaches further supports optimization of biochar-based treatment systems (Olunusi et al., 2023).

Regeneration and sustainability of biochar are critical for practical wastewater applications. Alsawy et al. (2022) reviewed chemical regeneration methods, noting that proper management of spent adsorbents (reuse, soil amendment, energy recovery) minimizes secondary pollution. Regeneration efficiency depends on adsorption mechanisms, surface functional groups, pore structure, and adsorbent stability. Challenges include scaling up to real effluent treatment, optimizing regeneration cycles, and mitigating toxic by-product formation (Selvakarthi & Ragupathy, 2024).

Natural adsorbents like tamarind seeds, date seeds, and palm leaves have also proven effective for industrial effluent treatment. Selvakarthi & Ragupathy (2024) combined these adsorbents with Vapor Absorption Technology (VAT), achieving a total removal efficiency of 85.92% for textile wastewater. Each material contributed differently: date seeds reduced turbidity, tamarind seeds neutralized pH, and palm leaves removed heavy metals. Process optimization using Response Surface Methodology (RSM) and Box-Behnken Design (BBD) demonstrated an eco-friendly, cost-effective, and scalable solution for wastewater remediation (Alsawy et al., 2022).

The table below can summarize these studies, showing biochar type, feedstock, modifications, target contaminants, performance, regeneration potential, and environmental considerations. Collectively, these studies indicate that biochar and natural adsorbents are promising candidates for sustainable, low-cost, and effective wastewater treatment, with future research needed to optimize regeneration, large-scale applicability, and circular economy integration (Kang et al., 2023; Huggins et al., 2016; Olugbenga et al., 2023; Selvakarthi & Ragupathy, 2024; Alsawy et al., 2022).

Table 2.6 Summary of Biochar and Natural Adsorbents for Wastewater Treatment

Biochar/ Adsorbent Type	Material	Modification	Target Contaminants	Performance	Regeneration	Environmental Notes
Wood biochar	Wood	Powdered, moderate/low capacity	Micropollutants (e.g., sulfamethoxazole)	Moderate capacity: environmental benefits in smog, global warming, respiratory effects; Low capacity: worse impacts for eutrophication, carcinogenics	N/A	Sequesters carbon; offsets wastewater facility carbon footprint
Magnetic biochar (MBC)	Biomass	Fe or Mn loading; hydrothermal synthesis	Heavy metals, dyes, pharmaceuticals	Magnetic separability allows repeated use; adsorption efficiency comparable to BC	High potential for regeneration; prevents secondary pollution	Needs techno-economic assessment and life-cycle evaluation

Granular biochar (BC)	Lodgepole pine wood	Macroporous granules	COD, PO_4, NH_4	High adsorption capacity for COD-T and nutrients; better fouling resistance than GAC	N/A	Macroporous structure enhances nutrient recovery and sustainability
Biomass-derived biochar	Various biomass	Catalytic/modified	Organic pollutants, heavy metals, nutrients, leachates	Effective in multiple contaminants; performance influenced by surface area, porosity, functional groups	Can be reused in agriculture, construction, refinery	Circular economy benefits; potential for machine learning optimization
Regenerated biochar	Various	Chemical regeneration (organic/inorganic agents)	Organic and inorganic pollutants	Regeneration performance depends on adsorption mechanism and pore structure; declines with cycles unless optimized	High reusability with proper management; reuse, soil amendment, energy recovery	Reduces cost and energy; careful handling needed to prevent

						secondary pollution
Natural adsorbents	Tamarind seeds, date seeds, palm leaves	Powdered; used with Vapor Absorption Technology	Textile effluent (heavy metals, turbidity, pH, TDS, COD, BOD)	Combined removal efficiency: 85.92%; specific improvements per material: date seeds reduce turbidity 67.7%, tamarind seeds reduce pH 20.5%, palm leaves remove heavy metals	N/A	Eco-friendly, renewable, cost-effective; optimized with RSM/Box-Behnken Design

References: (Environmental Science & Technology, 2016; Kang et al., 2023; Huggins et al., 2016; Olugbenga et al., 2023; Selvakarthi & Ragupathy, 2024; Alsawy et al., 2022)

The studies summarized in this table collectively highlight the potential of biochar and natural adsorbents as sustainable, low-cost, and effective solutions for wastewater treatment. Their versatility in targeting various pollutants, combined with possibilities for regeneration, circular economy integration, and process optimization, underscores their growing relevance in modern water treatment strategies. While laboratory and pilot-scale studies have shown promising results, further research is necessary to scale these technologies for real-world applications, optimize regeneration cycles, and fully assess environmental and economic impacts. Continued innovation in biochar modification, hybrid adsorption systems, and integration with digital tools such as machine learning will be crucial for advancing sustainable wastewater management practices.

2.8 Mahogany and Tamarind-Based Biochar

Biochar derived from agricultural wastes has emerged as an effective and low-cost adsorbent for water and wastewater treatment. Among these, mahogany (Swietenia macrophylla and Khaya senegalensis) fruit shells and tamarind (Tamarindus indica) seeds and shells are particularly promising due to their high lignocellulosic content, availability, and surface functionality. Conversion of these biomaterials into biochar, through pyrolysis or chemical activation, enhances surface area, porosity, and introduces active functional groups conducive to adsorption of heavy metals, dyes, fluoride, and pathogens.

Mahogany-Based Biochar:

Mahogany fruit shells (MFS) have been widely investigated as an adsorbent. Patil et al. (Patil et al., 2020; Suryakant A. Patil et al., 2020) synthesized MFS activated carbon (MFSAC) using concentrated H_2SO_4, achieving a maximum Pb(II) adsorption of 322.28 mg g^{-1} and 99.7% removal, following pseudo-second-order kinetics and Langmuir isotherms. Thermodynamic studies indicated the adsorption was spontaneous and endothermic. TiO_2-impregnated MFS biochar prepared from Khaya senegalensis demonstrated removal efficiencies of 98% for arsenic and 97% for cadmium (Danbature, 2024). In addition, MFS biochar has been used for methylene blue removal, achieving up to 99.05% removal without prior chemical activation (Olunusi et al., 2023), highlighting its cost-effectiveness and practicality. Studies on oil adsorption showed that finely ground MFS could adsorb up to 1.886 g oil/g bioadsorbent, although hydrophilicity limited oil uptake (Huggins et al., 2016).

Tamarind-Based Biochar:

Tamarind seeds and shells are efficient biosorbents for fluoride, heavy metals, and microbial contaminants. Tamarind seed biochar achieved maximum fluoride removal at neutral pH, following Langmuir adsorption isotherms and first-order kinetics, with desorption efficiency of 90% using 0.1 N HCl (Murugan & Subramanian, 2024). Chemical activation of giant sour tamarind fruit shell with KOH produced activated carbon with a high BET surface area of 572.61 m^2/g and a total pore volume of 0.2563 cm^3/g, forming a micro-mesoporous structure (Dumpan et al., 2024). Furthermore, tamarind shell has been used as a green precursor to synthesize silver nanoparticles, which, when integrated with activated carbon, achieved a 90% reduction in microbial load in wastewater treatment, demonstrating an eco-innovative application (Adur et al., 2024).

Mahogany biochar is particularly effective for heavy metals and dye removal, whereas tamarind biochar offers versatility in fluoride removal and antimicrobial applications. Both feedstocks present low-cost, sustainable solutions for water purification in areas where these materials are abundant.

Table 2.7 Summary of key characteristics and performance of Mahogany and Tamarind-based biochars

Material	**Activation**	**Target Contaminant**	**Surface Area (m^2/g)**	**Removal Efficiency**	**References**
Mahogany fruit shell (Swietenia macrophylla)	H_2SO_4-activated	Pb(II)	265.22	99.7%	(Kamali et al., 2021; Kang et al., 2023)

Mahogany fruit shell (Khaya senegalensis)	TiO_2-impregnated	As, Cd	-	98%, 97%	(Danbature, 2024)
Mahogany fruit shell	Raw	Methylene blue dye	-	99.05%	(Olunusi et al., 2023)
Mahogany fruit shell	Raw	Oil	-	1.886 g/g	(Huggins et al., 2016)
Tamarind seed	Powder / raw	Fluoride	-	High at pH 7	(Murugan & Subramanian, 2024)
Giant sour tamarind shell	KOH-activated	General adsorption	572.61	-	(Dumpan et al., 2024)
Tamarind shell	AgNPs + activated carbon	Bacteria	-	90% microbial reduction	(Adur et al., 2024)

Mahogany and Tamarind biochars are versatile, eco-friendly, and low-cost adsorbents. Their high surface area, tunable porosity, and functional groups enable efficient removal of heavy metals, dyes, fluoride, and microbes. With chemical activation or nanoparticle integration, these biochars can be optimized for specific water treatment applications, contributing to sustainable wastewater management.

2.9 Adsorption Isotherm Models for Biochar-Based Treatment

The evaluation of adsorption isotherms provides essential insight into how contaminants interact with the surface of biochar and other low-cost natural adsorbents. These models help quantify adsorption capacity, surface heterogeneity, and binding strength, forming the theoretical foundation for the design and optimization of adsorption-based wastewater treatment systems.

Maheshwari (2024) explored the adsorption behavior of tamarind shell carbon for monobasic and dibasic acids, applying both Langmuir and Freundlich models to interpret equilibrium data (Maheshwari, 2024). The adsorption of propanoic acid (0.01224) exceeded that of acetic acid (0.01172), while succinic acid (0.0126) surpassed oxalic acid (0.01186). This difference was attributed to the presence of additional CH_2 groups, which enhance surface affinity. The study confirmed that the Langmuir model best describes monolayer adsorption, whereas the Freundlich model accounts for surface heterogeneity, suggesting that both mechanisms coexist within the tamarind shell carbon surface.

Pandian et al. (2025) conducted sorption studies of deseeded tamarind fruits using gravimetric methods to understand water vapor adsorption–desorption behavior under controlled humidity (Pandian et al., 2025). Data were fitted with Henderson, Halsey, BET, GAB, and Iglesias–Chirife models. The GAB model provided the best fit, indicating multilayer adsorption with sigmoid-type isotherms. The moisture diffusivity ranged between 9.61×10^{-12} and 3.10×10^{-11} m^2/s, confirming that desorption requires less activation energy than adsorption. This finding implies that tamarind-based materials exhibit both monolayer and multilayer interactions, depending on the contaminant or sorbate type.

Janthabut et al. (2025) synthesized activated carbon from tamarind seeds through KOH-assisted hydrothermal carbonization and evaluated its performance for Ni^{2+} ion removal from synthetic wastewater (Janthabut et al., 2025). The resulting adsorbent had a high surface area (1172 m^2/g) and displayed 100 % nickel removal under optimal conditions. The equilibrium data fitted exceptionally well with the Langmuir isotherm ($R^2 = 0.994$), yielding a maximum adsorption capacity (q_{max}) of 39.25 mg/g, while kinetics followed a pseudo-second-order (PSO) model ($k_2 = 0.0807$ g/mg·min). Thermodynamic analysis confirmed spontaneity and endothermic nature, implying chemisorptive behavior on the carbon surface.

Similarly, Dumpan et al. (2023) reported that KOH-activated mahogany and tamarind fruit shells exhibit micro–mesoporous structures suitable for adsorption processes (Dumpan et al., 2023). The materials showed Type I/IV adsorption isotherms, confirming a mixed microporous–mesoporous structure, with the sample activated at 800 °C showing the highest BET surface area (572.61 m^2/g) and total pore volume (0.2563 cm^3/g). These structural features indicate that multilayer adsorption can occur concurrently with chemisorption, depending on the pollutant concentration and pore accessibility.

Recent findings by Sevim et al. (2025) expanded on hybrid modeling, demonstrating that Langmuir–Freundlich (LF) and Sips models provide a superior fit for bio-based adsorbents that exhibit both homogeneous and heterogeneous site characteristics (Sevim et al., 2025). These hybrid isotherms combine the simplicity of Langmuir with the flexibility of Freundlich, particularly effective for composite biochar systems derived from lignocellulosic materials such as tamarind or mahogany. The study further highlighted that temperature-dependent adsorption follows the Van't Hoff relationship, confirming the endothermic and spontaneous nature of these processes.

Collectively, these studies affirm that the adsorption mechanism of biochar-based materials is highly dependent on surface chemistry, activation method, and contaminant type. While Langmuir and Freundlich remain the most frequently used models, advanced approaches like GAB and Langmuir–Freundlich hybrids offer better predictive capabilities for complex, multilayer systems. The predominance of pseudo-second-order kinetics across studies underscores the role of surface chemisorption as the rate-determining step in pollutant removal.

Table 2.8 Summary of Adsorption Isotherm and Kinetic Models for Tamarind and Mahogany-Based Adsorbents

Material	Target Adsorbate	Isotherm Models Tested	Best-Fit Model	Kinetic Model	q_{max} (mg/g)	Key Findings
Tamarind shell carbon	Monobasic & dibasic acids	Langmuir, Freundlich	Langmuir	–	–	Monolayer adsorption dominant; CH_2 groups increased interaction energy.
Deseeded tamarind fruit	Moisture adsorption	BET, GAB, Halsey	GAB	–	–	Multilayer adsorption; hysteresis effect; lower activation energy in desorption.
Tamarind seed AC	Ni^{2+} ions	Langmuir, Freundlich	Langmuir (R^2 = 0.994)	PSO	39.25	Chemisorptive and endothermic adsorption; 100% Ni^{2+} removal.
Tamarind & mahogany fruit shell AC	–	Type I/IV (BET)	–	–	–	High porosity and surface area (572.61 m²/g); micro–mesoporous structure confirmed.
Biochar composites	Mixed ions and dyes	Langmuir–Freundlich, Sips	Langmuir–Freundlich	PSO	–	Hybrid model fits heterogeneous systems; adsorption spontaneous and endothermic.

2.10 Evaluation of Biochar Performance under Continuous Flow Conditions

Continuous column tests are an essential method for evaluating the dynamic performance of biochar in wastewater treatment, simulating practical flow conditions that are more representative of real-life applications than batch studies. Such tests provide insights into the adsorption capacity, breakthrough behavior, and operational efficiency of biochar under varying hydraulic and bed conditions.

Several studies have demonstrated the effectiveness of biochar and biochar-like adsorbents in continuous flow systems. Foo et al. (2013) investigated tamarind fruit seed activated carbon in laboratory-scale columns for landfill leachate treatment. The study varied bed height (15–21 cm) and hydraulic loading rates (5–20 mL/min) and reported maximum adsorption capacities of 84.69 mg/g for ammonical nitrogen and 55.09 mg/g for COD. The dynamic adsorption behavior was effectively described using Thomas and Yoon-Nelson models, indicating predictable breakthrough performance under varying operational conditions.

Similarly, Rajeshkannan et al. (2013) performed packed bed studies using tamarind seed for dye removal (malachite green and acid blue 9). The research highlighted the influence of flow rate and bed depth on breakthrough curves and demonstrated that the Thomas model provided reliable predictions for overall column performance, while Adams–Bohart and Yoon–Nelson models captured the initial adsorption dynamics. Bed Depth Service Time (BDST) analysis further confirmed the dependence of column service time on bed height, emphasizing the practical importance of column design parameters.

Rangabhashiyam et al. (2016) evaluated chemically modified Swietenia mahagoni shell in a packed bed column for Cr(VI) removal from synthetic and industrial effluents. Breakthrough times increased with bed height and decreased with higher flow rates or influent concentrations. Column models including Thomas, Adams–Bohart, Yoon–Nelson, and BDST accurately represented the experimental data, with Yoon–Nelson and BDST showing strong correlation. These findings underscore the utility of column modeling for predicting biochar performance in continuous systems.

Patel and Vashi (2011) also explored fixed-bed adsorption of Acid Yellow 17 dye onto tamarind seed powder, analyzing various operational parameters such as flow rate, initial dye concentration, bed height, and pH. The study employed Thomas, Yoon–Nelson, BDST, and Adams–Bohart models, showing that adsorption capacity increased with bed height and initial concentration but decreased with higher flow rates. Maximum adsorption capacity reported for Adams–Bohart modeling was 978.5 mg/g, illustrating the high potential of biochar-based adsorbents in continuous flow applications.

Most recently, Bautista Quispe et al. (2023) optimized biochar filtration for handwashing wastewater treatment. Using Response Surface Methodology (RSM), optimal conditions were determined as 1.25 mm particle size, 30 cm filter depth, and 1 L/h flow rate, achieving removal efficiencies of 97.63%, 99.85%, 85.94%, and 76.08% for color, turbidity, phosphates, and E. coli, respectively. This study demonstrated the applicability of biochar filters for decentralized wastewater treatment and water reuse, confirming the operational feasibility of continuous biochar systems in practical settings.

Overall, continuous column studies emphasize the importance of hydraulic parameters, bed depth, particle size, and flow rate in determining biochar performance. Column modeling using Thomas, Yoon–Nelson, Adams–Bohart, and BDST approaches provides predictive capability, allowing for the design and scale-up of biochar-based filtration systems for industrial and community-level wastewater treatment. These studies collectively establish that biochar possesses high potential for efficient and sustainable pollutant removal under continuous flow conditions.

CHAPTER 3: MATERIALS & METHODOLOGY

3.1 Wastewater Sample Collection

Wastewater samples were collected manually from the pond near the Babul Mondol road, north of AB bank, along the Dhaka-Mymensingh highway. The pond receives discharges from nearby houses and small-scale industries, resulting in a mixture of domestic and industrial wastewater. The samples were collected, following the standard sampling procedures, as described by APHA (APHA, 1998), in 5 L PET bottles, labeled and stored in a cool place to preserve their original characteristics. The bottles were pre-cleaned thoroughly with distilled water and air-dried before use. These samples were collected prior to the experiment and not stored for more than 5 days. To ensure accurate comparison with the experiment results, initial physicochemical parameters of the wastewater were measured immediately on the day of collection.

3.2 Physicochemical Parameter Analysis

In total, ten physicochemical parameters of the sample wastewater, including temperature, pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), turbidity, color, salinity, Dissolved Oxygen (DO), Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD_5), were measured in this study to assess the initial contamination level of the wastwater source. A calibrated portable HACH HQ40D multi-parameter meter was used to measure temperature, pH, salinity, DO and EC values. A HACH DR3900 split beam spectrophotometer (visible spectrum range: 320-1100 nm) was used for COD analysis, while BOD_5 was measured immediately after sample collection, for 5 days duration, following the APHA Standard Methods (5210B) using a VELP SCIENTIFICA FOC-120 E incubator and a HACH BODTrak II system. TDS was also determined using the APHA guidelines. Turbidity was measured using a calibrated portable HACH 2100Q turbidimeter and color was measured using a HACH DR2800 spectrophotometer. While DO was measured in situ, the wastewater sample bottles were shaken well to ensure the uniform dispersion of all the particles prior to the other measurements. The parameters were measured carefully until a stable value for each parameter could be recorded. A comparative overview of the physicochemical parameters' analysis of the sample wastewater with the guidelines set by the World Health Organization (WHO) and United States Environmental Protection Agency (US EPA) is presented in the following table (APHA, 1998; Rahman et al., 2025).

Table 3.1 Comparison of Physicochemical Parameters of Wastewater Samples with WHO, US EPA and ECR Guideline Values

Parameters	Wastewater Sample	Standards[1]	Permissible Level[2]	Permissible Level[3]
Temperature (°C)	24.6	N/A	N/A	N/A
Salinity (%)	0.35	N/A	0.5-1	N/A
pH	7.25	6.5-8.5	6.5-8.5	6.5-9
EC (μS/cm)	712	400-1500	1200	700
TDS (ppm)	346	≤ 1000	1000	500
DO (mg/L)	4	> 5	≥ 5	5
Turbidity (NTU)	54.5	≤ 5	10	50
COD (mg/L)	116	N/A	200	10
Colour (Pt-Co)	734	≤ 15	15	NA
BOD_5	35	≤ 3	6	3

N/A: Not available

[1] WHO Guidelines for Drinking Water Quality (WHO, 2017)

[2] Bangladesh Environment Conservation Rules (ECR), 1997 - Inland Surface Water Discharge Standards

[3] US EPA Inland Water Quality Standards

3.3 Experimental Method Overview

A detailed methodology was developed for all the parts of this study. The experimental steps are illustrated through flowcharts and subsequent sections describe the approaches elaborately.

3.3.1 **Batch Experiments**

To determine the efficiency, standard batch jar experiments were conducted at a room temperature of 27±2 °C.

3.3.1.1 Bio-coagulants

The experimental steps of batch experiments with bio-coagulants are illustrated through the flowchart here:

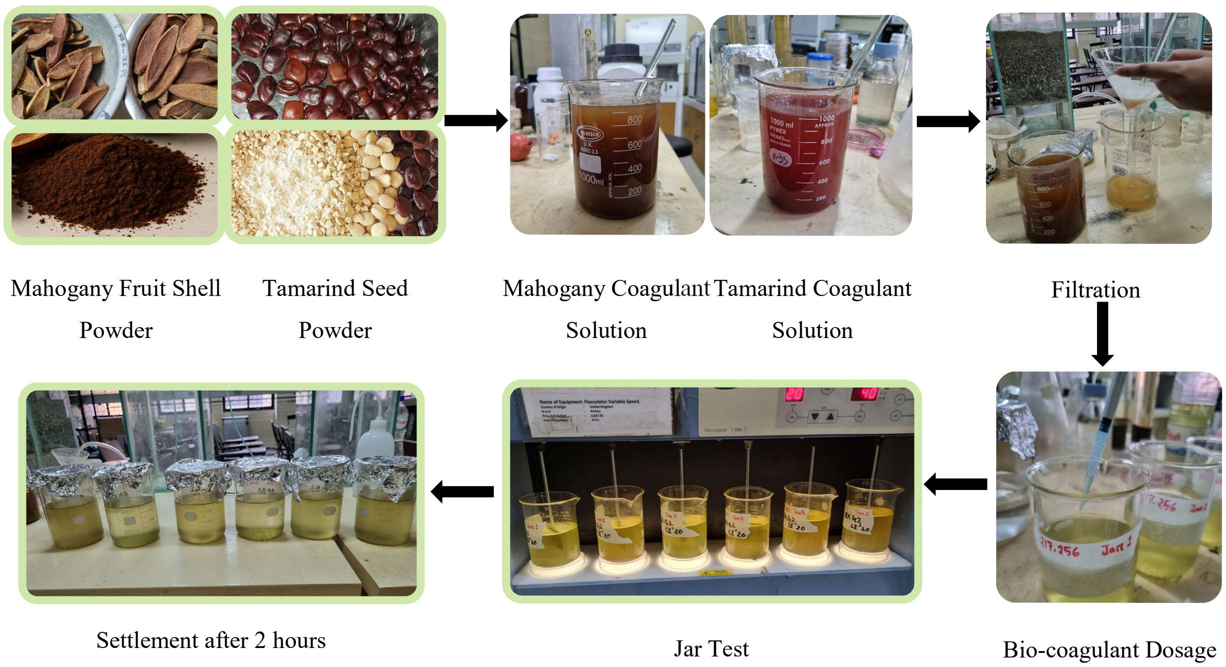


Figure 3.1 Experimental Setup of Batch Experiments with Bio-coagulants

Material Collection

All the materials were collected locally from waste products to ensure the most sustainable way possible to treat wastewater.

Mahogany Fruit Shell (Swietenia macrophylla)

Mahogany fruit shells were collected from the ground beneath mature trees located in the tree park of Islamic University of Technology (IUT) campus. The fruit shells were collected carefully to ensure only intact shells were selected, free from fungal growth and any kind of discoloration. Then, the selected shells were taken for further processing. The shells were stored in a cool and dry place to avoid any contact with moisture.

Tamarind (Tamarindus indica)

Tamarind seeds were collected from household kitchen waste. While collecting, it was made sure that no rotten or defective seeds were selected. Then, the selected seeds were taken for further processing. The seeds were stored in a cool and dry place to avoid any contact with moisture.

Material Preparation

After collecting the materials, both the collected mahogany fruit shells and the tamarind seeds were washed thoroughly with distilled water to remove any kind of adhering dirt, pulp or unwanted substances. Then, they were oven-dried at 378 K (100 °C) for 72 hours (3 days) until all moisture evaporated completely. The oven-dried materials were stored in a previously washed and sterilized air-tight container to maintain cleanliness and avoid any contamination. Before conducting the experiments, the stored materials were broken into small pieces using a sterilized hammer and then ground into fine powder using a kitchen mixer grinder machine. All the ground materials were sieved using an ASTM 200 sieve (75 microns) to ensure uniform particle sizes. The sieved fine powders of mahogany and tamarind were then stored in an air-tight, clean container for further use.

Preparation of Bio-coagulant Solution

For each of the bio-coagulant solution preparation, 10 g of the sieved material was added to 1 L of distilled water to get a solution concentration of 10 g/L. The solutions were hand-stirred well for the extraction of active coagulation components. To ensure better extraction, the bio-coagulant solution beakers were covered with aluminum foil and left at a cool place for 24 hours, to avoid any type of microbial growth. The next day, these solutions were filtered through Whatman filter paper to remove any kind of suspended particles. The filtered solutions, referred to as the crude extracts from mahogany fruit shell powder and tamarind seed powder, were stored in closed containers, labeled and kept under 4 °C and used within 2 days of preparation to avoid reduction in material efficiency and degradation of solution quality. After 2 days, new bio-coagulant solutions were prepared and extracted again for the next batch of experiments.

Bio-coagulant Dosage

To determine the optimum dosage of the bio-coagulants for the maximum coagulation efficiency, varying dosages from 10 mg/L to 500 mg/L were added to the experimental beakers. This range was chosen to cover both low and high dosages based on previous studies, maximizing the chances of identifying the optimum bio-coagulant dosage.

Table 3.2 Bio-coagulant Dosage

Jar	**Dosage(mg/L)**
1	10
2	25
3	50
4	100
5	250
6	500

Jar Test

Three standard batch jar experiments were conducted separately for mahogany fruit shell extracts, tamarind seed extracts and combined application of mahogany and tamarind respectively. All the experiments were carried out following the standards of the American Public Health Association (APHA, 2012). The jar test apparatus comprised six batch reactors. In every test, each of the six beakers was filled with 350 mL of previously collected sample wastewater, with an initial pH of 7.25. Then, different doses of the prepared bio-coagulant solutions, as mentioned in the above table, were added to the beakers using a micropipette, at a constant room temperature of 27±2 °C and pH 7.25. A rapid mixing phase was conducted at 125 rpm for 2 min to allow the rapid dispersion of the bio-coagulants and ensure uniform distribution. The speed was selected based on previous studies, as it provides effective dispersion of the coagulant while minimizing shear forces that might disrupt fragile natural flocs, thus preserving floc integrity and promoting efficient sedimentation (ACS Publications, 2017).

The stirring speed was reduced and slow mixing was conducted at 40 rpm for 20 min, to allow the floc formation and the gradual settlement of suspended solids. Upon completion of the jar tests, the beakers were covered with aluminum foil and left undisturbed to initiate flocculation and settlement. After 2 hours of settling, clarified supernatant samples were collected carefully using a micropipette from the surface of the beakers, avoiding any disturbance of the settled flocs. The collected samples were then analyzed for final water quality parameter values to determine the optimum bio-coagulant dosage for maximum efficiency. The final parameter values were compared with the initial values to assess the relative performance of each bio-coagulant. Analysis of the parameters, except for turbidity, color and COD, did not show any significant change. This study focuses on only turbidity and color removal efficiency of each bio-coagulant and their combined application.

3.3.1.2 Chemical Coagulants and Combined Application of Chemical Coagulants and Bio-coagulants

To obtain a comprehensive comparison of the turbidity and color removal efficiencies of bio-coagulants, chemical coagulants and their combined application, standard batch experiments were conducted again using chemical coagulants. The experimental steps of these batch experiments are illustrated through the flowchart here:

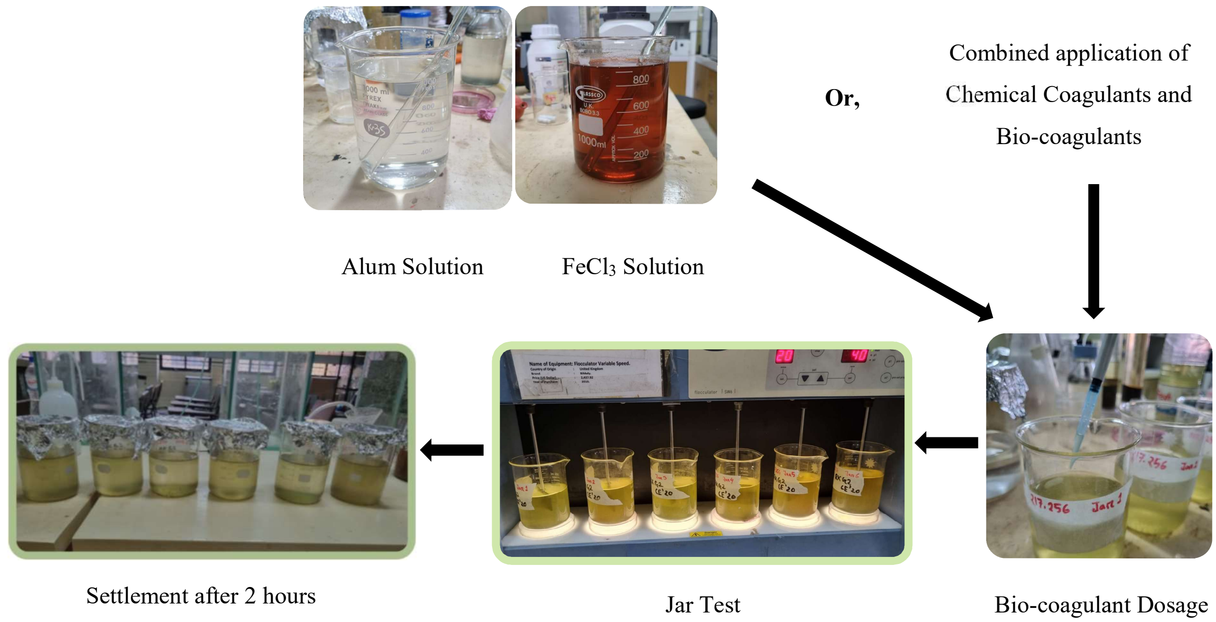


Figure 3.2 Experimental Setup of Batch Experiments with Chemical Coagulants and Combined Application of Chemical Coagulants and Bio-coagulants

Preparation of Chemical Coagulant Solution

For each of the chemicals, aluminum sulfate hexadecahydrate purified (also known as alum) ($Al_2(SO_4)_3.16H_2O$) and iron (III) chloride hexahydrate ($FeCl_3.6H_2O$), the chemical coagulant solutions were prepared in a similar way to that of the bio-coagulant solutions. 10 g of chemical coagulant was added to 1 L of distilled water to get a solution concentration of 10 g/L. The solutions were manually stirred properly until the chemicals dissolved fully into the water and the solutions appeared clear. Unlike the bio-coagulant solutions, no aluminum foil was used to cover the beakers as ferric chloride can react with aluminum. Instead, the coagulant solution beakers were loosely covered with watch glasses and kept in a dark place at a room temperature of 27±2 °C to avoid contamination and any type of reaction with heat or light. The solutions were left for 30 minutes to allow any heat generated during the preparation to dissipate and the solutions to reach the room temperature before use. The chemical coagulant solutions were prepared immediately prior to each batch of experiments to avoid hydrolysis and precipitation, which may occur due to longer storage and reduce the coagulants' efficiency.

Coagulant Dosage

For the individual application of chemical coagulants, similar to the bio-coagulant dosages, varying dosages from 10 mg/L to 500 mg/L were added to the experimental beakers to determine the optimum dosage of the chemical coagulants for maximum coagulation efficiency. The dosages were the same as the bio-coagulant dosages for easy comparison between the results. On the other hand, for the combined application of chemical coagulants and bio-coagulants, they were applied in different ratios to find the optimum combining ratio for maximum turbidity and color removal efficiency. The bio-coagulants were applied at their previously determined optimum dosage and the chemical coagulants were applied in the ratios given in the following table.

Table 3.3 Individual Chemical Coagulant Dosage

Jar	**Alum / $FeCl_3$ Dosage(mg/L)**
1	10
2	25
3	50
4	100
5	250
6	500

Table 3.4 Combined Application Ratios of Chemical Coagulants and Bio-coagluants

Jar	**Combined Application Ratios (Bio-coagulant : Chemical Coagulant)**
1	50:50
2	60:40
3	70:30
4	80:20
5	90:10

The ratios for the combined application began at 50:50, as the use of a bio-coagulant portion smaller than half does not fulfill the purpose of the study. The purpose was to determine the proportion of bio-coagulant that could effectively reduce both the amount of chemical coagulants required and the reliance on them, while still achieving maximum turbidity and color removal efficiency.

Jar Test

In total, eight standard batch jar experiments were conducted separately for the followings: alum, ferric chloride, alum combined with mahogany, alum combined with tamarind, ferric chloride combined with mahogany, ferric chloride combined with tamarind, combined application of mahogany and tamarind with alum, and combined application of mahogany and tamarind with ferric chloride. All the experiments were carried out following the standards of the American Public Health Association (APHA, 2012). In every test, each of the six beakers was filled with 350 mL of previously collected sample wastewater, with an initial pH of 7.25. The prepared coagulant solutions, in different dosages and ratios as mentioned in the previous table, were added to the beakers using a micropipette, at a constant room temperature of 27±2 °C and pH 7.25. A rapid mixing phase was conducted at 125 rpm for 2 min, similar to the bio-coagulant jar tests. The stirring speed was then reduced and slow mixing was conducted at 40 rpm for 20 min. Upon completion of the jar tests, the beakers were loosely covered with watch glasses and kept in a dark place at room temperature to avoid contamination and any type of chemical reaction with heat or light. The beakers were left undisturbed for 2 hours to initiate flocculation and settlement. After settling, clarified supernatant samples were collected carefully using a micropipette from the surface of the beakers, avoiding any disturbance of the settled flocs. The collected samples were then analyzed for final water quality parameter values to determine the optimum coagulant dosage and the optimum ratio for maximum efficiency. The final parameter values were compared with the initial values to assess the relative performance of each coagulant and coagulant combination. For proper comparison with the performance of the bio-coagulants, this study focuses on only turbidity and color removal efficiency of each chemical coagulant and their combined application with bio-coagulants.

3.3.1.3 Biochar

Biochars prepared from natural materials usually exhibit adsorption properties (Mubashir et al., 2025). To determine the adsorption efficiency of the biochars prepared from mahogany fruit shell powder and tamarind seed powder, standard batch jar experiments were conducted under similar conditions as before. The experimental steps are presented in the flowchart here:

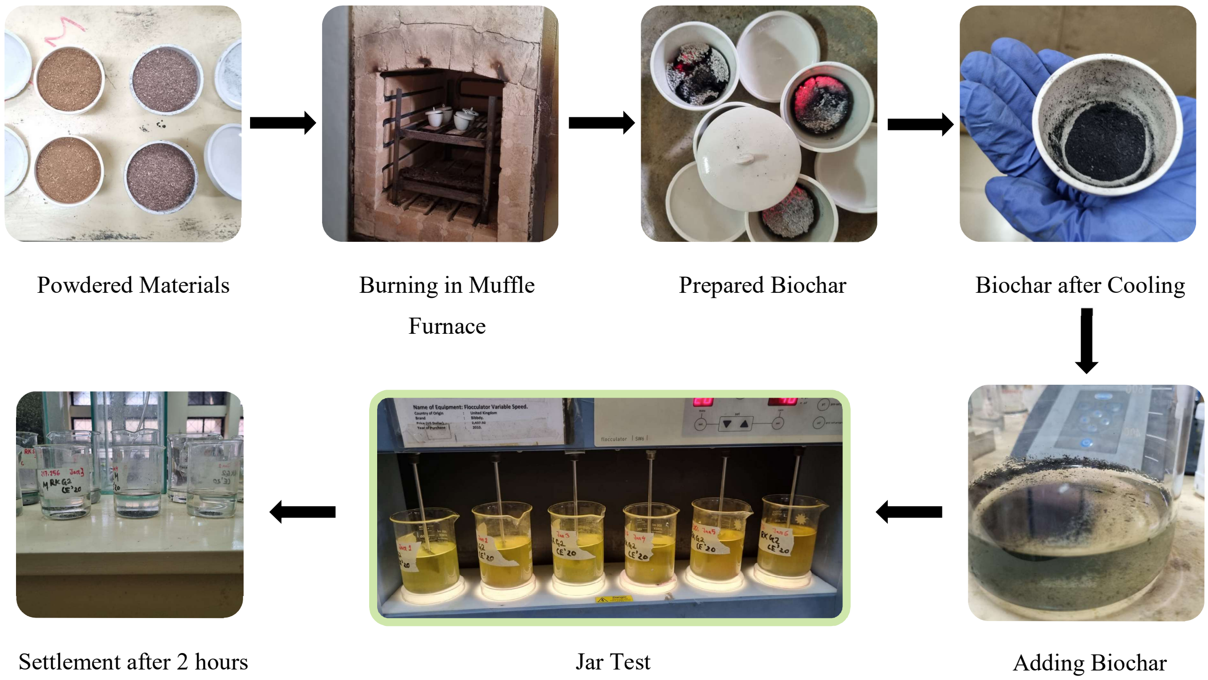


Figure 3.3 Experimental Setup of Batch Experiments with Biochars Prepared from Mahogany and Tamarind Powders

Biochar Preparation

For biochar preparation, 25 g of previously sieved mahogany fruit shell and tamarind seed powders were taken in each crucible. Four crucibles, two containing each type of material powder, were placed carefully in two rows inside the muffle furnace, maintaining proper distance from the furnace walls. The lids of the crucibles were kept slightly open to minimize oxygen contact and allow the escape of volatile gases formed during pyrolysis. The furnace temperature was increased at a rate of 10 °C/min until it reached the final temperature of 600 °C, which is suitable for water treatment applications. The holding time at that temperature was 1 hour. After the holding period, the muffle furnace was turned off and the samples were allowed to cool inside the furnace to room temperature, to avoid any possible oxidation. Then, the prepared biochars were thoroughly washed with distilled water to remove ashes, oven-dried at 100 °C and stored in air-tight containers at a room temperature of 27±2 °C. The final biochar weight was 4 g, corresponding to a 16% of biochar carbonization yield. The yield is comparatively lower than the standards, possibly due to the raw material type and atmosphere control. The biochars were produced from agricultural residues, mahogany fruit shells and tamarind seeds both of which are lignocellulosic materials. Agricultural residues usually have higher ash contents and are low on carbon contents, resulting in lower carbonization yield. Additionally, the pyrolysis was conducted in air atmosphere which may have further reduced the yield through partial combustion. The medium pyrolysis temperature, although suitable for biochar adsorption in water treatment, is also responsible for lower carbon contents but increases surface area (Zylabsolution, n.d.).

Biochar Dosage

To determine the optimum biochar dosage for mximum turbidity and color adsorption efficiency, varying dosages from 0.002 g to 0.1 g (corresponding to concentrations of 10 mg/L to 500 mg/L for 200 mL of sample wastewater) were added to the experimental beakers. The dosages represent the mass of biochar applied in each beaker of sample wastewater. This range was chosen to cover both low and high dosages based on previous adsorption studies, maximizing the chances of identifying the optimum biochar dosage. These dosages were also used for the development of adsorption isotherm models to evaluate the adsorption behavior of each biochar. The values are listed in the following table.

Table 3.5 Biochar Dosage

Jar	Biochar Mass, m (g)	Dosage (mg/L)
1	0.002	10
2	0.005	25
3	0.01	50
4	0.02	100
5	0.05	250
6	0.1	500

Jar Test

Two standard batch jar experiments were conducted separately for mahogany biochar and tamarind biochar, respectively. In every test, each of the six beakers was filled with 200 mL of previously collected sample wastewater, with an initial pH of 7.25. Then, different doses of the prepared biochars, as mentioned in the above table, were added to the beakers, at a constant room temperature of 27±2 °C and pH 7.25. A rapid mixing phase was conducted at 125 rpm for 2 min to allow proper dispersion of the biochar and ensure uniform distribution. The stirring speed was then reduced and slow mixing was conducted at 40 rpm for 20 min. Upon completion of the jar tests, the beakers were covered with aluminum foil, to prevent light-induced reactions or sample evaporation, and left undisturbed to allow sufficient time for the adsorption process. After 2 hours, clarified supernatant samples were collected carefully using a micropipette from the surface of the beakers, avoiding any disturbance. The collected samples were then analyzed for final turbidity and color values to determine the optimum biochar dosage for maximum adsorption efficiency. The final parameter values were compared with the initial values to evaluate the relative adsorption performance of each biochar.

3.3.2 **Adsorption Isotherm Models**

Adsorption isotherm models were developed for mahogany and tamarind biochars using the batch equilibrium method. The initial concentration of the adsorbate, C_o in the sample wastewater was measured before adding the biochar. The mass and volume data of biochar adsorbents and sample wastewater were recorded during the batch experiments. For 200 mL (V) of sample wastewater in six beakers, different dosages of biochar were added under identical conditions. After the standard batch jar experiments, turbidity and color parameters were measured at 2 hour intervals as indirect indicators of adsorption, reflecting the adsorption of suspended and colored particles present in the wastewater. Equilibrium was considered reached when the change in turbidity and color between consecutive measurements was less than 1%, which occurred after 24 hours. During the adsorption process, the samples were maintained at a room temperature of 27±2 °C and a constant pH of 7.25. After the equilibrium was reached, the biochar particles were removed by filtration and the equilibrium adsorbate concentration, C_e, in the filtrate from the six beakers was measured. These values were then used to develop the isotherm models. Langmuir, Freundlich, Temkin and Redlich-Peterson - these four adsorption isotherm models were applied to evaluate the adsorption capacity and adsorption mechanism of the biochars at the equilibrium state (Hassan et al., 2025). The formulas used for the development of the adsorption isotherm models are mentioned in the table here.

Table 3.6 Adsorption Isotherm Models

Isotherm Model	**Non-linear Equation**	**Linear Equation**	**Plot**
Langmuir	$q_e = \frac{q_m K_L C_e}{1 + K_L C_e}$	$\frac{1}{q_e} = \frac{1}{q_m K_L C_e} + \frac{1}{q_m}$	C_e/q_e vs C_e
Freundlich	$q_e = K_F C_e^{1/n}$	$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e$	$\ln q_e$ vs $\ln C_e$
Temkin	$q_e = \frac{RT}{b} \ln(AC_e)$	$q_e = \frac{RT}{b} \ln A + \frac{RT}{b} \ln C_e$	q_e vs $\ln C_e$
Redlich-Peterson	$q_e = \frac{AC_e}{1 + BC_e^{\beta}}$	$\ln \frac{C_e}{q_e} = \beta \ln C_e - \ln A$	$\ln (C_e/q_e)$ vs $\ln C_e$

References: (Al-Ghouti & Da'ana, 2020; Prasetyo et al., 2024; Ayawei et al., 2017)

And,

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

$$K = \frac{C_e}{q_e} \times 1000 \quad (2)$$

Here, C_o (mg/L) = the initial concentration of the adsorbate; C_e (mg/L) = Equilibrium concentration; q_e (mg/g) = adsorption capacity; m (g) = biochar mass; V (L) = sample wastewater volume and K (L/kg) = adsorption coefficient.

Langmuir: q_m = maximum monolayer adsorption capacity (mg/g)

Freundlich: 1/n = adsorption intensity (heterogeneity) (dimensionless)

Temkin: A = Temkin equilibrium binding constant (L/mg)

RT/b = heat of adsorption constant (dimensionless)

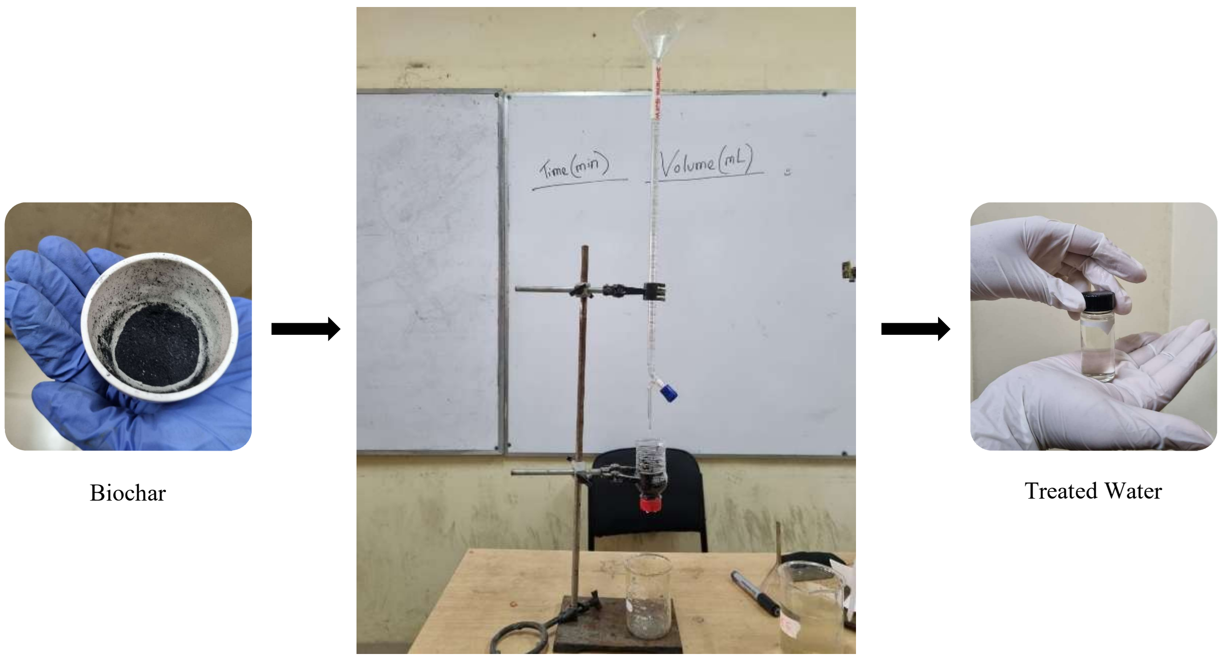
Redlich-Peterson: *B* = Redlich-Peterson constant (L/mg)

A = Isotherm constant (L/g)

β = exponent (0-1, dimensionless)

3.3.3 Continuous Column Adsorption

To evaluate the adsorption efficiency of mahogany and tamarind biochars, under continuous flow condition, two column studies were conducted. The experimental steps are presented through the flowchart here:



Biochar

Experimental Setup

Treated Water

Figure 3.4 Continuous Column Test of Biochar Adsorption

Continuous Column Experiment

The column studies were conducted using fixed-bed biochar columns with an internal diameter of 4 cm and a height of 9.5 cm. To minimize experimental costs, two plastic bottles were used as column reactors, representing two separate setups for mahogany biochar and tamarind biochar, respectively. Each bottle was packed carefully with 8 g of biochar to a bed height of approximately 2.5 cm, ensuring no air pockets were present. The caps of the bottles were perforated to allow water passage but to prevent the biochar particles from leaching through and clogging the holes, a cotton pad was placed at the bottom of each column. Another cotton pad was placed on the top of the biochar bed to ensure even distribution of the influent across the adsorbent surface, while maintaining a consistent downward flow. A burette was placed on top of the open end of each column to provide a continuous flow of sample wastewater. The burette and the biochar column were held firmly using clamps attached to a burette stand, aligned centrally in the same vertical line to ensure uniform flow and avoid lateral pressure on the column. A constant head of 5 cm was maintained throughout the operation. Before the adsorption tests, the biochar beds were pre-washed with 500 mL of distilled water passing through the packed beds to make them more compact. Then the sample wastewater was allowed to down flow from the burettes through the adsorbent beds. The flow rate of the wastewater was maintained 4 mL/min using the burette valves. The burettes were continuously filled with wastewater through a funnel to avoid any disruption in the continuous flow conditions. Effluent samples, passing through the perforated bottle caps, were collected into two separate beakers placed beneath the column setups. The effluent flow rate was measured to be 1 mL/min, lower than the influent rate due to head loss through the packed bed. Samples from the bottom of the columns were collected at 20 min regular intervals. The final turbidity and color values were recorded to assess the dynamic adsorption performance of each biochar column. The experiments were performed for 12 hours at a room temperature of 27±2 °C and a constant pH of 7.25. No leakage or channeling was observed during the experiments which ensure consistent flow through the biochar beds (Almahbashi et al., 2022; Naghizadeh et al., 2013; Viotti et al., 2024; G M et al., 2023).

3.3.4 **Analysis**

The treatment efficiencies of the bio-coagulants and biochars obtained from the jar and column experiments were evaluated using the following standard removal efficiency equations (Husen et al., 2024),

$$\text{Turbidity removal, \%} = \frac{C_o - C_f}{C_o} \times 100 \qquad (3)$$

Where, C_o and C_f represent the initial and final turbidity values, respectively.

$$\text{And, } Color\ removal = \frac{Abs_o - Abs_f}{Ab\ \ _o} \times 100 \qquad (4)$$

Where, Abs_o and Abs_f denote the initial and final absorbance of the surface water samples, respectively.

All analyses were conducted in triplicate to ensure accuracy. Instruments were calibrated prior to each experimental run and reagent blanks as well as standard solutions were used for COD and colorimetric measurements to maintain analytical accuracy.

CHAPTER 4: RESULT & DISCUSSION

4.1 General

This chapter presents and interprets the experimental findings obtained from the treatment of wastewater using Bio-coagulants, biochar, chemical coagulants, and their combined applications. Raw water quality was first assessed against the World Health Organization (WHO, 2022) standards, where several parameters were found to exceed acceptable limits, confirming the necessity of treatment prior to any potential reuse. In order to address these deficiencies, a systematic series of experiments were conducted. Batch coagulation-flocculation tests were carried out using mahogany fruit shell powder, tamarind seed powder, and their combination, with the objective of identifying optimum dosages and evaluating turbidity and color removal efficiencies. These results were compared with conventional chemical coagulants, namely alum and ferric chloride, which served as benchmarks due to their established performance in water treatment. Additional hybrid experiments were undertaken by combining natural and chemical coagulants to explore the potential for synergistic effects in turbidity and color removal. Subsequently, biochars derived from mahogany and tamarind were examined for their adsorption capacity through both batch and column experiments. The batch tests provided insight into dosage-dependent removal efficiencies, while the column experiments simulated continuous flow conditions to assess the long-term stability of treatment performance. Emphasis was given to turbidity and color removal trends as these represent critical indicators of water quality improvement also other parameters did not show significant changes through these experiments. By integrating the results across different treatment methods, this chapter seeks to provide a comparative assessment of natural, chemical, and hybrid approaches. The discussion highlights not only removal efficiencies but also the limitations and practical considerations of each method, with the aim of identifying sustainable strategies suitable for application in the context of wastewater treatment in Bangladesh.

4.2 Water Parameter Test

In assessing wastewater quality and evaluating the efficiency of wastewater treatment by Bio-coagulants, a comprehensive suite of physicochemical parameters including pH, turbidity, total dissolved solids (TDS), electrical conductivity (EC), salinity, color, dissolved oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) must be evaluated in relation to health-based and aesthetic benchmarks defined in the latest WHO Guidelines for Drinking-Water Quality (WHO, 2022). Evaluating all these parameters in one view allows a holistic understanding of water suitability for drinking along with regular and commercial uses and identifies which parameters are needed to be monitored and adjusted to bring the wastewater into compliance with WHO health, aesthetic, and operational guidelines.

Table 4.1: Comparison of Wastewater Parameters with WHO Standards

Parameters	Wastewater	WHO Standards
Temp. (°C)	24.6	No specific limit
Salinity (%)	0.35	No specific limit
pH	7.25	6.5–8.5
EC (μS/cm)	712	400–1500
TDS (ppm)	346	≤ 1000
DO (mg/L)	4	> 5
Turbidity (NTU)	54.5	≤ 5
COD (mg/L)	116	No specific limit
Color (Pt-Co)	734	≤ 15
BOD_5	35	≤ 3

The baseline analysis of the wastewater revealed several deviations from the recommended limits of the World Health Organization (WHO, 2022), highlighting its unsuitability for direct domestic or industrial use without treatment. Temperature (24.6 °C) and salinity (0.35%) were within acceptable natural ranges, as WHO does not prescribe specific limits for these parameters, though they influence water chemistry and biological processes. The pH (7.25) was within the permissible range of 6.5-8.5, indicating a neutral condition favorable for most treatment processes. Electrical conductivity (712 µS/cm) and total dissolved solids (346 mg/L) were also within acceptable limits suggesting moderate ionic content. However, measured dissolved oxygen was 4 mg/L, below the recommended threshold reflecting organic pollution and poor self-purification capacity (Islam, 2024). The most critical exceedances were observed in turbidity (54.5 NTU) which can reduce effectiveness in water treatment, color (734 Pt-Co) affecting aesthetics. BOD_5 (35 mg/L) indicating here is a large concentration of organic matter, which can result in a reduction of dissolved oxygen levels and harm aquatic life (Islam, 2024), and a very high COD value (116 mg/L, although no formal WHO limit exists), the presence of pollutants in the water (Islam, 2024). Such conditions not only make the water aesthetically unacceptable but also pose risks for microbial growth and disinfection inefficiency. Importantly, in subsequent treatment trials using natural coagulants and biochar, significant reductions were achieved in turbidity and color, with visible improvements during both batch experiments and column tests, demonstrating the potential of sustainable coagulant alternatives such as mahogany fruit shell and tamarind seed powder in improving water quality.

4.3 Batch Experiment

To evaluate the performance of different natural coagulants on wastewater treatment, a series of controlled batch experiments were conducted using Bio-coagulants (mahogany, tamarind, combined mahogany and tamarind), conventional chemical coagulants (alum and ferric chloride), biochar (mahogany, tamarind) and their combined applications. Batch experiments are widely adopted in coagulation-flocculation studies as they allow for systematic observation of dosage effects, rapid mixing, floc formation, and subsequent settling under laboratory conditions. Turbidity and color removal efficiencies at different dosages were observed through batch experiment, plotted in graphs and optimal dosages were found out. The dosages were revised again based on coagulant performances. The use of plant-based Bio-coagulants has gained attention due to their biodegradability, low toxicity, cost-effectiveness and local availability eliminating the need to store in a controlled room proving them as attractive alternatives to other chemical coagulants (Nimesha et al.,2022). However, chemical coagulants continue to be widely used because of their strong and predictable performance, particularly for turbidity and color removal. By comparing natural, chemical, and combined approaches, this study aimed to not only assess turbidity and color removal efficiencies of mahogany fruit shell powder and tamarind seed powder as Bio-coagulants but also to explore the potential effects of hybrid treatment, where Bio-coagulants may reduce chemical demand while maintaining or enhancing treatment performance. Such comparative experimentation provides valuable insights into developing a sustainable yet effective treatment strategy suitable for Bangladesh's water management context.

4.3.1 **Batch Experiment by Bio-coagulants**

The experimental results are shown here in tables along with their graphical representations. Table 4.2, Table 4.3, Table 4.4 presents the turbidity and color removal percentage data of mahogany fruit shell powder, tamarind seed powder and their combined application respectively over a wide range of 10-500 mg/L. Figure 4.1 shows that this turbidity removal efficiency varied across the dosage range and the highest removal percentage noticed was 63.67% at 10 mg/L dosage for mahogany fruit shell, 90.64% at 50 mg/L for tamarind seed powder and 91.19% at 25 mg/L for their combined application. Further tests were conducted to check the optimum value for mahogany fruit shells. However, the results confirmed the optimum value to be 10 mg/L with a removal efficiency of 63.67%. Similarly, Figure 4.2 shows their color removal efficiency percentages at different dosages achieving highest 53.13% at 10 mg/L dosage for mahogany, 88.96% at 50 mg/L for tamarind and 85.42% at 25 mg/L for their combined application.

Table 4.2: Turbidity and Color Removal Efficiency by Mahogany Fruit Shell Powder

Jar	Dosage (mg/L)	Initial Turbidity (NTU)	Turbidity (NTU)	Turbidity Removal (%)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal (%)
*	5		23.3	57.25%		388	47.14%
1	10		19.8	63.67%		344	53.13%
2	25		21.1	61.28%		433	41.01%
3	50	54.5	27.8	48.99%	734	471	35.83%
4	100		34.2	37.25%		537	26.84%
5	250		41.7	23.49%		647	11.85%
6	500		49.4	9.36%		688	6.27%

*Further test to confirm the optimum dosage

Table 4.3: Turbidity and Color Removal Efficiency by Tamarind Seed Powder

Jar	Dosage (mg/L)	Initial Turbidity (NTU)	Turbidity (NTU)	Turbidity Removal (%)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal (%)
1	10		9.39	82.77%		182	75.20%
2	25		6.62	87.85%		125	82.97%
3	50	54.5	5.1	90.64%	734	81	88.96%
4	100		7.22	86.75%		103	85.97%

5	250		10.93	79.94%		150	79.56%
6	500		13.1	75.96%		187	74.52%

Table 4.4: Turbidity and Color Removal Efficiency by Combined Mahogany Fruit Shell Powder and Tamarind Seed Powder

Jar	Dosage (mg/L)	Initial Turbidity (NTU)	Turbidity (NTU)	Turbidity Removal (%)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal (%)
1	10	54.5	8.26	84.84%	734	137	81.34%
2	25		4.8	91.19%		107	85.42%
3	50		5.8	89.36%		178	75.75%
4	100		7.68	85.91%		284	61.31%
5	250		13.2	75.78%		356	51.50%
6	500		18.6	65.87%		396	46.05%

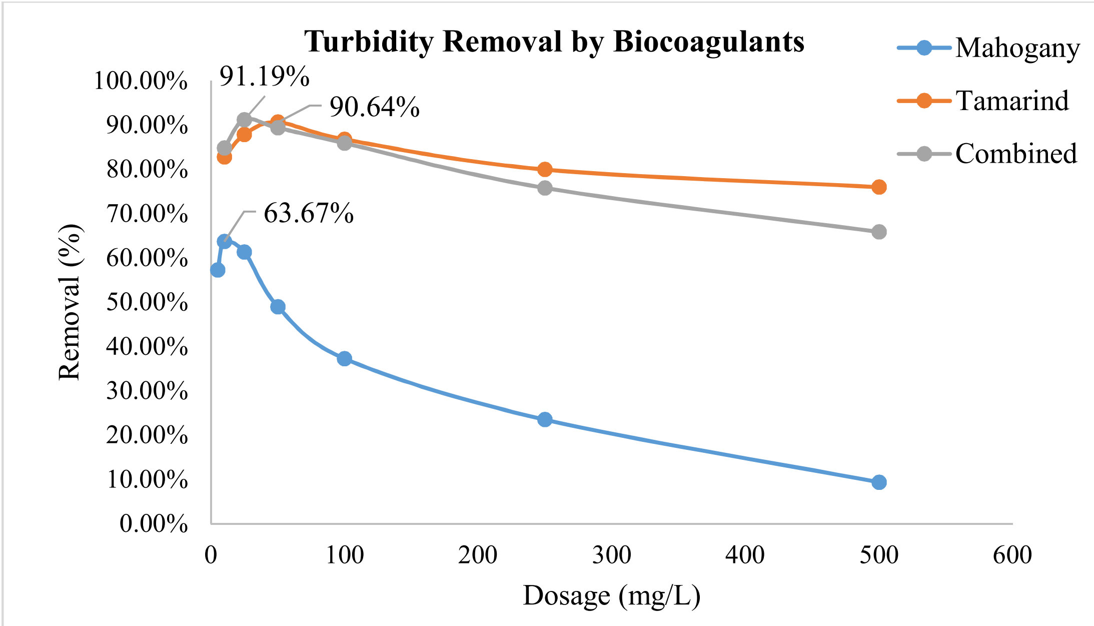


Figure 4.1 Turbidity Removal by Bio-coagulants

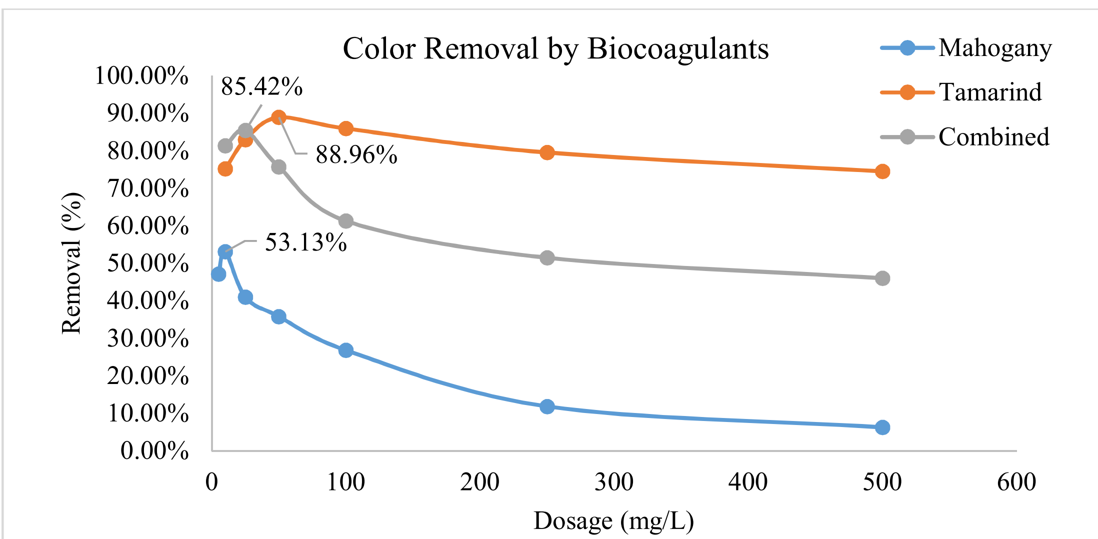


Figure 4.2 Color Removal by Bio-coagulants

The success of natural coagulants is based on the characteristics of coagulants used, water to be treated and the mixing process (Ang et al., 2020; Kumar et al., 2017). Mahogany seed extract demonstrated moderate coagulation efficiency in batch jar tests. At an optimal dosage of 10 mg/L, turbidity removal reached approximately 63.7%, reducing turbidity to about 19.8 NTU. Color removal peaked at 53.1%, with a residual color of approximately 344 Pt-Co. While the results confirm that mahogany has coagulating potential, the treated water still exceeded WHO standards for both turbidity and color. Previous studies have similarly reported that certain plant-based coagulants provide measurable turbidity reduction but generally fail to meet stringent drinking water guidelines unless supplemented with other treatments (Choubey et al., 2012). Thus, mahogany alone cannot be considered sufficient for producing potable water from highly contaminated sources.

Tamarind seed extract showed much higher performance compared to mahogany. At a dosage of 50 mg/L, turbidity removal reached a maximum of 90.6%, reducing turbidity to about 5.8 NTU, which is close to the WHO guideline limit. Color removal was also significant, averaging 81% and peaking at around 89%, with residual color between 80-190 Pt-Co depending on dose. These results indicate that tamarind is highly effective in removing turbidity and approaches the practical turbidity guideline. However, color levels remained substantially higher than recommended values. Literature supports these findings, as tamarind seed polysaccharides have been reported to achieve over 95.1% of SS removal at 10 mg/L dosage (Dewi et al., 2021). Nevertheless, its limitation in color removal highlights the need for complementary treatment steps such as filtration or adsorption. These bio-coagulants behave differently depending on the level of dosage. Increasing the dosage beyond optimum point made it less effective. This is a common issue known as overdosing where excessive coagulant can destabilize floc formation (Namane, 2024).

The combined use of mahogany and tamarind extracts produced the best overall results. At a combined dosage, turbidity removal reached 91.2%, reducing turbidity to 4.8 NTU, which meets the practical WHO limit for safe disinfection. Color removal was also improved compared to mahogany alone, reaching 85.4% with a residual of approximately 107 Pt-Co. These outcomes demonstrate a synergistic effect when both coagulants are applied together as blending natural coagulants enhances flocculation performance.

Despite this improvement, residual color remained above the desirable level, confirming that additional polishing processes are necessary.

Overall, among the tested coagulants, tamarind and the combined mahogany-tamarind formulation both produced turbidity levels near the WHO recommended threshold, with the combined approach slightly outperforming tamarind alone. However, none of the treatments reduced color to acceptable levels for drinking water. This suggests that natural coagulants can significantly improve raw water quality but should be integrated with secondary treatments, such as filtration or adsorption, to achieve compliance with international standards. These findings align with existing literature on the potential and limitations of plant-based coagulants in sustainable water treatment (Nimesha et al., 2022).

4.3.2 Batch Experiment by Chemical Coagulants

The experimental results are shown in tables along with their graphical representations. Table 4.5 and Table 4.6 present the turbidity and color removal percentage data of alum and ferric chloride respectively over a range of 10-500 mg/L. Figure 4.3 and Figure 4.4 show this turbidity and color removal efficiency variation respectively for both alum and ferric chloride.

Table 4.5: Turbidity and Color Removal Efficiency by Alum

Jar	Dosage (mg/L)	Initial Turbidity (NTU)	Turbidity (NTU)	Turbidity Removal (%)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal (%)
1	10		28.7	47.34%		411	44.01%
2	25		24.2	55.60%		364	50.41%
3	50	54.5	17.2	68.44%	734	295	59.81%
4	100		9.35	82.84%		156	78.75%
5	250		2.3	95.78%		1	99.86%
6	500		5.29	90.29%		67	90.87%

Table 4.6: Turbidity and Color Removal Efficiency by Ferric Chloride

Jar	Dosage (mg/L)	Initial Turbidity (NTU)	Turbidity (NTU)	Turbidity Removal (%)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal (%)
1	10		27.1	50.28%		381	48.09%
2	25		22	59.63%		362	50.68%
3	50	54.5	18.5	66.06%	734	231	68.53%
4	100		10.8	80.18%		122	83.38%
5	250		1.83	96.64%		89	87.87%
6	500		3.97	92.72%		229	68.80%

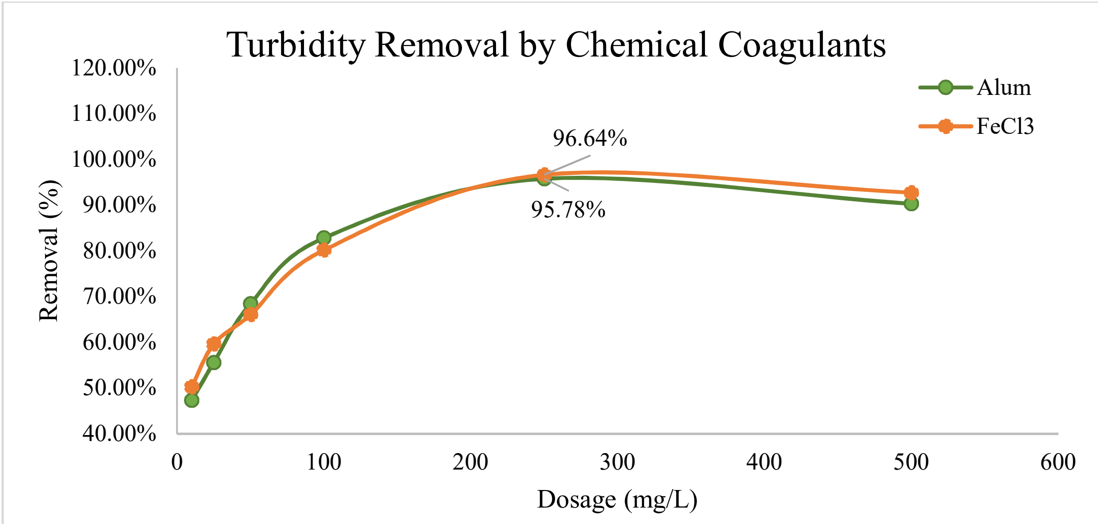


Figure 4.3 Turbidity Removal by Chemical Coagulants

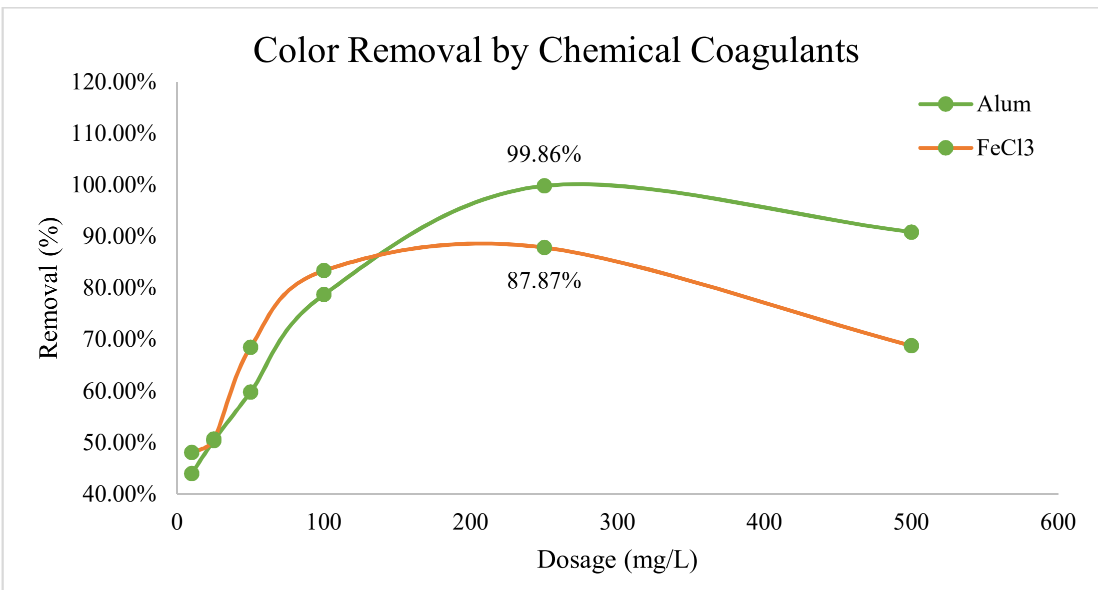


Figure 4.4 Color Removal by Chemical Coagulants

Chemical coagulants such as alum (aluminum sulfate) and ferric chloride ($FeCl_3$) demonstrated high efficiency in turbidity and color reduction in wastewater treatment. Turbidity, which was recorded at 54.5 NTU in the raw sample, showed substantial removal after coagulation, often exceeding 90% removal under optimized dosages. For instance, alum typically achieved 46-96% turbidity removal at neutral pH conditions peaking at 250 mg/L dose with 95.78% removal efficiency with residual turbidity of 2.3 NTU, while ferric chloride performs slightly better, reaching values above 96%, peaking at 250 mg/L achieving 96.64% efficiency with residual turbidity of 1.83 NTU. Similarly, color reduction, which initially measured 734 Pt-Co units, was significantly improved, with reductions in the range of 40-99% for alum whereas removal efficiencies achieved using ferric-based coagulants at different dosages are slightly lower yet effective. (Sperczyńska, 2016; Tahraoui et al., 2024).

These findings align with WHO (2022) guidelines that highlight turbidity (<5 NTU) and color (<15 Pt-Co) as critical aesthetic and health-related water quality parameters. Although chemical coagulants effectively brought both parameters closer to permissible levels, residual aluminum concentrations require careful monitoring to avoid potential health risks (WHO, 2022).

Overall, the results indicate that chemical coagulants are highly effective in addressing critical pollution indicators of the wastewater-namely turbidity and color making them a benchmark for comparison with Bio-coagulants and hybrid approaches in subsequent experiments.

4.3.3 **Batch Experiment by Bio-coagulants and Chemical Coagulants**

Batch experiments were conducted combining Bio-coagulants and chemical coagulants. Their dosage levels were determined maintaining the ratio of Bio-coagulant and chemical coagulant as 50:50, 60:40, 70:30, 80:20 and 90:10 keeping the dose of Bio-coagulants constant (optimum dose achieved during individual batch experiment). The experimental results are demonstrated in the following tables (Table 4.7, Table 4.8, Table 4.9) and graphs (Figure 4.5, Figure 4.6, Figure 4.7).

Table 4.7: Turbidity and Color Removal Efficiency by Mahogany and Chemical Coagulants

	Mahogany and Alum							Mahogany and $FeCl_3$					
Mahogany Dosage (mg/L)	**Chemical Coagulant Dosage (mg/L)**	**Initial Color (Pt-Co)**	**Color (Pt-Co)**	**Color Removal (%)**	**Initial Turbidity (NTU)**	**Turbidity (NTU)**	**Turbidity Removal (%)**	**Initial Color (Pt-Co)**	**Color (Pt-Co)**	**Color Removal (%)**	**Initial Turbidity (NTU)**	**Turbidity (NTU)**	**Turbidity Removal (%)**
	10		198	73.02%		15.42	71.71%		160	78.20%		19.9	63.49%
	7		217	70.44%		15	72.48%		243	66.89%		18.4	66.24%
10	4	734	168	77.11%	54.5	13.7	74.86%	734	158	78.47%	54.5	16.9	68.99%
	2.5		221	69.89%		14.9	72.66%		200	72.75%		18.3665	66.30%
	1		280	61.85%		15.4	71.74%		217	70.44%		19.3	64.59%

Table 4.8: Turbidity and Color Removal Efficiency by Tamarind and Chemical Coagulants

		Tamarind and Alum						Tamarind and $FeCl_3$					
Tamarind Dosage (mg/L)	**Chemical Coagulant Dosage (mg/L)**	**Initial Color (Pt-Co)**	**Color (Pt-Co)**	**Color Removal (%)**	**Initial Turbidity (NTU)**	**Turbidity (NTU)**	**Turbidity Removal (%)**	**Initial Color (Pt-Co)**	**Color (Pt-Co)**	**Color Removal (%)**	**Initial Turbidity (NTU)**	**Turbidity (NTU)**	**Turbidity Removal (%)**
50	50	734	368	49.86%	98.1	15.7	84.00%	734	242	67.03%	98.1	23.3	76.25%
	34		372	49.32%		15.5	84.20%		239	67.44%		25.2	74.31%
	22		312	57.49%		14.5	85.22%		248	66.21%		23.5	76.04%
	13		371	49.46%		20.4	79.20%		215	70.71%		22.2	77.37%
	6		394	46.32%		20.9	78.70%		253	65.53%		23.5	76.04%

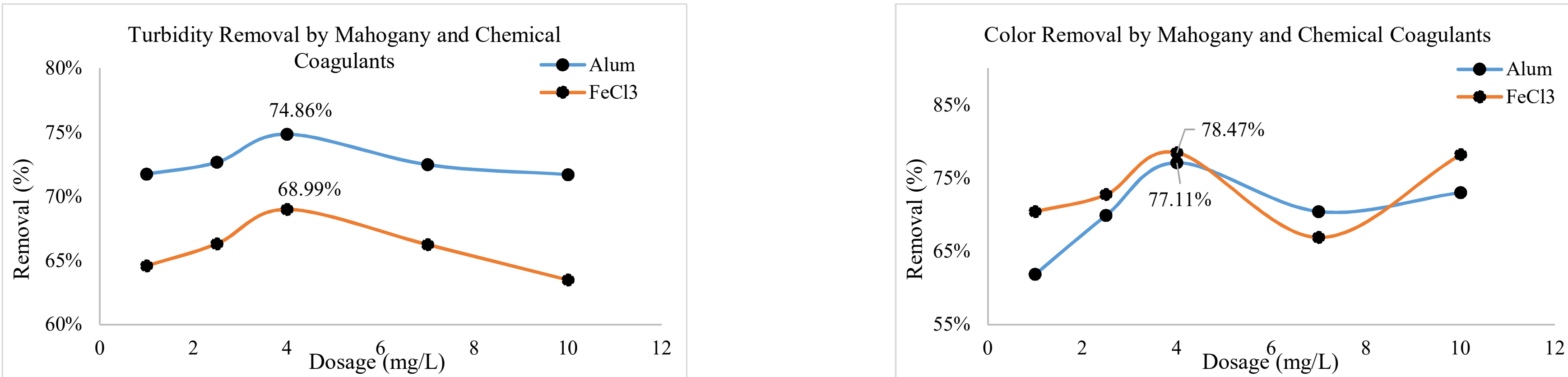


Figure 4.5 Turbidity and Color Removal by Mahogany and Chemical Coagulants

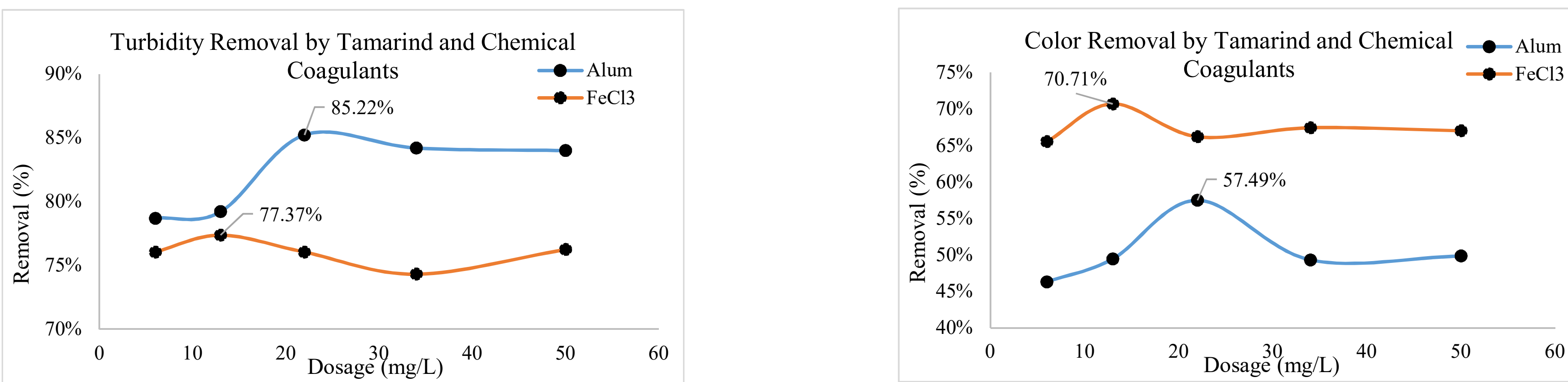
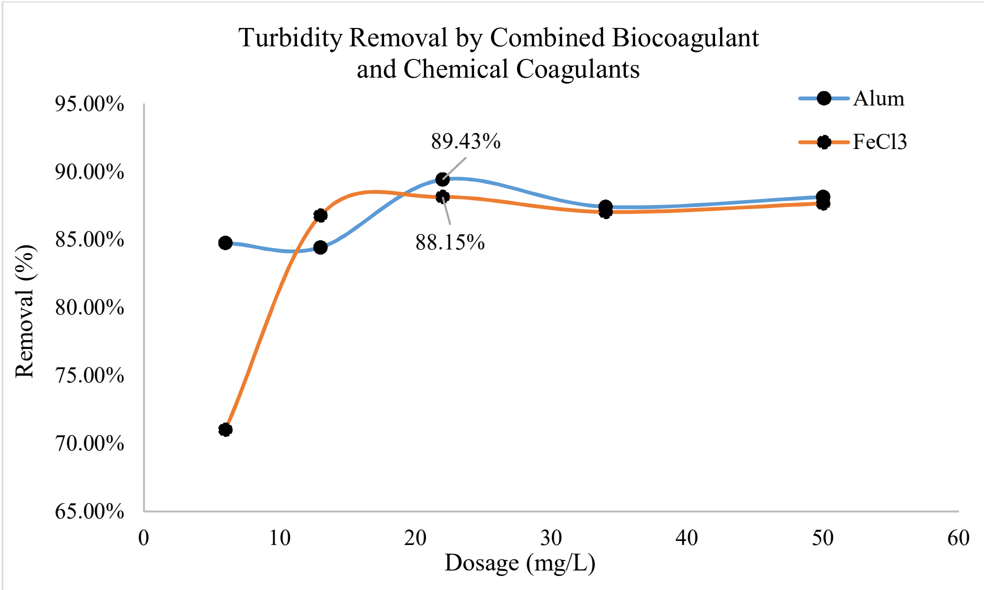


Figure 4.6 Turbidity and Color Removal by Tamarind and Chemical Coagulants

Table 4.1 Turbidity and Color Removal Efficiency by Combined Bio-coagulants and Chemical Coagulants

		Combined and Alum						Combined and $FeCl_3$					
Bio-coagulant Dosage (mg/L)	**Chemical Coagulant Dosage (mg/L)**	**Initial Color (Pt-Co)**	**Color (Pt-Co)**	**Color Removal (%)**	**Initial Turbidity (NTU)**	**Turbidity (NTU)**	**Turbidity Removal (%)**	**Initial Color (Pt-Co)**	**Color (Pt-Co)**	**Color Removal (%)**	**Initial Turbidity (NTU)**	**Turbidity (NTU)**	**Turbidity Removal (%)**
25 (each)	50	734	204	72.21%	54.5	6.46	88.15%	734	188	74.39%	54.5	6.72	87.67%
	34		200	72.75%		6.85	87.43%		188	74.39%		7.06	87.05%
	22		197	73.16%		5.76	89.43%		181	75.34%		6.46	88.15%
	13		238	67.57%		8.48	84.44%		222	69.75%		7.2	86.79%
	6		239	67.44%		8.3	84.77%		466	36.51%		15.8	71.01%



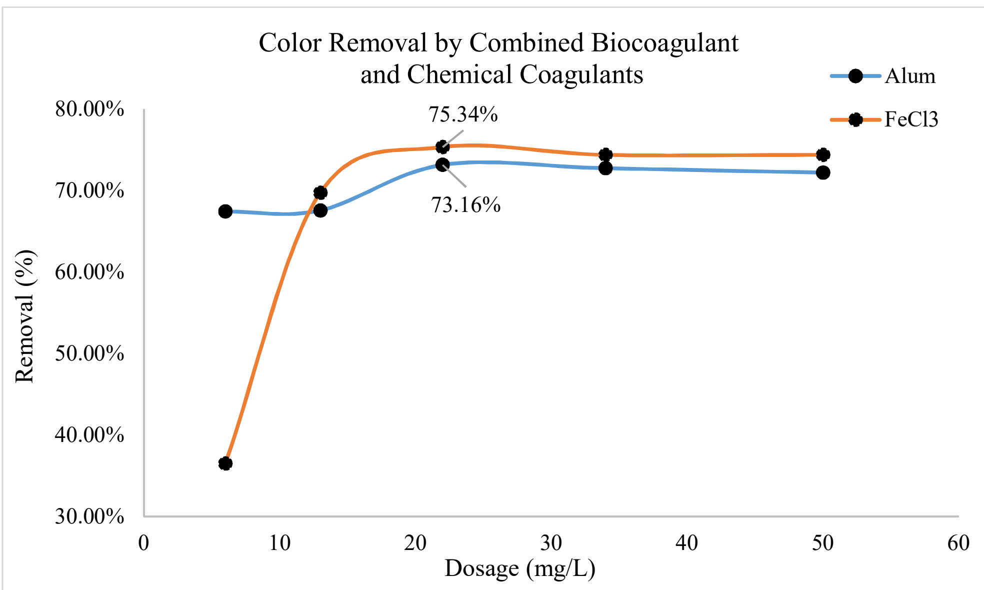


Figure 4.7 Turbidity and Color Removal by Combined Bio-coagulants and Chemical

The combination of Bio-coagulants (mahogany and tamarind extracts) with conventional chemical coagulants (alum and ferric chloride) did not lead to substantial improvement in treatment efficiency when compared with the individual use of those Bio-coagulants and chemical coagulants. The raw water characteristics revealed an initial turbidity of 98.1 NTU and color 734 Pt-Co where both significantly exceeding the WHO (2022) permissible limits of ≤5 NTU and ≤15 Pt-Co, respectively. When Bio-coagulants were applied individually, turbidity removal efficiency reached up to

91.19% while color reduction reached 88.96%. Similarly, chemical coagulants such as alum and ferric chloride achieved turbidity reductions of 90–95% and color removal up to 99%. However, when both types of coagulants were used in combination, the performance did not improve. Turbidity removal reached 74.86% (at 10+4 mg/L with the ratio 70:30) and color removal reached 77.11% (at 10+4 mg/L with the ratio 70:30) by mahogany and alum combined usage. Turbidity reached 68.99% by mahogany combining with ferric chloride whereas color removal reached 78.47% at the same optimum dosage as mahogany and alum. Chemical coagulants combining with tamarind showed similar results where turbidity reached 85.22% (at 50+22 mg/L) and color could reach only up to 57.49% (at 50+22 mg/L) by tamarind and alum again with the ratio 70:30. In case of ferric chloride combining with tamarind turbidity removal reached 77.37% (at 50+13 mg/L) and color removal efficiency reached 70.71% at the same dose as for turbidity with the dosage ratio of tamarind and ferric chloride as 80:20. Later the Bio-coagulants were combined and batch experiment was conducted at different dosage levels for chemical coagulants and fixed dose for combined Bio-coagulant (25 mg/L each) where they showed slightly better result than individual mixing. Highest turbidity removal efficiency was achieved by mixing with alum (89.43% at 25+22 mg/L dosage) where mixing with ferric chloride gave similar result of 88.15% removal at the same dose with the Bio-coagulants and chemical coagulant ratio as 70:30. Highest color reduction was also achieved at the same dose for both (75.34% mixing with ferric chloride and 73.16% mixing with alum). The results indicate that by optimizing the ratio of mixed Bio-coagulant and chemical coagulant, it is possible to challenge the traditional notion that higher chemical dosage always ensures better pollutant removal performance.

Compared to Bio-coagulants alone, the combination did not provide higher removal efficiency though combined mixing was better than that of individual mixing. Further treatments are necessary as combining treatment methods can improve water quality (Ang and Mohammad, 2020). The lack of marked improvement may be attributed to overlapping coagulation mechanisms, where the charge neutralization and particle destabilization induced by alum and ferric chloride dominate the process, leaving little scope for additional flocculation effects from Bio-coagulants. Previous studies have reported similar findings, noting that while hybrid systems can sometimes enhance treatment, in certain cases natural coagulants do not contribute significantly beyond what chemicals already achieve (Choy et al., 2014). Therefore, in this study, the combined system did not offer clear advantages in turbidity or color removal compared to Bio-coagulants and chemical coagulants alone.

4.3.4 **Batch Experiment by Biochar**

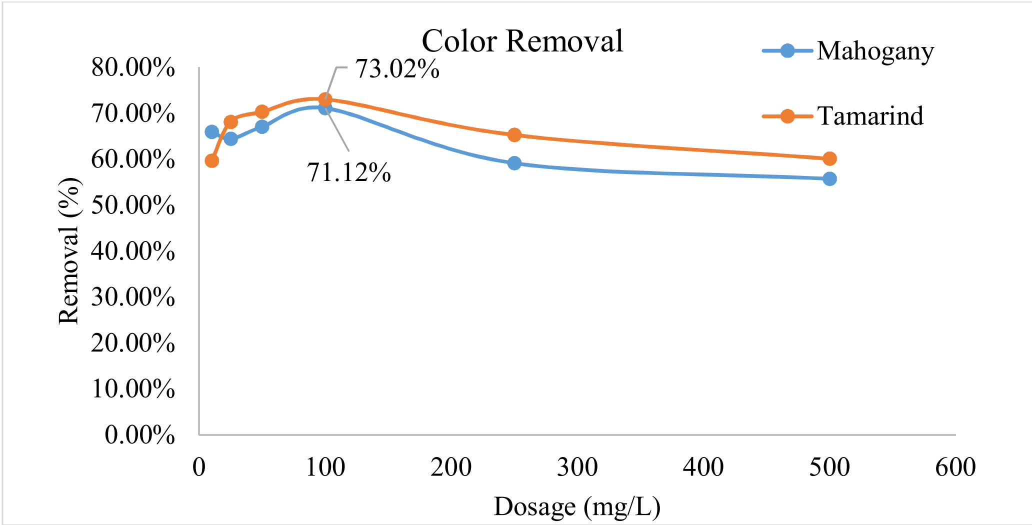
Batch experiment was conducted using mahogany and tamarind biochar following similar dosage levels to their Bio-coagulants. Following tables (Table 4.10, Table 4.11) and graphs (Figure 4.8) show corresponding removal efficiencies along with the residual values to their dosage levels.

Table 4.10: Turbidity and Color Removal Efficiency by Mahogany Biochar

Jar	Dosage (mg/L)	Initial Turbidity (NTU)	Turbidity (NTU)	Turbidity Removal (%)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal (%)
1	10	98.1	13.1	86.65%	734	250	65.94%
2	25		8.24	91.60%		261	64.44%
3	50		9	90.83%		242	67.03%
4	100		7.91	91.94%		212	71.12%
5	250		12.4	87.36%		300	59.13%
6	500		31.4	67.99%		325	55.72%

Table 4.11: Turbidity and Color Removal Efficiency by Tamarind Biochar

Jar	Dosage (mg/L)	Initial Turbidity (NTU)	Turbidity (NTU)	Turbidity Removal (%)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal (%)
1	10	98.1	17.8	81.86%	734	296	59.67%
2	25		9.19	90.63%		234	68.12%
3	50		8.35	91.49%		218	70.30%
4	100		11.7	88.07%		198	73.02%
5	250		9.83	89.98%		255	65.26%
6	500		12	87.77%		293	60.08%



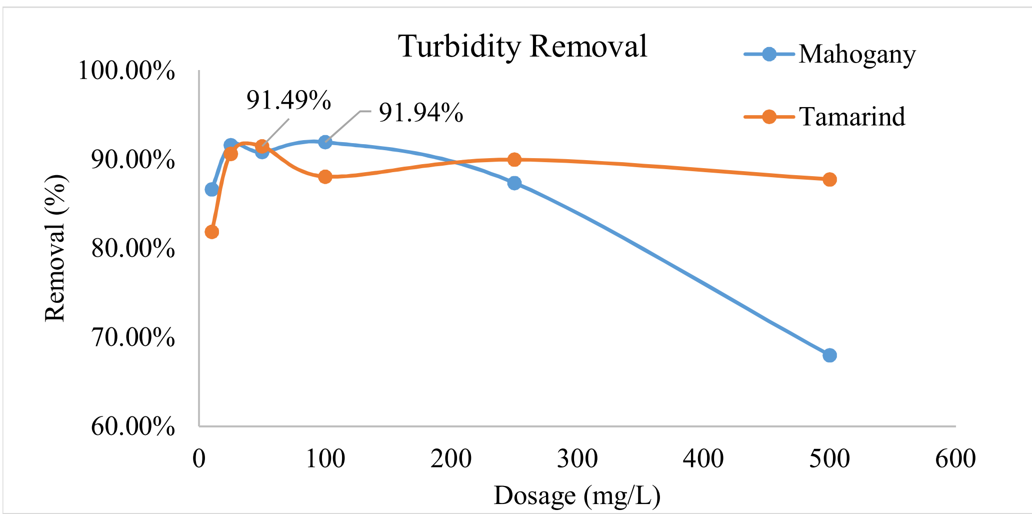


Fig 4.8: Turbidity and color removal efficiency by biochar

The application of biochar derived from mahogany and tamarind proved effective in reducing turbidity and color from wastewater, although results varied with dosage. The raw water initially had a turbidity of 98.1 NTU and color of 734 Pt-Co, significantly higher than the WHO (2022) limits of ≤5 NTU for turbidity and ≤15 Pt-Co for color. For mahogany biochar, turbidity removal efficiencies ranged between 86-92% achieving highest removal efficiency (91.94%) at 100 mg/L dose, with residual turbidity values reduced to a range of 7-31 NTU. Color removal was slightly lower, ranging from 55-71%, peaking at the same dose as turbidity resulting in final color values of 212 Pt-Co within the range 325-212 Pt-Co. Tamarind biochar showed similar performance, with turbidity removal efficiencies of 82-92% (residual turbidity 8-18 NTU) achieving highest 91.49% removal efficiency at 50 mg/L and color reductions of 60-75% (residual color 198-296 Pt-Co) with 73.02% highest removal at 100 mg/L. These results demonstrate that while biochar filtration significantly improved the aesthetic quality of water, neither mahogany nor tamarind biochar was sufficient alone to achieve complete compliance with WHO guidelines, particularly for color.

The treatment efficiency of biochar can be attributed to its porous structure, which enhances adsorption of dissolved organic matter and facilitates particle entrapment. Several studies have reported comparable findings, where mahogany pericarps are used as feedstock to produce biochar and was improved further (Dong et al., 2023). Tamarind seed proved itself as an effective biochar removing Co (II) ions from water (Lavanya et al., 2023). Chen et al. (2008) reported that wood-derived biochar could reduce organic compounds, while Tan et al. (2015) observed removal of heavy metals, organic pollutants and other inorganic pollutants using biochar.

Overall, the results of this study confirm that biochar offers a promising low-cost and sustainable option for turbidity and color removal from wastewater although there are not enough studies available to signify that. However, residual values above WHO standards suggest that biochar alone may not be sufficient for drinking-water treatment, and integration with advanced or combined methods may be required.

4.3.4.1 Equilibrium Isotherm Models

The adsorption equilibrium data for turbidity removal by mahogany and tamarind biochar were fitted to the Langmuir, Freundlich, Temkin and Redlich-Peterson isotherm models. The correlation coefficient R^2 was used as the main criterion for evaluating the model's performance. A higher R^2 value indicates that the model describes the adsorption system more accurately (Diaz-Uribe et al., 2022; Pieczykolan, 2025). Table 4.12 represents their respective R^2 values and Figure 4.9 visually represents the fittings of these isotherm models with experimental data.

Table 4.12: Correlation coefficient values of different isotherm models for turbidity removal efficiency by Mahogany and Tamarind biochar

Biochar	R^2			
	Langmuir	**Freundlich**	**Temkin**	**Redlich-Peterson**
Mahogany Fruit Shell	0.8302	0.956	0.623	0.9318
Tamarind Seed	0.584	0.9528	0.7799	0.9145

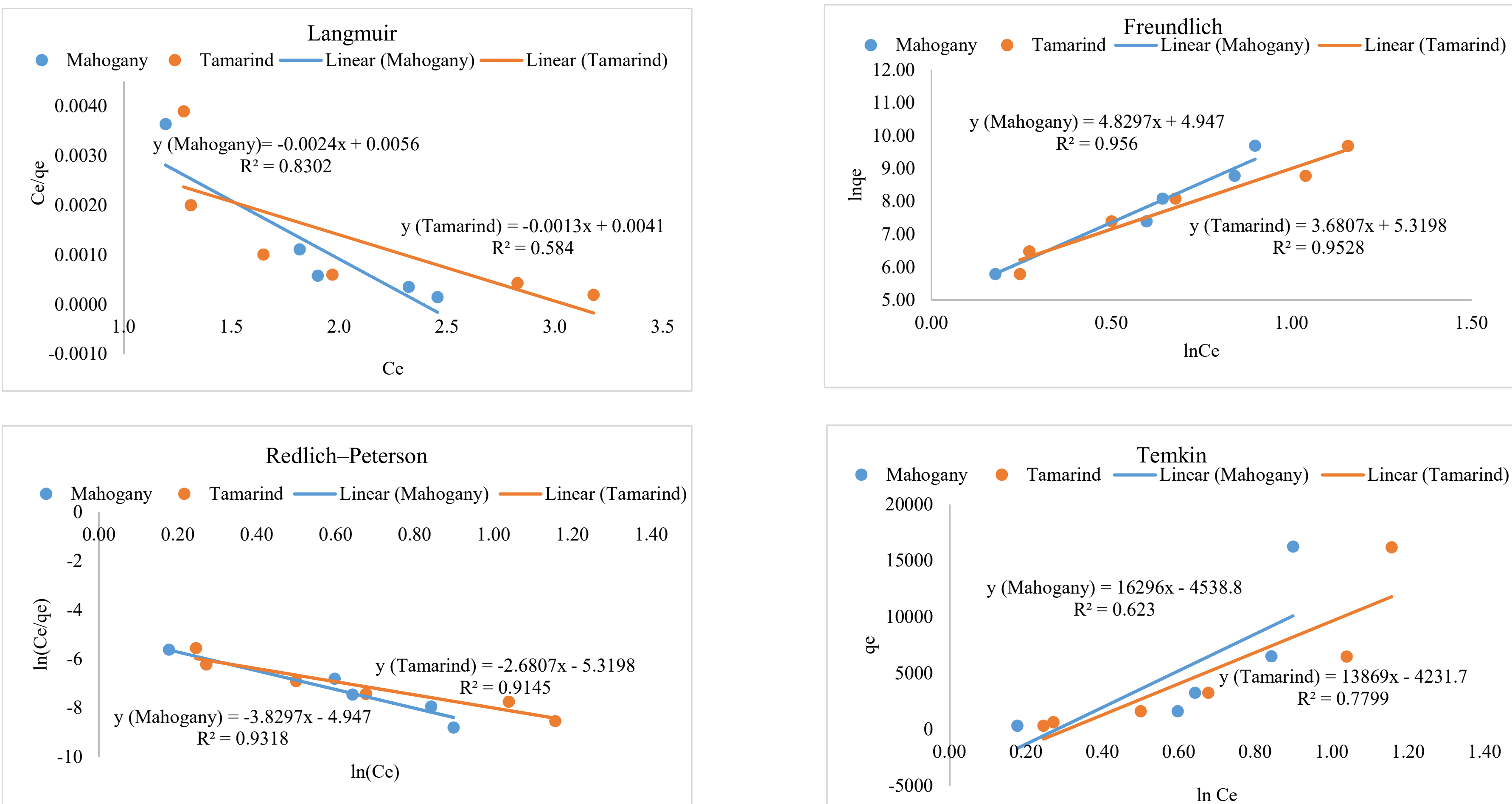


Fig 4.9: Isotherm models of turbidity removal by mahogany and tamarind biochar

For both mahogany and tamarind biochar, the Freundlich isotherm showed the highest R^2 values (for mahogany biochar and for tamarind biochar) compared to other three isotherm models. This demonstrates that the adsorption process of turbidity onto these biochars is best described by the Freundlich model. Although the Redlich-Peterson model was not the best fitting model, its R^2 value was still greater than 0.90, demonstrating that it also describes the adsorption reasonably well. The Redlich-Peterson model is a hybrid isotherm that combines features of both Langmuir and Freundlich models and thus can represent adsorption behavior in systems that are neither purely homogeneous nor purely heterogeneous (Ayawei et al., 2017).

The dominance of the Freundlich isotherm suggests that adsorption occurs on heterogeneous surfaces with varying site energies rather than on a uniform monolayer surface as assumed by the Langmuir model. Moreover, the Freundlich constant n values less than one (slope of the model $1/n > 1$), indicating the adsorption is favorable (Abdulrahman et al., 2008). The better fit of the Freundlich model implies multilayer adsorption of turbidity particles on the biochar surface, which is consistent with the irregular pore structure and diverse surface functional groups of biochar meaning it is of heterogeneous surface with non-uniform adsorption energy (Karthik et al., 2020). This indicates that these biochars are particularly suitable for treating real wastewater, where turbidity-causing particles vary in size and chemical nature, making heterogeneous adsorption advantageous. The findings also align with previous adsorption studies that emphasized the applicability of the Freundlich model to biochar systems (Diaz-Uribe et al., 2022; Pieczykolan, 2025).

4.4 Column Test

To evaluate the performance of tamarind and mahogany-derived biochars, column adsorption experiment under continuous flow condition was conducted with a fixed bed height of 2.5 cm. The purpose was to assess their efficiency in removing turbidity and color from water. The columns were packed with biochar, and influent water was passed through at a controlled flow rate (4mL/min) while samples were collected periodically (20 minutes interval for turbidity and 1 hour interval for color at 1mL/min constant flow rate) to measure removal efficiency. The results of this experiment are shown in Figure 4.10.

The rapid initial decline in turbidity (within the first 1-2 hours) demonstrates the high affinity of both biochars for suspended solids, and the early stabilization of color removal suggests effective capture of colored organics at low residual concentrations. In this study the biochar-packed columns-maintained turbidity removal throughout the whole experimental period (12 hours) of continuous flow where Patel et al. (2012) confirmed fixed bed of tamarind seed powder was difficult to get exhausted. Color removal was even more effective, with the columns achieving complete removal after 4 hours and kept removing color completely throughout the whole conduction period. This confirms the potential of biochar beds as sustainable adsorbents for extended water treatment.These dynamic results are consistent with prior column adsorption studies. For example, Patel et al. (2011) conducted fixed-bed studies using tamarind seed powder and showed effective dye removal with breakthrough behavior that fit standard models. Rajeshkannan et al. (2013) also used tamarind-derived adsorbents in packed beds to remove dyes, demonstrating bed depth and flow rate dependence. In the case of mahogany, Rangabhashiyam et al. (2016) employed chemically modified mahogany shell in column experiments for Cr(VI) removal, confirming that mahogany-based materials can function effectively in continuous adsorption systems.

The performance trend observed in our study is that fast removal followed by more gradual stabilization aligned with the typical behavior of fixed-bed adsorbents. The practical implication is that a biochar column can serve as an efficient polishing step in a treatment train, capable of reducing turbidity and color to levels acceptable for regular uses. Optimization of flow rate, bed depth, and regeneration cycles will be essential to sustain performance over longer durations.

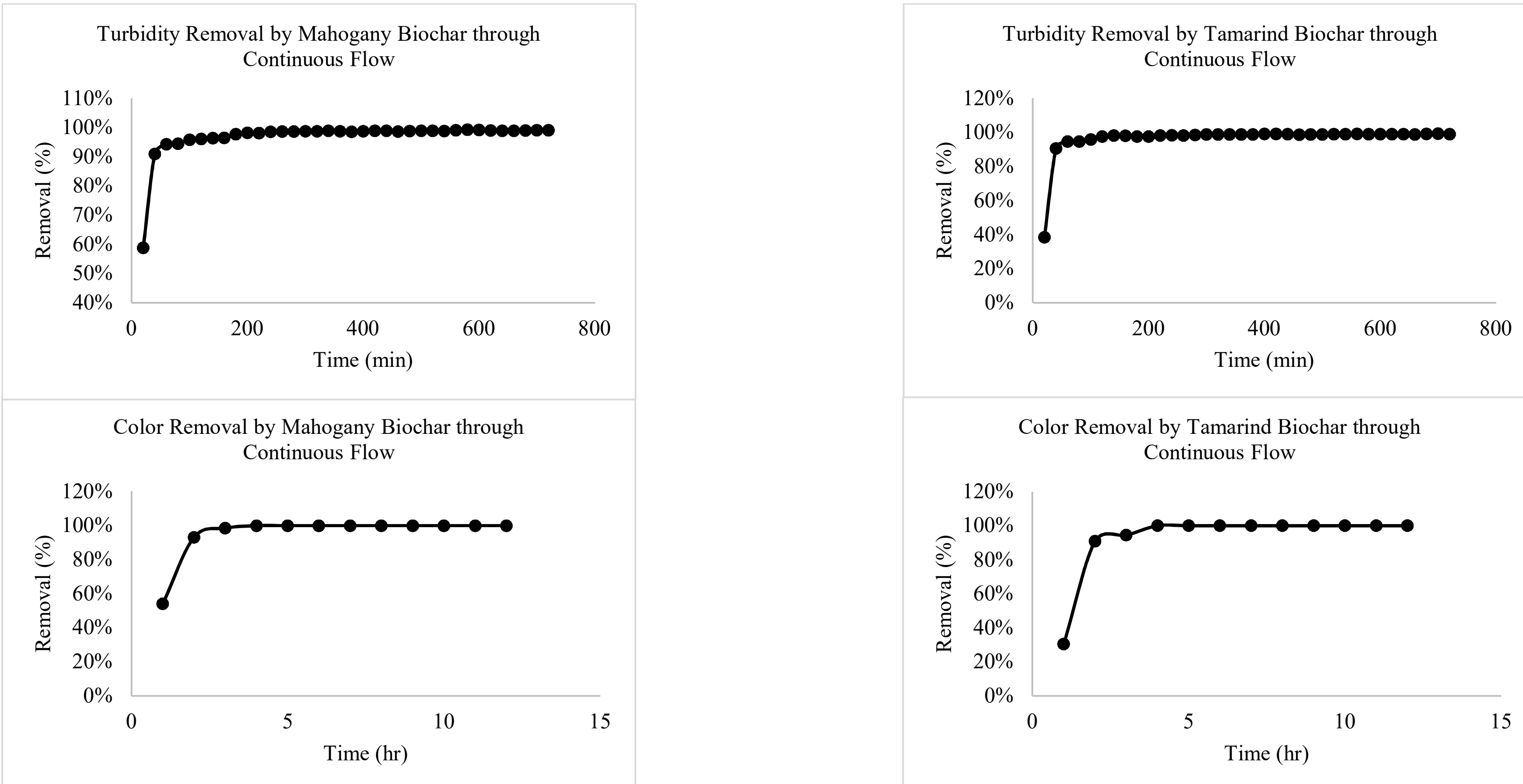


Fig 4.10: Turbidity and Color Removal Efficiency by Mahogany and Tamarind Biochar through Column Test

4.5 Result Summary

Table 4.13: Summarization of the overall results

	Bio-coagulant			**Combining Bio-coagulants and Chemical Coagulants**						**Biochar Adsorption**		**Continuous Column by Biochar**	
	Mahogany	**Tamarind**	**Combined**	**Mahogany + Alum**	**Tamarind + Alum**	**Combined + Alum**	**Mahogany + $FeCl_3$**	**Tamarind + $FeCl_3$**	**Combined + $FeCl_3$**	**Mahogany**	**Tamarind**	**Mahogany**	**Tamarind**
Optimum Dosage (mg/L)	10	50	25 (each)	10+4 (70:30)	50+22 (70:30)	25+22 (70:30)	10+4 (70:30)	50+13 (80:20)	25+22 (70:30)	100	50 (turbidity) & 100 (color)	-	-
Turbidity Removal efficiency	63.67%	90.64%	91.19%	74.86%	85.22%	89.43%	68.99%	77.37%	88.15%	91.94%	91.49%	99%	100%

Color Removal efficiency	53.13%	88.96%	85.42%	77.11%	57.49%	73.16%	78.47%	70.71%	75.34%	71.12%	73.02%	98%	100%
Best fitted Isotherm Model	-	-	-	-	-	-	-	-	-	Freundlich		-	-
Time					2 hours					-		4 hours	

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study aimed to explore the potential of using locally available natural materials such as mahogany fruit shells and tamarind seeds as Bio-coagulants, and their biochar derivatives as adsorbents, for the treatment of wastewater in the context of Bangladesh. The study covered batch coagulation tests, hybrid treatments combining Bio-coagulants and chemical coagulants, batch adsorption by biochar, and continuous flow column adsorption. The results provide clear evidence that such nature-based and low-cost approaches can significantly improve water quality, especially in terms of turbidity and color, which are two major visible indicators of pollution in Bangladesh's drain and surface waters.

In the batch coagulation experiments, tamarind seed powder showed the highest performance among the natural coagulants, achieving turbidity and color removal efficiencies of 90.64% and 88.96%, respectively, at an optimum dosage of 50 mg/L. Mahogany fruit shell powder demonstrated moderate results with a maximum turbidity removal of 63.67% and color removal of 53.13% at a lower optimum dosage of 10 mg/L. When both were combined in equal proportion (25 mg/L each), the turbidity removal increased to 91.19%, and color removal reached 85.42%, indicating a synergistic effect between the two natural materials.

However, the use of chemical coagulants such as alum and ferric chloride, though effective, comes with significant drawbacks. Residual aluminum or iron in treated water can pose long-term health hazards, including neurological and digestive disorders. Moreover, the sludge generated from chemical treatments is often toxic and difficult to manage. In Bangladesh, such sludge frequently ends up in open landfills, drains, or nearby canals, worsening environmental pollution. The continuous use of imported coagulants also increases treatment costs, making it unsustainable for small communities and industries. These challenges highlight the necessity of adopting safer and more eco-friendly alternatives such as plant-based coagulants and biochar, which produce less waste and have no harmful by-products.

When Bio-coagulants were combined with chemical coagulants such as alum and ferric chloride produced mixed but encouraging results. Although these hybrid systems did not surpass the performance of chemical coagulants alone, they achieved comparable turbidity and color removal while using less chemical dosage. For instance, a 70:30 ratio of combined Bio-coagulant and alum achieved 89.43% turbidity removal and 73.16% color removal, whereas ferric chloride combinations reached up to 88.15% turbidity removal and 75.34% color removal. This demonstrates that replacing a portion of chemical coagulants with natural materials can reduce chemical usage, cost, and residual sludge toxicity, aligning with environmentally sustainable practices suitable for Bangladesh's wastewater treatment scenario.

Biochar adsorption performed better than coagulation treatments. In batch adsorption, both mahogany and tamarind biochars achieved turbidity and color removal efficiencies between 71% and 92%, with the best results observed at 100 mg/L for mahogany and 50-100 mg/L for tamarind biochar. The adsorption data fitted best with the Freundlich isotherm model, indicating multilayer adsorption on heterogeneous surfaces, which reflects the porous and diverse structure of biochar materials.

The continuous flow column test showed the most promising performance among all methods. Both mahogany and tamarind biochars achieved near-complete removal of turbidity and color, with up to 99-100% removal within four hours of operation. This suggests that biochar columns can be highly effective for small-scale, continuous wastewater treatment applications. The fixed-bed setup remained efficient over extended flow duration without early saturation, making it a practical and reliable system for regular use.

When comparing the three treatment approaches used in this study, Bio-coagulants, hybrid Bio-coagulant-chemical coagulants, and biochar adsorption-the biochar column system clearly proved to be the most effective. The Bio-coagulants performed well, particularly tamarind and its combination with mahogany, which achieved over 90 percent turbidity and color removal. The hybrid treatments achieved similar results while reducing chemical dependency. However, the biochar system surpassed both, reaching complete removal levels (99-100%) under continuous flow conditions. In addition, biochar filters offer several advantages: they produce no harmful sludge, require minimal maintenance, and can be regenerated or reused.

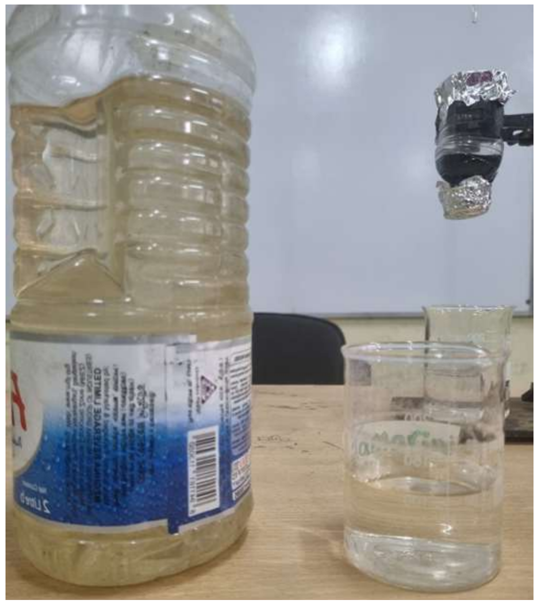


Figure 5.1 Wastewater (left) and treated water (right)

These findings are highly relevant for Bangladesh, where untreated wastewater from households, markets, and small industries continues to pollute surface and groundwater systems. In districts such as Gazipur, Narayanganj, Savar, and Chattogram, domestic and industrial effluents flow directly into open canals and rivers, threatening both human health and aquatic ecosystems. Implementing bio-based and locally prepared treatment systems like those developed in this study can significantly improve water quality while reducing environmental damage and dependence on expensive imported chemicals.

Overall, the study successfully achieved its objectives. The results confirmed that both mahogany and tamarind-based materials can be transformed into efficient, safe, and low-cost treatment agents. Tamarind seed extract emerged as the most effective Bio-coagulant, while biochar columns proved to be the most sustainable and efficient treatment option, capable of achieving almost complete removal of turbidity and color. These materials are biodegradable, locally available, and suitable for decentralized wastewater management at the community, institutional, and small-industry levels.

In conclusion, the use of tamarind and mahogany-based coagulants and biochar offers a practical and environmentally responsible solution to Bangladesh's growing wastewater challenges. This approach not only promotes cleaner water and healthier communities but also encourages resource recovery, waste utilization, and local employment opportunities. With proper awareness, technical training, and policy support, these natural methods can play an important role in building a cleaner, more sustainable water management system across Bangladesh.

5.2 Future Scopes

The outcomes of this study open several practical directions for future development and field application, particularly in the context of Bangladesh, where low-cost and sustainable water treatment technologies are in high demand. The results clearly showed that biochar, especially when applied through a continuous column setup, achieved the highest removal efficiency for both turbidity and color. Therefore, future work should focus on designing and testing pilot-scale biochar filtration units that can be implemented in rural and peri-urban communities. Such systems can be operated by local users using simple tools and gravity-based flow, eliminating the need for electricity or advanced mechanical parts.

Further research should investigate the long-term performance of biochar columns under continuous operation, including their adsorption capacity over time, breakthrough behavior, and regeneration possibilities. The regeneration and reuse of spent biochar through drying, heating, or chemical activation should be examined to ensure cost-effectiveness and sustainability. Studies should also assess the safe disposal or secondary use of exhausted biochar, for example as a soil amendment, which can promote a circular and eco-friendly waste management approach in Bangladesh.

Future studies may also explore the combination of Bio-coagulant and biochar systems into a single treatment chain. Coagulation using tamarind or combined Bio-coagulants can serve as a primary step for suspended particle removal, followed by a biochar column for polishing and color reduction. Such integrated setups can deliver reliable water treatment for small communities, educational institutions, and local markets at minimal cost. The design can be customized using materials like clay pots, bamboo frames, or PVC pipes, which are readily available across rural Bangladesh.

In addition to household and community water treatment, this method can be applied in small-scale industries such as textile dyeing, tanneries, and food processing units where wastewater is often discharged untreated. By introducing biochar-based filtration systems and Bio-coagulant-assisted settling tanks, such industries can significantly reduce pollution before discharge into nearby water bodies, supporting local environmental protection efforts. Future work should also involve collaboration with government agencies, universities, and NGOs to test these technologies in real field conditions. Awareness and training programs can be developed to teach communities how to produce biochar from agricultural waste, prepare Bio-coagulants from local seeds and fruit shells, and manage small-scale treatment systems efficiently. These programs can help create livelihood opportunities for rural youth and encourage local entrepreneurship centered on biochar production and water treatment materials.

To strengthen long-term sustainability, economic feasibility and life-cycle analyses should be conducted to compare the cost, energy demand, and environmental footprint of bio-based systems with conventional chemical treatments. Further investigation should also address other contaminants such as heavy metals, nutrients, and microbial pollutants, expanding the applicability of these natural materials to various types of wastewater.

If properly developed and supported by local authorities, these bio-based treatment methods have strong potential to transform community-level water management in Bangladesh. They can provide clean water for domestic and agricultural purposes, reduce pollution loads in drains and canals, and contribute to the country's progress toward Sustainable Development Goals related to clean water, sanitation, and sustainable production. The continuation of this work at larger scales will help bridge the gap between laboratory innovation and real-world practice, making clean water more accessible through nature-based and locally driven solutions.

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CHAPTER 7: APPENDIX

7.1 APPENDIX 1: Continuous Column Test Data

Table 7.1: Turbidity removal through column test by mahogany biochar

Time (min)	Initial Turbidity (NTU)	Final Turbidity (NTU)	Turbidity Removal
20	56.6	23.3	59%
40		5.12	91%
60		3.2	94%
80		3.1	95%
100		2.34	96%
120		2.2	96%
140		2.04	96%
160		2	96%
180		1.26	98%
200		1	98%
220		1.08	98%
240		0.8	99%
260		0.76	99%
280		0.75	99%
300		0.7	99%
320		0.72	99%
340		0.63	99%
360		0.73	99%
380		0.82	99%
400		0.73	99%
420		0.63	99%
440		0.6	99%

460		0.77	99%
480		0.65	99%
500		0.632	99%
520		0.61	99%
540		0.66	99%
560		0.5	99%
580		0.4	99%
600		0.45	99%
620		0.55	99%
640		0.62	99%
660		0.62	99%
680		0.55	99%
700		0.52	99%
720		0.5	99%

Table 7.2: Turbidity removal through column test by tamarind biochar

Time (min)	Initial Turbidity (NTU)	Turbidity (NTU)	Turbidity Removal
20		34.8	39%
40		5.34	91%
60		3.05	95%
80		3	95%
100		2.34	96%
120		1.39	98%
140	56.6	1.03	98%
160		1.13	98%
180		1.35	98%
200		1.34	98%
220		1	98%
240		0.9	98%
260		0.98	98%

280	0.81	99%
300	0.7	99%
320	0.65	99%
340	0.65	99%
360	0.62	99%
380	0.7	99%
400	0.5	99%
420	0.5	99%
440	0.55	99%
460	0.77	99%
480	0.62	99%
500	0.66	99%
520	0.6	99%
540	0.55	99%
560	0.5	99%
580	0.6	99%
600	0.54	99%
620	0.55	99%
640	0.57	99%
660	0.64	99%
680	0.45	99%
700	0.42	99%
720	0.56	99%

Table 7.3: Color removal through column test by mahogany biochar

Time (hr)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal
1	338	155	54%
2		23	93%
3		5	99%
4		0	100%

5	0	100%
6	0	100%
7	0	100%
8	0	100%
9	0	100%
10	0	100%
11	0	100%
12	0	100%

Table 7.4: Color removal through column test by tamarind biochar

Time (hr)	Initial Color (Pt-Co)	Color (Pt-Co)	Color Removal
1	338	235	30%
2		31	91%
3		19	94%
4		0	100%
5		0	100%
6		0	100%
7		0	100%
8		0	100%
9		0	100%
10		0	100%
11		0	100%
12		0	100%

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