DUAL-SCALE TECHNO-ECONOMIC ASSESSMENT OF COAGULATION-FLOCCULATION FOR GREYWATER TREATMENT AND RESOURCE RECOVERY USING LOCAL COAGULANTS IN BENIN CITY, EDO STATE, NIGERIA.

BY

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PLAGIARISM

This work **DUAL-SCALE TECHNO-ECONOMIC ASSESSMENT OF COAGULATION-FLOCCULATION FOR GREYWATER TREATMENT AND RESOURCE RECOVERY USING LOCAL COAGULANTS IN BENIN CITY, EDO STATE, NIGERIA** by OJO, Otti Oise, Matriculation Number ENG2002111, of the Department of Civil Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria, has PASSED the PLAGIARISM TEST.

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CERTIFICATION

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DEDICATION

I dedicate this project work to my loving family, whose unwavering support and encouragement have been my pillars of strength throughout this journey. Your belief in me fuels my aspirations.

This work is a testament to the bonds of family and friendship, and I express my deepest gratitude to each one of you.

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ABSTRACT

This study assessed the dual-scale techno-economic feasibility of using *Moringa oleifera* as a natural coagulant–flocculant for greywater treatment. The study aimed to evaluate the dual-scale techno-economic feasibility of using locally sourced coagulants for coagulation-flocculation treatment of greywater, with a focus on treatment efficiency, cost-effectiveness and possible reuse.

The study involved the collection of greywater from a commercial kitchen and its treatment in a fabricated coagulation–flocculation water treatment prototype using locally sourced materials. *Moringa oleifera* seeds were processed into powder and applied at optimized dosages in operational use of the prototype for greywater treament. Physico-chemical parameters including pH, electrical conductivity, turbidity, total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD) and biochemical oxygen demand (BOD) were analyzed before and after treatment. A techno-economic analysis compared the experimental moringa-based system with a conventional alum-based system in terms of capital expenditure (CAPEX), operating expenditure (OPEX), energy consumption, sludge management and payback period.

The results of this study revealed substantial reductions in key pollutants: turbidity decreased from 8.4 NTU to 3.7 NTU, TSS from 22.4 mg/L to 8.7 mg/L, COD from 800.4 mg/L to 310.6 mg/L, and BOD from 101.3 mg/L to 79.4 mg/L, while colour reduced from 10.4 Pt.Co to 5.3 Pt.Co. However, TDS and EC values decresed from 2577 mg/L to 2554 mg/L and 5153 µS/cm to 5107 µS/cm respectively but remained above permissible limits, indicating a need for further treatment. The techno-economic analysis showed that the moringa-based system required lower CAPEX (₦ 2.2 million vs ₦ 3.0 million), reduced OPEX (₦ 540,000/yr vs ₦ 820,000/yr), and achieved a faster payback (3.8 years vs 6.5 years), yielding a return on investment of 28% compared to 15% for alum. The study concluded that *Moringa oleifera* is an effective, eco-friendly and cost-efficient coagulant suitable for decentralized greywater treatment. It is recommended that further optimization of dosage, integration with biological post-treatment and pilot-scale community deployment be pursued to enhance reuse potential and policy adoption.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

BOD – Biochemical Oxygen Demand

CAPEX – Capital Expenditure

CFU – Colony Forming Units

COD – Chemical Oxygen Demand

DO – Dissolved Oxygen

EPA – Environmental Protection Agency

FAS – Ferrous Ammonium Sulfate

MBR – Membrane Bioreactor

NTU – Nephelometric Turbidity Units

OPEX – Operating Expenditure

ROI – Return on Investment

SBR – Sequencing Batch Reactor

SDG – Sustainable Development Goal

TDS – Total Dissolved Solids

TEA – Techno-Economic Assessment

TS – Total Solids

TSS – Total Suspended Solids

UASB – Upflow Anaerobic Sludge Blanket

UV – Ultraviolet

WHO – World Health Organization

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Grey water is wastewater from household activities and sources such as showers in bathrooms, laundry but excluding kitchen and toilets which can be treated and used for non-potable uses such as irrigation, laundry and washing. The treatment of grey water has benefits which include reduction in strains on water purification facilities, reduction in potable water utilization, cost and effectiveness in water production and purification. The goal of purifying grey water is to produce water that fits specific purposes. The discharge of untreated grey water to topsoil and consequential percolation to sub-soil may pose detrimental effects to other potable water sources such as boreholes, wells, streams and plants and animals which may be affected by the pathogen and COD carrying grey water (Ghafari et al., 2010). This is prevalent in rural areas where there are no proper design and deployment of water discharge facilities which undermines environmental health and safety.

The United Nations Millennium Development Goals has amongst its proposals to reduce by over 50% the number of people globally who lack access to clean safe water. Due to the numerous deaths and illnesses caused by waterborne pathogens, various household water treatment devices and safe storage technologies have been developed to treat and manage water at the household and even commercial levels. The new approaches being examined require durability, lower overall cost and more effective in the removal of the contaminants.

In 2022, globally, a minimum of 1.7 billion people use drinking water sources contaminated with faeces and other organic matters. Naturally occurring organic matter is a range of heterogeneous hydrophobic and hydrophilic components in water sources. The presence of NOM in water sources adequate for drinking water treatment, mainly humic and fulvic acids, contributes to the formation of disinfection by-products (DBPs) when water is treated with a disinfecting agent such as chlorine or chloramine, which leads to the potential presence of carcinogenic compounds in conventionally treated waters. These DBPs in drinking water have been found to be toxic and associated with many forms of cancer endocrine disorders and other diseases. (Gilca et al., 2020) Coagulation-flocculation is among the most applied processes for NOM removal from water sources like grey water from homes. Coagulation is based on NOM particle destabilization using positively charged metals with the formation of larger particles (flocs). This is followed by the settling of organic pollutants.

The efficiency of coagulation and flocculation to remove NOM from water mainly depends on the coagulants type and dosage, pH value, mixing conditions, water temperature, flocculants type and dosage, properties of the NOM (Dayarathne et al., 2021; Teh et al., 2016). Due to public health concerns on the potential health effects of DBPs, there have been set safe limits for NOM set by the European Union (EU) prior to disinfection and the consequential formation of BDPs. Flocculation is a process by which colloidal particles suspended in a liquid clump together to form larger settle able flocs. It is basically achieved by adding chemicals called flocculants which neutralize the electrical charges that keep particles apart allowing them to clump together.

A large number of chemicals may be used as coagulants and flocculants in treating different types of wastewaters (Srivastava et al., 2005). These materials include inorganic and organic-based coagulants (Amuda and Amoo 2007). A large percentage of the world population who are subject to this deficiency in accessing clean safe water are from the developing world, especially the rural communities where there is prevalence of low-income and adequate technology. (WHO, 2021). Small communities face the greatest difficulty in receiving water of an adequate quality and quantity because they lack experienced water managers to maintain and upgrade their water supply. Interruptions in water services due to inadequate management as well as violations of reusable water standards are contributing causes to the consumers who are at risk of waterborne diseases. In addition to this, there has been proliferation of substandard water purifying facilities, while others are quite expensive to acquire making it difficult for people to have access to clean, less costly and sustainable water systems. The most common cause of illness and deaths in the developing world is watery diarrhoea called cholera (WHO, 2023; Clasen et al., 2006). In view of these shortcomings, it has become pertinent to develop cheap and sustainable small to medium water purification solutions to produce safe and clean water for various purposes using local technology such as the coagulation-flocculation for water treatment. Achieving this requires a detailed techno-economic assessment of the coagulation-flocculation process for grey water treatment using locally sourced synthetic and bio coagulants.

1.2 Statement of the Problem

The escalating demand for freshwater, compounded by rapid urbanization and industrial expansion, has resulted in an unsustainable strain on limited freshwater resources. Simultaneously, vast volumes of greywater wastewater from showers, sinks, and laundries are discharged untreated into the environment, especially in low-income regions. Though greywater contains fewer pathogens than blackwater, it still harbors nutrients, surfactants, heavy metals, and organics that can degrade soil and water quality and pose public health risks (Carden et al., 2007; WHO, 2018).

Despite the availability of treatment technologies, their high cost and complexity limit adoption in decentralized or resource-constrained contexts. Conventional chemical coagulants like alum and ferric salts generate hazardous sludge and require precise dosing and pH conditions, making them less desirable for widespread community-level use. Moreover, techno-economic assessments in literature often overlook the comparative scalability and economic feasibility of using local coagulants like *Moringa oleifera* or *Tamarindus indica*, which offer biodegradable, low-toxicity alternatives.

Therefore, there is a pressing need to evaluate the dual-scale performance both laboratory and projected of local coagulant-based coagulation-flocculation systems for greywater treatment, including their technical efficiency, sludge characteristics, and economic viability for resource recovery and sustainable reuse.

1.3 Aim and Objectives

The aim of this study is to evaluate the dual-scale techno-economic feasibility of using a locally sourced coagulant for coagulation-flocculation treatment of greywater, with a focus on treatment efficiency, cost-effectiveness and possible reuse.

The specific objectives are to:

a. identify and prepare a selected locally available coagulant (*Moringa oleifera*) using standardized processing methods.
b. develop the design and fabrication of a coagulation-flocculation water purification facility to treat the grey water.
c. collect untreated domestic greywater and carry out treatment using the coagulation-flocculation water purification facility with the selected coagulant.
d. analyze (turbidity, colour, BOD, COD, pH, TDS, TSS) the treated greywater and carry out a comparative techno-economic assessment of the coagulation-flocculation water purification system and conventional water purification systems.

1.4 Scope of the Study

The scope of the present study involves design and fabrication of an experimental scale grey water purification facility which encompasses the coagulation-flocculation process. The purification system will be aimed at treating grey water that can be used for non-potable processes such as laundry and plant watering. The purification process is aimed at decontaminating samples of grey waters by removing dissolved solids. The research will carry out laboratory analysis of the test samples of purified and unpurified grey water to determine the efficacy of the test facility.

1.5 Justification of the Study

This study is warranted by the dual challenges of freshwater scarcity and inadequate greywater treatment infrastructure, especially in developing regions. By exploring local coagulants as sustainable alternatives, the research promotes environmental conservation, public health protection, and economic empowerment through locally sourced materials.

The dual-scale techno-economic assessment ensures the findings are not only scientifically valid but also practically and financially feasible. While lab-scale experiments provide precision, scaling up reflects real-world constraints such as resource availability, labor costs, and treatment efficiency over time.

This research aligns with global sustainability agendas, including SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production), and provides actionable insights for NGOs, water authorities, environmental policymakers, and local communities aiming to implement low-cost, effective, and sustainable greywater treatment solutions.

CHAPTER TWO

LITERATURE REVIEW

2.1 Concept of Grey Water and Its Characteristics

Greywater refers to domestic wastewater generated from household activities that does not contain fecal contamination (in essence, it is not mixed with toilet waste, which is classified as blackwater). It is distinct from blackwater due to its lower pathogen content and organic load, making it more suitable for reuse after minimal treatment (EPA, 2022; WHO, 2018).

Greywater typically includes wastewater from:

a. Showers and bathtubs
b. Bathroom sinks
c. Laundry machines
d. Kitchen sinks (though some classifications exclude kitchen wastewater due to higher grease and food residue content)

Unlike blackwater, which requires extensive treatment before being reused, greywater can often be repurposed for irrigation, toilet flushing and other non-portable applications with basic filtration and disinfection (Al-Jayyousi, 2003).

2.1.1 Sources of Greywater

Greywater is generated from various household activities, each contributing to different levels of contaminants. The primary sources include:

1. Bathroom Greywater

a. Showers and Bathtubs

i. Accounts for a significant portion of household greywater.
ii. It contains soap, shampoo, skin cells and minimal organic matter.
iii. Generally low in pathogens unless contaminated with bodily fluids (from illness).

b. Bathroom sinks

i. Water from handwashing, face washing and teeth brushing.
ii. May contain traces of toothpaste, soap and bacteria but is less polluted than kitchen wastewater.

2. Laundry Greywater

a. Generated from washing machines.

b. Contains detergent, fabric softeners and lint.

c. Depending on detergent type (phosphate free vs conventional), it may be more or less suitable for irrigation (Jefferson et al., 2000).

2.1.2 General Characteristics of Greywater

Grey water contains various resources depending on the source. (Reid et al., 2010) observed that grey water contains sodium, chlorides, and other nutrients such as nitrogen (N), ammonia (NH_3) and phosphates. Travis et al. (2010) observed that the large quantities of sodium (Na) and phosphates (PO_4) found in grey water emanate from washing machine powders. They note that washing detergents are the primary source of phosphates in grey water in countries that have not yet banned phosphorus containing detergents. Similarly, according to Barker-

Reid et al. (2010) and Carden et al. (2007) grey water contains chlorides, ammonia, phosphates and sodium in considerable amounts. However, (Carden et al., 2007) further observed that grey water also contains significant amounts of boron and cadmium. Correspondingly, Bolivian researchers Al-Zu'bi and Al-Mohamadi (2008) discovered a significant presence of heavy metal concentrations such as cadmium and nickel in grey water. However, the grey water that was used in Al-Zu'bi and Al-Mohamadi's (2008) investigation was not only sourced from households but included industrial wastewater. Palmquist and Hanaeus (2010), who investigated the availability of resources in grey water from ordinary Swedish households, found mainly calcium, iron, potassium, sodium, magnesium, cadmium, cobalt, copper, lead, tin and zinc in the grey water. Eriksson et al. (2010) argue that metals in grey water have not been studied in great detail. However, they insist that the concentrations found in the influent and effluent greywaters in Denmark agree with results obtained by (Palmquist and Hanaeus, 2010) in Sweden. The only difference is that Eriksson et al. (2010) found high levels of cadmium (9.0 μg/l) in grey water. (Eriksson et al., 2010) further observed that resources such as ammonium, nitrogen, nitrogen, phosphorus, nitrates and nitrites are found in grey water. Their availability is dependent on grey water sources (Eriksson et al., 2010). They further stated that since grey water is wastewater from washing, bathing, washing basins and laundry, its main contaminants include organic material, soaps, detergents and various oils.

Based on the above arguments, it can be concluded that grey water contains contaminants such as organic material, soaps, detergents and oils. However, it also contains nutrients such as sodium, chlorides, nitrogen (N), ammonia (NH_3) and phosphates among other nutrients.

The quantities of the contaminants and nutrients in grey water are dependent on the source of the grey water.

2.1.3 Properties of Greywater

1. Physical properties of greywater

Greywater's physical properties vary depending on its source but generally include:

Turbidity: Ranges from slightly cloudy(bathwater) to heavily soiled (kitchen wastewater).

b. Color: Typically, greyish due to soap and organic matter.

c. Temperature: Warmer than tap water if recently discharged from showers or laundry.

d. Suspended Solids(ss): Low to moderate (50-200mg/l) in bathroom greywater. Higher in kitchen greywater (200-500mg/L) due to food particles (Eriksson et al., 2010).

2. Chemical properties of greywater

a. Organic matter

- i. Biochemical Oxygen Demand (BOD): 50-300mg/l (lower than sewage but still significant).
- ii. Chemical Oxygen Demand: 100-600mg/l, indicating oxidizable pollutants (WHO, 2006).

b. Nutrients

- i. Nitrogen(N): 5-20 mg/l (from urine traces in showers/sinks).
- ii. Phosphorus(P): 1-15 mg/l (from detergents).

c. Surfactants and Salts

- i. Sodium (Na^+) and Chloride (Cl^-): High in laundry water due to detergents.

ii. Surfactants: Found in soaps and shampoos (can harm plants if untreated).

d. Ph Levels

Typically, neutral to alkaline (7-9) due to soap content.

3. Biological properties of greywater

a. Microbial Content

i. Total coliforms: 10^3-10^6 CFU/100 mL (from skin flora).

ii. E coli and fecal coliforms: present in low amounts (if there is no cross contamination with blackwater).

iii. Opportunistic pathogens: Pseudomonas aeruginosa and staphylococcus spp. may be found (Ottoson and Stenstrom, 2003).

b. Decomposition and Odor

i. If stored too long, organic matter decomposes producing foul odors (Fiedler et al., 2006).

ii. Anaerobic conditions promote harmful bacteria (Ottoson and Stenstrom, 2003; WHO, 2006).

Table 2.1: Constituents of Greywater

S/N	Types of Constituents	Parameters	Range
1.	Physical Constituents	Temperature	18-35˚C
		Turbidity	19-444 NTU
		Electrical conductivity	14-3000 µS/cm
		Suspended solids	190-537 mg/L
2.	Chemical Constituents	pH	7.3-8.1
		Alkalinity	-
		Nitrates	0.067 mg/L
		Phosphates	0.012 mg/L
		BOD	100-188 mg/L
		COD	250-375 mg/L
		Chlorides	53 mg/L
		Oil and grease	7 mg/L
		Magnesium	0.11 mg/L
		Calcium	32-50 mg/L
3.	Biological Constituents	Total coliforms	$1.2\times10^3 – 8.2 \times10^8$
		E.coli	6.5×10^6
		Fecal coliforms	1×10^6
		Pseudomonas aeruginosa	1.4×10^4

Source: (Awasthi et al., 2021)

2.1.4 Safety Regulations and Standards in Grey-Water Treatment

The World Health Organization (WHO) recommends limits on naturally occurring constituents that may have adverse health impacts. According to the National Environmental Standards and Regulations Enforcement Agency (NESREA) standard effluent quality metrics from treated grey water is presented in Table 2.2.

Table 2.2: Effluent limitation guidelines in Nigeria for all categories of industries units in milligram per liter (mg/L)

Parameters	Limit for discharge
Temperature	< 40°C
PH	6-9
BOD at 20°C	50
Total suspended solids (TSS)	30
Total dissolved solids (TDS)	2000
Chloride (Cl)	600
Sulphate ($S0_2$)	1000
Sulphide (S^{2-})	0.2
Cyanide (CN^-)	0.1
Oil and grease	20
Nitrate (as $N0^{3-}$)	10
Phosphate (as $P0_4^{3-}$)	10
Arsenic (As)	0.1
Barium (Ba)	5

Parameters	Limit for discharge
Tin (Sn)	10
Iron (Fe)	20
Manganese (Mn)	5
Phenolic compounds (phenol)	0.2
Chlorine (free)	1.0
Cadmium (Cd)	< 1
Chromium (trivalent and hexavalent)	< 1
Copper (Cu)	< 1
Lead	< 1
Mercury	0.05
Nickel	< 1
Selenium	< 1
Silver	0.1
Zinc	< 1
Total metals	3
Calcium (as Ca^{2+})	200
Magnesium (as Mg^{2+})	200
Boron (B)	5
Polychlorinated Biphenyl (PCBs)	0.003
Pesticides (Total)	< 0.01
Alpha emitters, µc/mL	10-7
Beta emitters, µc/mL	10-6

Parameters	Limit for discharge
Coliform (daily average)	500 MN/100mL

Source: (Iwuozor and Emuobosa, 2018)

2.2 Environmental and Health Impacts of Untreated Greywater

2.2.1 Pollution potential of untreated greywater

Greywater-wastewater from sinks, showers, laundry, and kitchens (excluding toilet waste) can have significant environmental impacts if left untreated. While generally less polluted than blackwater, untreated greywater contains contaminants such as:

a. Nutrient pollution

i. Phosphates from detergents and nitrates from organic matter can leach into groundwater or surface water, promoting algal blooms (Friedler et al., 2006).

ii. High BOD depletes oxygen in aquatic ecosystems, harming fish and other organisms (Eriksson et al., 2010).

b. Chemical contaminants

i. Sodium, boron and surfactants from soaps can accumulate in soil, reducing fertility and plant growth (Travis et al., 2010).

ii. Heavy metals (e.g. lead, zinc) from plumbing fixtures may be present in trace amounts (WHO, 2006).

c. Soil degradation

i. Long-term irrigation with untreated greywater can cause soil salinity and clogging due to suspended solids (Al-Hamaiedeh and Bino, 2010).

2.2.2 Public Health Risks of Untreated Greywater

a. Pathogenic Microorganisms

i. E coli, salmonella and Pseudomonas aeruginosa have been detected in greywater due to cross contamination (Ottoson and stenstrom, 2003).

ii. Skin contact or ingestion (e.g., by irrigation) can cause gastrointestinal, respiratory and skin infections. (WHO, 2018).

b. **Chemical Exposure**

i. Detergent residues may cause skin irritation.

ii. Heavy metals can accumulate in crops, entering the food chain (Travis et al., 2010).

b. Stored greywater attracts mosquitoes, increasing risks of dengue and malaria (EPA, 2022).

2.2.3 Need for Decentralized Treatment Systems

Centralized wastewater treatments are often impractical for greywater, necessitating small scale decentralized solutions:

a. Benefits of decentralized systems

i. Reduces strain on municipal sewage plants.

ii. Lowers energy use compared to large scale treatment (Jefferson et al., 2004).

iii. Enables local reuse (e.g., irrigation, toilet flushing).

b. Common treatment methods

i. Sand and bio-filters which remove suspended solids and organic matter.

ii. Constructed wetlands which are natural treatment using plants and microbes.

iii. Membrane filtration which is effective for pathogen removal.

c. Policy and implementation challenges

i. Lack of regulations in some regions (EPA., 2022).

ii. Public resistance due to perceived health risks (Friedler et al., 2006)

2.3 Challenges of grey water

Usage of greywater poses several challenges, including issues related to its storage, quality, and potential public health risks. These challenges are explored in detail in the following sub-sections.

2.3.1 Grey water storage challenges

Carden at al. (2007), are of the opinion that grey water storage is difficult and presents an opportunity for pathogen growth. Along with an increase in the number of pathogenic micro-organisms depletion of oxygen occurs which can result in a very bad odour. Many authors agree that it is better to avoid grey water storage, but disinfection of the grey water could offer a solution to the problem (Carden et al., 2007). Ngaga et al. (2012) were of the view that there are a number of problems related to the use of untreated grey water. They argue that the risk of spreading diseases due to the exposure to microorganisms in the grey water is a crucial point if grey water is to be re-used for toilet flushing or irrigation. Both inhaling (aerosols) and hand-to-mouth contact can be dangerous. The possible growth of micro-organisms and some chemicals within an untreated grey water system is another source of concern (Eriksson et al., 2010). Grey water intended for re-use must also be of satisfactory physical quality. Palmquist and Hanaeus (2010) are of the view that suspended solids in grey water can cause clogging of the distribution system. They also argue that there is always a risk of sulphide production, which is produced when oxygen is depleted and results in a bad odour. According to Misra and Patel (2009), tanks containing grey water provide an ideal breeding ground for pathogenic microorganisms and mosquitoes. This is a source of a pungent smell that poses a health hazard. They recommend that grey water tanks need to be vented and child-proof and should comply with local health by-laws. Such tanks should be accessible for cleaning. Grey water storage requires the addition of a disinfectant to avoid the biological degradation of fats, soaps and hairs as the characteristics of grey water depend on the products used in bathrooms, laundry and eventually the kitchen, there is no simple solution in selecting appropriate disinfectants. Therefore, storage of grey water presents several challenges. It has a pungent smell due to sulphide production, provides an ideal breeding ground for pathogenic microorganisms and mosquitoes and hand-to-mouth contact can be dangerous. It is essential to avoid storage of grey water if possible. However, grey water can be disinfected to reduce production of pathogens and odour. Grey water tanks need to be vented and cleaned regularly to maintain high hygiene standards (Yaka, 2018).

2.3.2 Grey water quality concerns

Qishlaqi et al. (2008) identify the variation in greywater quality as a key challenge in its use. They point out that greywater commonly contains elevated levels of salts, total suspended solids (TSS), biochemical oxygen demand (BOD), and nutrients such as nitrogen, ammonia, and phosphates, all of which can be detrimental to plant health.

When these constituents surpass acceptable limits, treatment is advised. However, Al-Hamaiedeh and Bino (2010) notes that treating greywater is inherently challenging and often involves significant costs. Furthermore, the use of untreated greywater can lead to various environmental issues, including increased soil salinity, reduced water infiltration rates, specific ion toxicity (from elements like sodium, chloride, and boron), altered soil characteristics, elevated pH levels, and the build-up of heavy metals (Qishlaqi et al., 2008), all of which can adversely impact plant growth (Gross et al., 2005; Carden et al., 2007).

In conclusion, the quality of greywater raises considerable concerns due to its high concentrations of salts, TSS, BOD, and nutrients that are harmful to vegetation. If not treated beforehand, greywater can result in soil degradation, toxic ion accumulation, and other negative effects on soil and plant health.

2.3.3 Public health concerns of grey water use

Grey water may contain sewage contaminants albeit in lower concentrations compared to black water, the sewage concentration levels in grey water may be well above international drinking, bathing, and irrigation water standards. Maimon et al. (2010) emphasize that grey water can contain pathogens not only derived from faecal contamination and food handling, but also opportunistic pathogens such as those found on the skin, which can pose a public health hazard. It has also been established that grey water contains substantial amounts of cadmium. According to Thomas et al. (2008), human exposure to even low levels of between 2 to 3 µg of cadmium per g may result in kidney damage and affect bones that may lead to fractures. Grey water is contaminated underground with nitrogen, phosphate and heavy metals which poses a hazard to humans, plant and sea life Al-Zu'bi and Al-Mohamadi (2008). It can be summarized that grey water may contain pathogens that can pose a public health hazard. Low levels of cadmium found in grey water can also cause kidney damage and affect bones that may lead to fractures. Furthermore, pose nitrogen, phosphate and heavy metals in grey water hazards to both human and plant life.

2.3.4 Effect of grey water on plant growth and production

Grey water may contain toxic substances such as chlorides, boron and cadmium in excessive amounts which negatively affects plant growth. Although these plant nutrients are essential for plant growth, they are only required in relatively small concentrations. Furthermore, Omami (2011) established that salinity affects plant growth in a variety of ways which include reduced infiltration, a deterioration of the physical structure of the soil, which diminishes free state permeability and soil aeration. Salinity also causes an increase in the concentration of certain ions which have an inhibitory effect on plant metabolism. The general response of plants to soil salinity is a reduction in plant growth which includes germination (Agarwal and Pandey, 2011). (Bauder et al., 2011) suggests that soils with a high concentration of salts often suffer from severe leaf damage and general crop failure. Research on the external quality of crops being irrigated with grey water is limited. However, Zavadil (2009) discovered that grey water does not improve the crop quality of sugar beet (sugar content) and the starch percentage of early potatoes. In summary, high levels of toxic substances in grey water such as chlorides, boron and cadmium negatively affect plant growth and it has once more been established that soil salinity inhibits plant growth and germination.

2.4 Overview of Greywater Treatment Technologies

Various technologies, differing in both complexity and effectiveness, are used globally for greywater treatment. Treatment methods range from simple, low-cost options such as manually collecting greywater from bathroom outlets using buckets to more advanced systems. Greywater treatment systems are classified into three types: physical, chemical, and biological and followed by a disinfection process and pretreatments to prevent clogging for microbiological disinfection. Advanced mathematical modeling tools, such as simulink, are used by researchers to better understand the interactions between various routes in the greywater treatment units (Kuriqi et al., 2019). Since the 1970s, various investigations on greywater treatment and recycling have been conducted. The former technologies investigated were primary treatment like solid removal or membranes, which were frequently combined with disinfection. Biological-based technologies such as Moving biological systems, aerated bio filters, and sequencing bioreactors were invented between 1980 and 1990s. Simultaneously, simple physical separators with disinfection methods were designed and implemented in single residences. Reports on the use of complex technology like sophisticated membrane bioreactors (MBRs) and simple technologies such as reed beds and ponds emerged late in the 1990s. Interestingly, only three chemical treatments have been documented in literature: electrocoagulation, photo catalysis, and conventional coagulation. Nevertheless, some sophisticated systems received interest as well. (Awasthi et al., 2021).

2.4.1 Physical Treatment

Physical technologies achieve substantial water clarity by eliminating organic pollutants from greywater (Shaikh and Ahammed, 2021). Standard physical treatments include coarse sand, dust, and membrane separation. A standard physical process cleans water in three ways: Physical particle screening, chemical sorption of contaminants to the soil surface, and absorption, which occurs when aerobic microorganisms consume nutrients from wastewater. Oron et al. (2014) conducted research on the personal lawns of Israeli homeowners using a decentralized greywater treatment unit comprised of sand filtration and electrolysis, which resulted in higher organic content after the treatment. Al-Mughalles et al. (2012) used a granular activated carbon (GAC) reactor in conjunction with a sand filter to handle greywater reuse in a mosque Sanaa. According to the findings, the chemical oxygen demand (COD) was reduced with a treatment effectiveness of 65%; nevertheless, eliminating nitrate proved difficult for the system. Another research, established on a novel decentralized greywater treatment unit, successfully removed all organic pollutants nitrogen and phosphorus content from greywater (Ahmadi and Ghanbari, 2016). This technology was improved by stacking multiple layers of polyurethane foam trays and using a clogging-resistant soil known as ‘Kanuma soil.’

2.4.2 Chemical Treatment

This section of the study highlights the literature on primary to advanced chemical techniques for GW treatment and recycling. Precipitation, electromagnetic resin ionization, catalytic degradation, granulated carbon activation, electrode enhanced UV, and electrolysis are the reported chemical treatment methods. (Awasthi et al., 2021). The research findings of selected studies are discussed below to understand the difference between past to present and new technologies. The efficacy of precipitation, electromagnetic resin ionization methods based on a GW collected from the student residence at Cranfield University in UK was used to study various greywater sources. 1 litre of greywater was quickly poured into the container before adding the coagulant for coagulation test. Sample was then emulsified and allowed to settle. After estimating the appropriate dosage and settling for an hour, the electromagnetic resin was made. The resin and GW were mixed, and the residue was poured into de ionized water. Even if these procedures achieved enough levels of organic removal, certain nation's greywater reuse regulation would not be reached (Pidou et al., 2008). Sanchez et al. (2010) performed another study on hotel greywater. A 1 litre cylindrical glass photoreactor with a low-pressure mercury lamp immersed in a quartz sleeve surrounded by a water jacket was employed. Due to low dissolved organic carbon (DOC), titanium dioxide (TiO2) photocatalyst treatment was found appropriate for greywater treatment. Utilization of diverse metal electrode systems for potential electrodes was investigated to enhance the current system and better understand the electrolysis process. Vuppaladadiyam et al. (2019) conducted a study to evaluate the efficiency of different electrode combinations for the removal of turbidity (TD), chemical oxygen demand (COD), and biological oxygen demand (BOD) from water. The Al–Fe electrode combination removed 95% of TD, 85% of COD, and 90% of BOD efficiently. They concluded that inter-electrode distance, electrode areas, and electrode couplings (Al–Fe and Fe–Al) are essential parameters for electrode performance. Chopra and Sharma (2013) experimented using a 5L reactor. They found that increasing the electrode's outer space and decreasing the area within the electrodes improved pollutant removal. According to the study, a 160 cm^2 electrode area and an electrode spacing of 2.5 cm resulted in the ideal electrodes conditions. The reported cost of the system was 0.25 (US\$/m^3). Vakil et al. (2014) examined an electrochemical reac tor using aluminum electrodes in the same way. They achieved the removal of 70% of COD and 99.9% of microorganisms with a power consumption of 0.3 kW h/ m^3 of greywater when used with a total potential variation of 12 V. The aluminum electrodes of the electrochemical reactor showed potential for scaling up to the real world to household level to eradicate pathogens, turbidity, and COD from greywater. In line with this, Ozay et al. (2018) carried out comprehensive research with various electrode combinations, such as aluminum and iron electrode (Al–Fe Al–Fe) and aluminum and aluminum electrode (Al–Al Al–Al) iron and iron electrode (Fe–Fe Fe–Fe) and iron aluminum electrode (Fe–Al Fe–Al). The hybrid aluminum and iron electrode combination was the most effective for COD elimination. Several operational parameters, including current density, pH, and support ing electrolyte content, were examined to identify ideal conditions. COD was reduced from 87.9 to 29.4 mg/L at pH 7 by employing a current of 1 mA/cm^2. Under optimum conditions, the Al–Fe–Fe–Al electrode combination consumed 9.46 kWh/m3 energy. Similarly, Barzegar et al. (2019) demonstrated TOC and COD reduction from greywater through electrocoagulation process with the combination of electrocoagulation with ozone (EC + O3) and electrocoagulation with ozone and ultraviolet light (EC + O3 + UV) electrodes. Results indicated the removal of COD and TOC approximately 70–85% in 60 minutes at pH 7.0 with a current supply of 15 mA/cm^2. When combined with an electrochemical technique for greywater treatment, ozone proved excellent compared with reported chemical oxidants (24eroxydisulfate ($Na_2S_2O_8$) and hydrogen peroxide (H_2O_2). According to the observations, UV irradiation considerably improved EC/ozone performance, but ultraviolet light had minimal influence on the EC/ ozone process. TOC and COD were removed 87-95 % by UV treatment. Besides, the electrocoagulation with ozone and ultraviolet light technique eliminates 4 logs of TC and 96% of E. coli. Calculated costs for electrocoagulation with ozone and electrocoagulation with ozone and ultraviolet light were 1.9 and 4.03 $\$/m^3$. In recent years, significant improvements have been made in the chemical treatment procedure. Calskan et al. (2021) studied an Ultraviolet A (UV-A) enhanced electrocoagulation method using aluminum and iron electrodes in a hybrid reactor. They reported the 88–97% elimination of COD and turbidity using Al electrodes at pH 7.4 and 3 mA/cm^2 with 1 g Na2SO4/L electrolyte with 40 min reaction time. Simultaneously, Fe electrodes removed 79% COD and 99% turbidity under ideal conditions. The presence of total nitrogen, phosphate, suspended solids and BOD_5 were also examined. The removal efficiencies with Al electrodes were 62- 88% and 78–98% with Fe electrodes, respectively. UV-A irradiation, on the other hand, had a negligible contribution. COD and turbidity were efficiently removed, whereas BOD_5 was rapidly reduced to regulated standards for reclaimed water set by United States Environmental Protection Agency (USEPA). The study findings may benefit and assist in developing simple, mobile, and low-cost treatment systems for reusing greywater, particularly in onsite, small dwelling areas, and rural or military settlements. Modifications in current chemical treatment procedures that incorporate new concepts, such as alternative electrode combinations or different nanomaterials, may be beneficial in greywater reclamation. Separate collection and treatment of greywater can be a feasible long-term alternative to prevent contamination of potable water resources, especially in remote areas, commercial and residential establishments, and emergencies (Awasthi, 2021).

2.4.3 Biological Treatment

Biological treatment systems have been used directly or in combination with various physical treatment techniques for GW treatment since the late twentieth century. membrane-based filtration proved effective for greywater treatment and showed promising technology for eliminating a wide range of contaminants. Several experimental research on membrane-based systems has been conducted. However, in this section, the data is compiled to understand the efficacy of the membrane-based system. Rotating biological contactors (RBCs), sequencing batch reactors (SBR) and anaerobic sludge blankets (UASB) have all been tested by various researchers (Eriksson et al., 2010; Hernandez et al., 2010). Prior to biological treatments, pretreatment methods including sedimentation, septic tank, and screening were used (Friedler et al., 2006). Apart from membrane biological reactors, several biological procedures involve sand filtration and disinfection to fulfill non-potable reuse standards. In RBCs, a disk is continually moving and partially immersed in water and opens into the air, producing microbe growth with biofilm formation on the moving disks. When disks were immersed, organic material was removed. According to the RBCs for greywater reclamation findings, when pretreated with sand filtration, RBCs can effectively treat greywater (Abedin and Rakib, 2013). Another one is the sequence batch reactor (SBR). It has five operational phases: filling, reacting, settling, drawer decanting, and idle. SBR was used to treat GW from the bathrooms of Tunis's El Manzeh student residence (Lamine et al., 2012). According to the findings, SBR could efficiently remove nutrients and reduce COD to 90%. Process also assures the biodegradation of organic matter from greywater with solid sludge settling qualities. On the other side, Hermawan et al. (2019) concluded that SBR may reduce BOD to less than 5 mg/L and effective for removing five organic compounds paraben biocides (methyl-, ethyl-, pro pyl, butyl-, and iso-butyl-esters of para hydroxybenzoic acid). According to their findings, the removal effectiveness of the selected biocides varied from 87 to 99% as the bacterial community were using paraben as a source of carbon for reproduction. Similarly, high-strength greywater was treated in an SBR, retention period was set 11.7 h, and duration of sludge retention was kept to 15 days. Results indicate that concentration of COD (830 mg/L), TP (7.7 mg/L), TN (53.6 mg/L) and ammonia (1.2 mg/L) in the influent was reduced significantly in the treated effluent with concentration of COD (130 mg/L), TP (6.5 mg/L), and TN (34.4 mg/L) and ammonia (0.41 mg/L), respectively. To treat high-strength greywater, another sequencing batch reactor (SBR) was used (Hernandez et al., 2010). Throughout the study, the sludge retention period was increased to 378 days through out the experiment, although the hydraulic retention time was reduced to 5.9 h. COD, TP, TN, and ammonia levels in effluent were decreased from influent values of 827 mg/L, 8.5 mg/L, 29.9 mg/L, and 0.8 mg/L, respectively, to effluent levels of 100 mg/L, 5.8 mg/L, 26.5 mg/L, and 0.44 mg/L. Organic nitrogen presents 90% in effluents, whereas total nitrogen presents 74%, indicating a minimal transformation of particulate organic nitrogen to ammonia during oxidation process. According to the study, aerobic degradation removed 80% of anionic surfactants from GW. Hernandez et al. (2011) developed a UASB GW treatment device at a production plant, determining that the UASB system could remove about 50% of chemical oxygen demand with 24% of anionic surfactants removal at HRTs of 7.0 at 12.5 h. A cylindrical or rectangular column and a gas–liquid–solid separator constituting of a UASB reactor were used for the experiment. Sludge is injected from the reactor's bottom; after a certain period of time, a thick sludge bed appears and organically combines with the sludge blanket. The extraction of biogas and wastewater occurs at the top of the sludge bed (Laaffat et al., 2019). According to a study on UASB reactors for GW treatment conducted by the Hamburg University of Technology in Germany, the anaerobic degradability of a single-stage UASB reactor was greater than that of a traditional septic tank, even at minimum temperatures. Furthermore, a two-stage UASB reactor may minimize its hydraulic retention significantly (Oteng et al., 2018). Later researchers centered on a hybrid membrane-based reactor. MBR is divided into two types: side-streaming and submerged. Submerged MBRs employ submerged membranes to particulate from fluids in sedimentation tanks. Side-stream MBR membranes are positioned outside of the bioreactor, and sludge is injected directly into the mem brane; submerged MBRs were favored due to lower operational budget (https:// www. thembrsite.com/ membrane- bior actor-basics/what-are-mbrs/). The airlift external circulation MBR is a side-stream MBR that has been advanced one. It combines the benefits of both submerged and side-stream MBRs. Decentralized GW remediation in residence of Crete, Greece, employing a submerged bio-membrane reactor, dis covered that systems were easily operative, with an 80% mean decline in COD and anionic surfactants. Treated greywater proved safe and appropriate for lavatory flushing (Fountoulakis et al., 2016). Despite significant scientific advances and applied uses of MBRs, a main worry is mem brane fouling that happens unavoidably throughout mem brane filtering resulting in increased consumption of energy and maintenance charges (Akhondi et al., 2014). It is concluded from the above findings that membrane-based systems showed high efficiency for greywater reclamation. Advancement in membrane-based systems enhanced the sustainability of membrane technology. However, the major issue with the membrane-based system is its cost and maintenance. A combination of less sophisticated technologies or nature-based techniques in membrane systems will be the new area for future research work. That could make this established technology more robust to overcome the issues of greywater reclamation.

2.5 Principle of Coagulation-Flocculation Process

Coagulation is defined as a physical-chemical process that adds coagulants to water to assist in the agglomeration of suspended particles, it is one of the first steps in most conventional water purification processes. Common coagulants like Aluminum Sulfate or Ferric Chloride work by neutralizing the electric charges on particles, leading to their aggregation and subsequent removal during sedimentation or filtration (Lata, 2025). The coagulation-flocculation process is a critical step in greywater and wastewater treatment, where colloidal particles and dissolved contaminants are aggregated into larger flocs for easier removal. Particles can be inorganic such as clay and silt or organic such as algae, bacteria, viruses, protozoa and natural organic matter. Inorganic and organic particles contribute to the turbidity and color of water. The coagulation flocculation process which is a focus of the present study is shown in the process flow diagram in Figure 2.1. This section explains the mechanisms and key factors influencing efficiency, supported by recent peer-reviewed references.

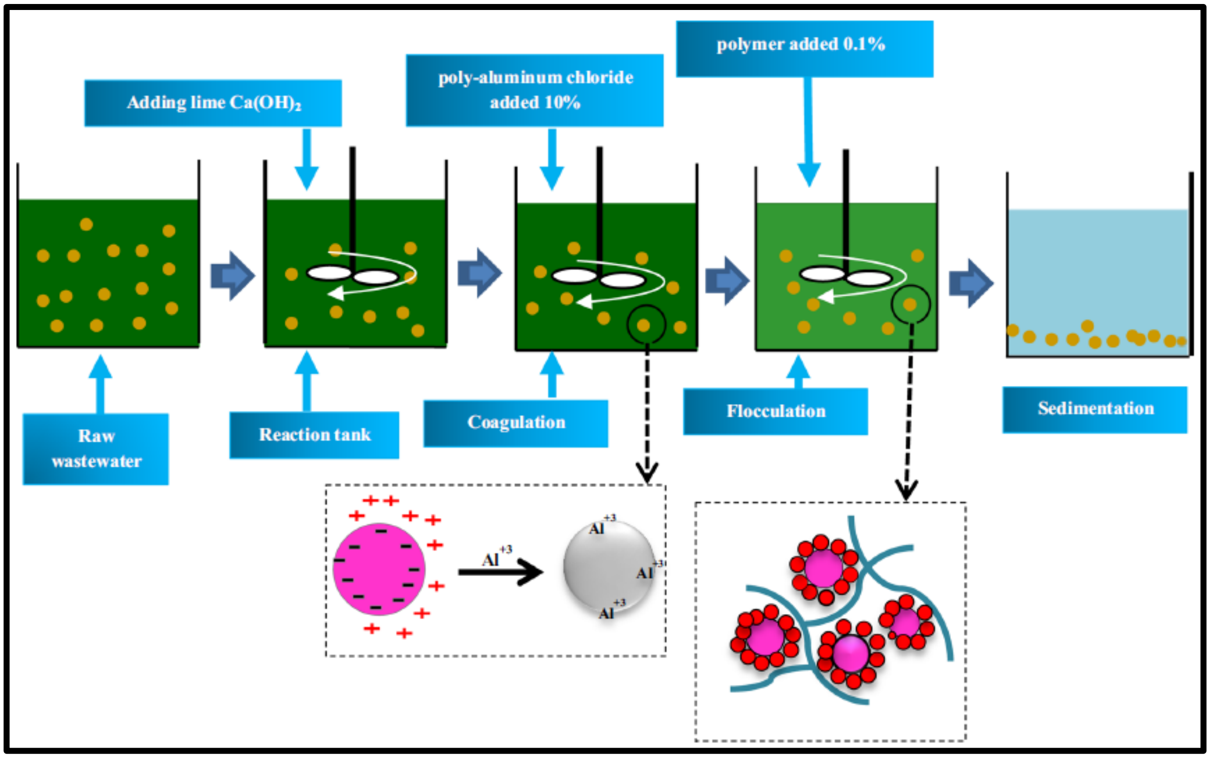

Figure 2.1: Coagulation and Flocculation process

2.5.1 Mechanisms of Coagulation-Flocculation

a. Charge Neutralization

i. Colloidal particles in water typically carry a negative surface charge, causing repulsion.

ii. Coagulants (e.g., Al^{3+}, Fe^{3+} salts) neutralize these charges, reducing electrostatic repulsion and allowing particles to collide and stick together (Bratby., 2016).

b. Bridging (Polymer flocculation)

i. Polymeric coagulants (e.g, polyaluminium chloride, polyacrylamide) form long chains that bridge between particles, creating larger flocs (Bolto and Gregory, 2007).

ii. More effective for low-turbidity water where charge neutralization alone is insufficient.

c. Sweep Flocculation (Enmeshment in Precipitates)

i. At high coagulant doses, metal hydroxides (e.g., $Al(OH)_3$, $Fe(OH)_3$) form a gel-like precipitate that traps particles as it settles (Duan and Gregory, 2003).

ii. Dominant mechanism in high-pH conditions.

2.5.2 Factors Affecting Coagulation-Flocculation Efficiency

a. pH

i. Optimal pH range for alum: 5.5–7.5 (Bratby., 2016).

ii. Iron salts ($FeCl_3$): Effective at pH 4–9 (Zhou et al., 2020).

iii. Outside optimal pH: Hydroxide precipitates may not form properly, reducing efficiency.

b. Coagulant dose

i. Underdosing: Incomplete charge neutralization leads to poor floc formation.

ii. Excess coagulant restabilizes particles via charge reversal (Jiang, 2015).

c. Mixing conditions

i. Rapid Mixing (Coagulation Step): High shear (G-value:300–1000 s^{-1}) ensures uniform coagulant dispersion (Edzwald., 2010).

ii. Slow Mixing (Flocculation Step): Gentle agitation (G-value: 20–80 s^{-1}) promotes floc growth without breaking aggregates.

d. Temperature and Water Composition

Cold water: Slows reaction kinetics, requiring higher coagulant doses.

2.5.3 Applications in Greywater Treatment

a. Household systems: Small-scale jar tests optimize coagulant doses (WHO, 2018).

b. Decentralized plants: Polyaluminum chloride (PACl) preferred for wider pH tolerance (Li et al., 2022).

2.6 Types Of Coagulants Used in Wastewater Treatment

Coagulants play a vital role in water and wastewater treatment by destabilizing colloidal particles and facilitating their removal. They can be broadly classified into inorganic, organic/polymer-based, and natural coagulants, each with distinct mechanisms and applications.

2.6.1 Inorganic Coagulants

These include aluminum sulfate and ferric chloride. They work primarily through charge neutralization. When added to water, these coagulants dissociate into positive ions, which attract negatively charged colloidal particles. This attraction reduces the electrostatic repulsion among particles, leading to their aggregation (Lata, 2025). They are metal salts that neutralize the negative charges on suspended particles, forming insoluble precipitates that aid in particle removal. The most commonly used inorganic coagulants include:

a. Alum (Aluminum Sulfate, $Al_2(SO_4)_3$)

Alum is one of the oldest and most widely used coagulants in water and wastewater treatment. It hydrolyzes in water to form aluminum hydroxide ($Al(OH)_3$) flocs, which adsorb and entrap suspended particles (Jiang, 2015). It is a common inorganic coagulant known for its high efficiency in removing turbidity. It has a key characteristic of rapidly forming coagulant flocs when dissolved in water. This makes it a beneficial choice in both municipal and industrial water treatment settings. The unique feature of aluminum sulfate is its capability to work effectively across a wide range of pH levels, making it versatile for different water qualities.

One of the advantages of aluminum sulfate is its ease of use and availability. However, it can produce aluminum residuals that may pose health concerns if not properly managed. Thus, proper dosing and monitoring are necessary to mitigate any potential risks (Lata, 2025).

Figure 2.2: Powdered Alum (Raju et al., 2018)

b. Ferric Chloride ($FeCl_3$) and Ferric Sulfate ($Fe_2(SO_4)_3$

Ferric salts are alternatives to alum, particularly effective in phosphate removal and color reduction in industrial wastewater (Tchobanoglous et al., 2020). Its key characteristic is its ability to perform well in higher turbidity levels compared to aluminum sulfate. Ferric chloride is a beneficial choice particularly in industrial applications where high removal efficiency is required (Lata, 2025). It works effectively in cold water (unlike alum, which performs poorly at low temperatures) (Bratby, 2016). It also offers better organic contaminants (Jiang, 2015).

2.6.2 Organic and polymer-based coagulants

Organic coagulants, including synthetic polymers (polyacrylamides) and natural polymers (chitosan, starch derivatives), function through charge neutralization and bridging mechanisms (Bolto and Gregory, 2007).

a. Synthetic polymers(polyacrylamides)

Polyacrylamides are a type of organic coagulant characterized by their ability to adsorb particle surfaces, enhancing floc formation. Their beneficial aspect lies in the ability to tailor them for specific water treatment processes, enhancing their application flexibility. Polyacrylamides can reduce sludge production, which is a significant advantage in terms of environmental sustainability.

However, the potential for toxicity if improperly dosed poses a challenge. Therefore, strict application protocols must be followed to mitigate any risks associated with their use (Lata, 2025).

b. Natural polymers

Natural polymers, derived from plant and animal sources, provide an eco-friendly option for coagulation. Their key characteristic is their natural origin, which typically results in fewer chemical by-products when used. Natural polymers are becoming a popular choice among facilities looking to move towards sustainable practices in water treatment.

One advantage is their biodegradable nature, which reduces long-term environmental impact. Nonetheless, their effectiveness can be inconsistent based on the water quality, which may limit their application under certain conditions.

The choice between organic and inorganic coagulants depends on specific treatment goals, available technology, and regulatory standards that govern water quality (Lata, 2025).

2.6.3 Drawbacks of Conventional Coagulants

Despite their widespread use, conventional coagulants have several limitations:

a. Sludge production

Inorganic coagulants generate significant sludge volumes, increasing disposal costs (Yang et al., 2020). Sludge containing aluminum or iron may require additional treatment before landfill disposal (Tchobanoglous et al., 2020).

b. Residual metal content

Alum and ferric salts can leave trace metals in treated water, raising health concerns (WHO 2021). Aluminum exposure has been linked to neurodegenerative disorders (Jiang, 2015).

c. pH sensitivity

Inorganic coagulants often require pH adjustment for optimal performance, increasing operational complexity (Bratby, 2016).

d. Environmental concerns

2.7 Local and natural coagulants: sources and efficiency

An alternative greener and sustainable approach is the use of natural coagulants for turbidity removal. Natural coagulants from plant-based materials or renewable sources are attracting a lot of attention due to their various advantages over chemical counterparts. They are biodegradable (Asrafuzzaman et al., 2011) non-toxic, non-corrosive and cheaper than chemical coagulants. Since they produce lesser sludge with high nutritional value (Choy et al., 2014), the sludge handling and treatment cost is minimal. Despite these advantages, natural coagulants are not commercialized so far (except few such as *Moringa oleifera* seeds) (Choy et al., 2014). Challenges in harvesting and processing of natural coagulants from plants might be the major factors limiting their commercialization.

Waste or non-useful materials such as orange peel, banana pith and neem leaf powder have also been utilized as natural coagulants (Anju and Mophin-Kani, 2016; Kakoi et al., 2016).

2.7.1 Plant Based Coagulants

a. *Moringa oleifera* (Drumstick Tree)

Moringa oleifera seeds contain proteins that act as natural coagulants, effectively removing turbidity and bacteria (Ndabigengesere, 2019). Its mechanism of action involves the active protein (MO2.1) destabilizing colloidal particles through charge neutralization and adsorption (Ghebremichael et al., 2021). It also exhibits antimicrobial properties, reducing E. coli and other pathogens (Pritchard et al., 2020). It is biodegradable, producing less sludge than alum (Okuda et al., 2021) and locally available in tropical and subtropical regions (Kansal and Kumari, 2020) some of its only limitations are that higher turbidity requires more seeds (Ndabigengesere et al., 2019) and it may significantly increase biochemical oxygen demand (BOD) in treated water (Pritchard et al., 2020). A 2021 study found Moringa reduced turbidity by 85-95%, comparable to alum but with 50% less sludge (Okuda et al., 2021). Another study highlighted its potential for emergency water treatment in disaster-hit areas (Ghebremichael et al., 2021).

Figure 2.3: ***Moringa oleifera*** **seed and powder (Raju et al., 2018)**

b. Tamarindus indica (Tamarind Seed)

Tamarind seed kernel powder, discarded as agricultural waste, is an effective agent to make turbid municipal and industrial wastewater clear. The present practice is to use aluminium salt to treat such water. It has been found that alum increases toxic metals and ions in treated water and could cause diseases like Alzheimer's. Kernel powder, compared to alum, is not toxic and biodegradable (Raju et al., 2018). Tamarind seed extract contains polysaccharides that act as natural flocculants (Choy et al., 2014). It works by forming a gel-like substance that entraps suspended particles. It is suitable for drinking water treatment (Choy et al., 2014) and effective in heavy metal removal (e.g., lead, cadmium).

Figure 2.4: Tamarindus Indica seed and powder (Raju et al., 2018)

2.7.2 Mineral and Clay based Coagulants

a. Bentonite Clay

Bentonite, a naturally occurring clay, has gained significant attention in wastewater treatment due to its unique properties and efficiency, Bentonite's structure allows it to absorb large quantities of water, increasing its volume significantly. This property is crucial for removing contaminants from wastewater. Its high surface area and absorption capacity help in reducing organic pollutants, including oils and greases. As a natural flocculating agent, bentonite aids in aggregating fine particles, making them easier to remove. Its limitations include high dosage requirements for effective treatment (Kansal and Kumari, 2020) and Sludge volume can be substantial (Tareq et al., 2021).

b. Kaolin and Other Local Clays

Kaolin is a clay mainly composed of kaolinite ($Al_2Si_2O_5(OH)_4$), which has been widely applied in numerous technological applications. Due to the low-cost and large abundance, the use of clays like kaolin converts the adsorption process into an attractive and promising technique. Kaolin is used in colloidal particle removal, particularly in rural areas (Onyango et al., 2023) also it is non-toxic, making it safe for potable water treatment (Zhou et al., 2020). One of its limitations is that it is less effective for organic pollutants compared to activated carbon (Tareq et al., 2021).

Figure 2.5: Kaolin Powder (Raju et al., 2018)

Table 2.3: Performance Comparison with Synthetic Coagulants

Parameter	**Natural Coagulants**	**Synthetic Coagulants**
Sludge Production	Lower	Higher
Cost	Cheaper	More expensive
Toxicity	Non-toxic	Residual metals/monomers
Efficiency	Moderate to high (dependent on water quality)	Consistently high

Parameter	Natural Coagulants	Synthetic Coagulants
Environmental Impact	Biodegradable	Pollution risks

Source: (Bratby, 2016; Jiang, 2015; Okuda et al., 2021; Renault et al., 2009; Tchobanoglous et al., 2020; WHO, 2021; Yang et al., 2020)

2.8 Resources Available in Greywater

Subjected to the sources of the grey water, it contains various resources. Barker-Reid et al. (2010) observed that grey water contains sodium, chlorides, and other nutrients such as nitrogen (N), ammonia (NH_3) and phosphates. In addition, Travis et al. (2010), observed that the large quantities of sodium (Na) and phosphates (PO_4) that are found in grey water emanate from washing machine powders. They noted that washing detergents are the primary source of phosphates in the grey water of countries that have not yet banned phosphorus-containing detergents. A similar study to Barker-Reid et al. (2010) by- Carden, Armitage, Sichone and Winter (2007) established that grey water contains chlorides, ammonia, phosphates and sodium in considerable amounts. Carden et al. (2007) furthermore observed that grey water also contains significant amounts of boron and cadmium. Correspondingly, Bolivian researchers (Al-Zu'bi and Al-Mohamadi, 2008) discovered heavy presence of high levels concentrations such as cadmium and nickel in grey water. However, the grey water being used in the investigation of Al-Zu'bi and Al-Mohamadi (2008) was not solely sourced from households, also but included industrial wastewater. The investigation of Palmquist and Hanaeus (2010) into the availability of resources in grey water from ordinary Swedish households, confirmed the presence of mainly calcium, iron, potassium, sodium, magnesium, cadmium, cobalt, copper, lead, tin and zinc. Although Eriksson et al. (2012) argue that metals in grey water have not been studied in great detail, they admit that their investigation into concentrations in the influent and effluent greywaters of Denmark correlate with the results obtained by (Palmquist and Hanaeus, 2010) in Sweden. The only difference being that Eriksson et al. (2010) also found high levels of cadmium (9.0μg/L) in grey water. Eriksson et al. (2010) further observed that contingent upon the sources of the grey water, non-metal resources such as ammonium, nitrogen, nitrogen, phosphorus, nitrates and nitrites are also found in grey water. It can be summarised that subject to the source of the grey water, it contains on the one hand various resources such as chlorides, ammonia, phosphates and sodium in considerable amounts and on the other hand baron, cadmium and heavy metals. The large quantities of sodium and phosphates in grey water emanate from washing powders.

2.9 Techno-Economic Assessment in Water Treatment Studies

Techno-Economic Analysis (TEA), in simple terms, is a set of methods that helps in evaluating the economic performance of a technology. It allows analysts to evaluate benefits over costs objectively, thus assessing the overall value of the technology. Accordingly, a techno-economic assessment of coagulation-flocculation for greywater treatment involves evaluating the feasibility and economic viability of using coagulants for treating wastewater. Coagulants offer a sustainable and cost-effective solution for wastewater treatment by utilizing nutrients and contaminants from wastewater for their growth while producing oxygen and biomass (Piyush, 2024). The key components which typically are involved in conducting a TEA for greywater treatment can be outlined as follows:

2.9.1 Capital Expenditure (CAPEX)

Capex involves the initial investments made to acquire or upgrade assets. These are typically large, one-time expenses, including:

a. Initial investment in infrastructure (e.g., membranes, reactors, filtration systems).

b. Land acquisition, construction, and installation costs.

c. Costs of permits and regulatory compliance.

When planning Capex, consider the flow rate of water to be treated, quality of incoming water, contaminants to be extracted, standards to be met, technologies chosen, automation, legislative constraints, redundancy requirements, instrumentation, material selection, and wastewater management.

2.9.2 Operating Expenditure (OPEX)

Opex refers to the ongoing costs necessary for daily operations and maintenance of treatment facilities, including:

a. Energy Consumption: Energy-intensive processes, especially in reverse osmosis and MBR systems.

b. Chemical Usage: Chemicals for disinfection, coagulation, and pH adjustment.

c. Labor and Maintaenance: Skilled personnel for operation and maintenance.

d. Monitoring and Compliance: Continuous monitoring of water quality and regulatory compliance.

Opex factors include energy costs, consumables (media, membrane, filter), spare parts, wastewater discharge fees, labor costs, equipment calibration, and maintenance contracts. Specific needs such as health and safety requirements, training costs, and system performance issues should also be considered.

2.9.3 Cost per Liter Treated

A critical metric for comparing different technologies. It is calculated as

$$\text{Cost per litre} = \frac{\text{Total CAPEX+OPEX (over project lifetime)}}{\text{Total Volume Of Water Treated}} \qquad (2.1)$$

2.9.4 Return On Investment (ROI) and Payback Period

Return on Investment (ROI) is a financial metric used to gauge the profitability of an investment. Expressed as a percentage, it is calculated by dividing the net gain from the investment by the initial cost and multiplying the result by 100. The formula for ROI is:

$$\text{ROI} = \frac{\text{Net Profit}}{\text{Total Investment}} \times 100\% \qquad (2.2)$$

Payback period is the total time taken to recover initial investment.

2.10 Previous Related Studies

Numerous studies have been conducted to explore the technical viability and economic feasibility of greywater treatment systems, particularly those leveraging the coagulation-flocculation process. These works provide a strong foundation for the current study, which aims to bridge laboratory research and practical community-scale application using locally sourced coagulants.

(Ghaitidak and Yadav, 2013) provided a comprehensive review on the composition and treatment of greywater, underscoring its potential for reuse and the environmental risks it poses if left untreated. They highlighted that greywater constitutes the majority of household wastewater up to 75% yet remains underutilized due to inadequate treatment strategies. Their findings justify the need for decentralized, low-cost systems, especially in water-stressed and low-income regions.

In terms of treatment methods, (Okuda et al., 2021) performed a study between alum and *Moringa oleifera* seed extract in greywater treatment. Their research demonstrated that Moringa achieved comparable turbidity removal to alum while significantly reducing sludge production by nearly 50%. This finding supports the growing view that natural coagulants can offer environmentally friendly and cost-effective alternatives to conventional chemicals.

Ghebremichael et al. (2021) further supported the potential of *Moringa oleifera*, noting its dual role as a coagulant and an antimicrobial agent. Their study emphasized Moringa's ability to reduce not only turbidity but also bacterial contamination, including E. coli, making it especially suitable for decentralized treatment applications where disinfection capacity may be limited.

(Palmquist and Hanaeus, 2010) also played a critical role by characterizing the heavy metal content in greywater from domestic sources, including cadmium, zinc, and copper. Their work highlighted the need for treatment approaches that not only remove organic matter and turbidity but also address trace metal contaminants one of the performance indicators for coagulants in this study.

The environmental and health implications of untreated greywater have been further outlined by (Carden et al., 2007), who emphasized its contribution to soil salinization, groundwater contamination, and pathogen transmission. Their findings advocate for decentralized greywater treatment systems that can be safely operated at the household or community level without extensive technical expertise.

The World Health Organization also supports decentralized water treatment strategies, particularly in regions where centralized infrastructure is lacking (WHO, 2021). WHO emphasizes the importance of residual safety, sludge minimization, and ease of use—criteria that are addressed by natural coagulants like Moringa and tamarind.

Lastly, the broader context of techno-economic assessment is discussed by (Piyush, 2024), who outlined the necessity of evaluating both the technical and financial dimensions of water treatment technologies. He stressed that successful implementation depends not only on pollutant removal but also on metrics such as capital cost, operational cost, cost per liter treated, and return on investment all of which are integrated into the current study's dual-scale assessment framework.

Collectively, these studies provide critical benchmarks and validation for the experimental design and assessment framework of this research. However, a persistent gap remains in the scaling of natural coagulant-based systems from lab conditions to realistic community-scale deployment, a gap this study seeks to fill by combining treatment efficiency tests with cost modeling, scale-up equations, and sensitivity analyses under real-world constraints.

CHAPTER THREE

METHODOLOGY

3.1 Coagulant Identification and Preparation

A locally available natural coagulant, *Moringa oleifera* seeds was selected based on availability, previous literature, and traditional usage in water clarification.

a. Collection: Mature seeds of *Moringa oleifera* were sourced from local markets.

b. Preparation:

i. The seeds were cleaned and sun-dried.
ii. Kernels were ground into fine powder using a locally available grinder.
iii. The powder was sieved to achieve uniform particle size.

c. **Storage:** Coagulant powders were stored in airtight containers and labeled accordingly for use during tests.

3.2 Design and Fabrication of a Coagulation-Flocculation Water Treatment Facility

A small-scale batch treatment prototyp**e** was fabricated using locally sourced materials to simulate the coagulation-flocculation process.

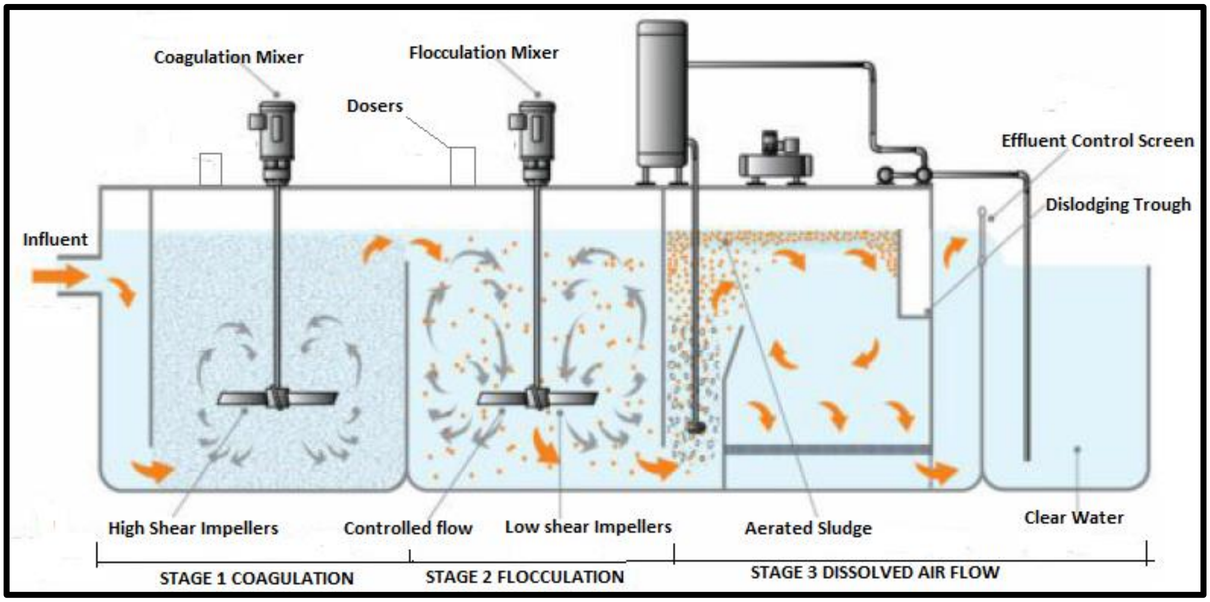

Figure 3.1: Grey water coagulation-flocculation treatment facility.

3.3 The Working Process of the Grey Water Coagulation-Flocculation Facility

The objective was to create microfloc from particulate matter, agglomerate the particles to facilitate the sedimentation process. Particulate matter, non-settleable particulate matter in surface water carries a negative charge. To neutralize negatively charged particles, a positively charged coagulant, *Moringa oleifera* was added and within a few seconds micro particles were created as the particles were neutralized. Further mixing created macro flocs that settled to the bottom. At this stage the mixer power is usually high as flash mixing is essential to get the micro flocs to ultimately floc together to create larger macro flocs, which are more conducive to settling.

a. Flocculation Process

In the flocculation process there were various sizes of flocs.

Larger Macro flocs

Blade Impeller

Low RPM and HP

Low Mixer Power

The macro flocs were moved to the last basin for the sedimentation process. The low mixer power and flow helped maintain the flocs and improved settling for the next stage.

3.4 Greywater Sample Collection

Greywater was collected from commercial kitchen within the community.

Physio-chemical studies were conducted on the greywater sample to determine its major properties (i.e., pH, Turbidity, TDS, TSS, COD, BOD). All tests were performed at the Marlet Environmental Research Laboratory Limited, Benin City, Edo State.

3.5 Operational Use of Fabrication for Greywater treatment

A test run was conducted in the laboratory using the water treatment facility.

a. 1000 ml per jar of greywater was mixed with optimum dosage of the coagulant (i.e., 0.4 g/500ml).

b. Rapid mixing (coagulation) was done for 5 minutes, followed by slow mixing (flocculation) for 30 minutes.

c. The mixture was allowed to settle for 60 minutes in the sedimentation unit.

d. Supernatant samples were taken for post-treatment analysis.

3.6 Laboratory Analysis

3.6.1 Determination of pH

a. Apparatus

i. pH meter (calibrated, with temperature compensation)

ii. Combination pH electrode (glass electrode + reference electrode)

iii. pH buffer solutions (pH 4.01, 7.01, and 10.01 at 25°C)

iv. Beakers

v. Stirring rod or magnetic stirrer

vi. Distilled water

vii. lint-free wipe

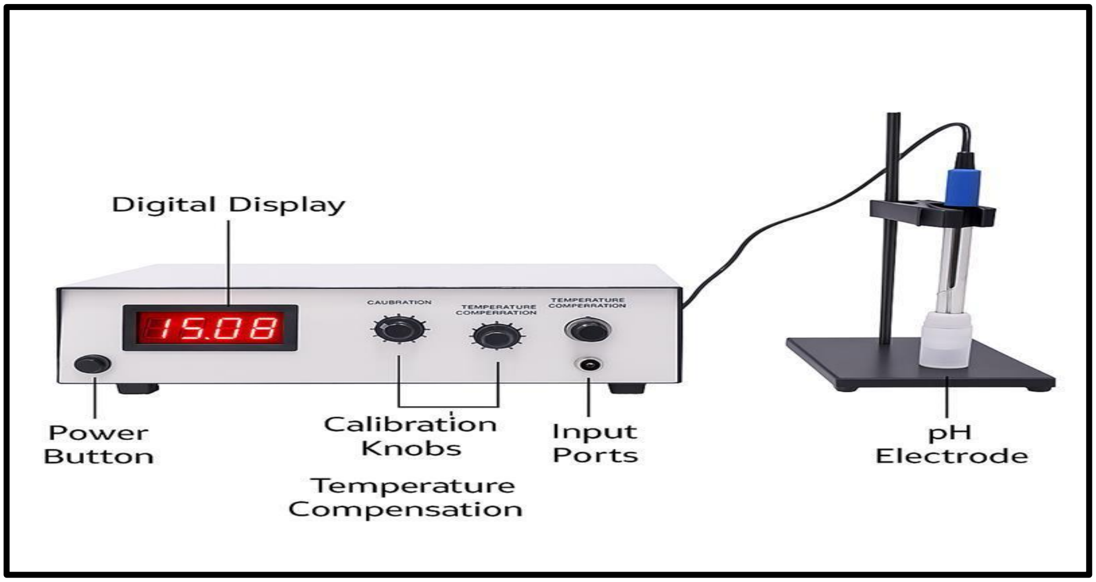

Figure 7 3.2: pH meter

b. Procedure

The pH meter was turned on and allowed to stabilize for 30 minutes. It was calibrated using at least two standard buffer solutions. The electrode was rinsed with distilled water between buffer solutions to avoid contamination. The sample to be tested was placed in a beaker and temperature compensation was applied in the case of discrepancies between buffer and sample temperature. The electrode was immersed by 2cm ensuring the glass bulb and reference junction are fully submerged in the sample. The sample was stirred gently to ensure homogeneity without introducing air bubbles. At a stabilized reading the pH value was recorded.

3.6.2 Determination of Electrical Conductivity

a. Apparatus

i. Conductivity meter (calibrated, temperature– compensated)

ii. Conductivity cell (platinum or graphite electrodes)

iii. Standard KCl solution (0.01 M, 1413 µS/cm at 25°C)

iv. Thermometer (if conductivity meter lacks automatic temperature compensation)

v. 100cm^3 Beakers

vi. Distilled Water

viii. lint– free wipe

b. Procedure

The conductivity cell was rinsed with distilled water, and the meter was calibrated to read in µS/cm using a standard potassium chloride (KCl) solution of 0.01M concentration having a conductivity of 1413µS/cm at 25°C.

The water sample was gently mixed to ensure uniformity; the cell was rinsed with distilled water and then filled with the sample water. The cell was immersed in the sample to ensure the electrodes were fully covered. The electrical conductivity (EC) and temperature reading was recorded after 10 seconds to ensure stability.

If the temperature is not at 25°C, a correction was applied using:

$$\mathrm{EC}_{25} = \mathrm{EC}_{\mathrm{t}} \times [1 + 0.02 \times (\mathrm{t} - 25)] \tag{3.1}$$

EC_{25} is the Electrical Conductivity at 25°C

EC_{t} is the Electrical Conductivity at t°C

t is the sample temperature in °C

3.6.3 Determination of Colour

a. Apparatus

i. Spectrophotometer

ii. Cuvette

iii. Filter system

b. Procedure

Hazen or Platinum– Cobalt (Pt/Co) scale was applied using a spectrophotometer. The spectrophotometer was set to a standard of 455nm. The instrument was calibrated to zero using distilled water.

The filter was rinsed by pouring $50m^3$ of the sample through it and discarding that water. Another $50m^3$ was poured through the filter and $25m^3$ of this filtered sampled water was used to fill a clean cuvette. The sample colour was read at 455nm. The colour of the samples was determined by using a spectrophotometer and recorded in as Pt.Co unit (PCU).

3.6.4 Determination of Turbidity

a. Apparatus

i. Nephelometer or turbidimeter

ii. Cuvettes

iii. Formazin

iv. Lint-free cloth

Figure 3.3: Turbidity meter (Yaka, 2018)

b. Procedure

The turbidity meter was calibrated using series of calibration standards by diluting formazin stock suspension to desired NTU levels of 0, 5, 10, 20, 40, 100 and 400 NTU. The cuvette was filled with each standard and placed in the turbidimeter to calibrate it.

The sample was stirred gently to distribute any settled particles and prevent creation of air bubbles, if large particles are present, they were decanted carefully to avoid affecting measurement readings.

The water sample was placed in a clean cuvette ensuring no air bubbles are formed. The exterior of the cuvette was wiped clean with a lint–free cloth to remove fingerprints and moisture before it was placed into the nephelometer. A stable reading of the turbidity was recorded after 10 to 20 seconds in Nephelometric Turbidity Unit (NTU).

3.6.5 Determination of Total Solids

a. Apparatus

i. Weighing balance (±0.1 mg sensitivity)

ii. Drying oven

iii. Desiccator

iv. Filtration apparatus

v. Evaporating dish

vi. Graduated cylinder

viii. Distilled water

ix. Wash bottle

x. Lint-free wipes

b. Procedure

The evaporating dish was cleaned, dried and placed in the drying oven at 103–105°C for at least 1 hour. It was allowed to cool in a desiccator at room temperature and weighed using a weighing balance with its weight recorded as $W_{1.}$ The filter paper was placed on the filtration set up (flask and funnel) and washed using distilled water and then allowed to drain. It was oven dried at 103–105°C for 1 hour. It was allowed to cool in a desiccator at room temperature and weighed using a weighing balance with its weight recorded as $W_{2.}$ The sample was shaken thoroughly and then filtered through the pre–weighed filter paper, to separate the dissolved solids and water (filtrate) from the suspended solids (residue).

A volume of 100cm^3 of the filtrate was measured and placed in the pre–weighed evaporating dish. The dish was placed in a steam bath or hot plate at about 100°C until it is near–dry. After which, it was placed in the drying oven at 103–105°C for at least 1 hour. The dish was allowed to cool in a desiccator at room temperature and weighed using a weighing balance with its weight recorded as W_3. The TDS was computed in mg/l to the nearest whole number using:

$$\mathrm{TDS} = \frac{W_3 - W_1}{\text{Volume of filtrate}} \tag{3.2}$$

Where, TDS is the Total Dissolved Solids.

W_1 is the weight of the empty evaporating dish.

W_3 is the weight of the evaporating dish and oven dried filtrate.

The residue and filter paper were placed in the drying oven at 103–105°C for at least 1 hour and then allowed to cool in a desiccator at room temperature. The oven dried filter paper and residue was weighed using a weigh balance and the value read was recorded as W_4. The TSS was computed in mg/l to the nearest whole number using:

$$\mathrm{TSS} = \frac{W_4 - W_2}{\text{Volume of filtrate}} \tag{3.3}$$

Where, TSS is the Total Dissolved Solids.

W_2 is the weight of the filter paper.

W_4 is the weight of filter paper and oven dried residue.

The total solids (TS) will then be computed using:

$$\mathrm{TS} = \mathrm{TDS} + \mathrm{TSS} \tag{3.4}$$

Where, TS is the Total Solids

TDS is the Total Dissolved Solids

TSS is the Total Suspended Solids

3.6.6 Determination of COD

a. Apparatus

i. Reflux apparatus with condenser (or digestion vials with heating block for closed reflux)

ii. 50cm3 Burette

iii. Volumetric flasks

iv.Pipettes

v. Hot plate

b. Reagents

i. Standard potassium dichromate solution (0.0417M of $K_2Cr_2O_7$)

ii. Concentrated sulfuric acid (H_2SO_4) with silver sulfate (Ag_2SO_4) catalyst

iii. Mercuric sulfate ($HgSO_4$)

iv. Standard ferrous ammonium sulfate (FAS) titrant (0.1 N)

v. Ferroin indicator

vi. Distilled or deionized water

vii. Standard COD solutions (potassium hydrogen phthalate for calibration)

c. Procedure

50cm^3 of the sample was measured into a conical flask, 1g of $HgSO_4$ and 5 mL $H_2SO_4^-$ Ag_2SO_4 reagent was added and mixed before 25cm^3 of 0.0417M of $K_2Cr_2O_7$ was added. A reflux greaseless condenser was attached, and the compound was heated gently for 2 hours and allowed to cool at room temperature. The excess dichromate was titrated using FAS and ferroin as indicators. The end point was a change of colour from bluish green to reddish brown.

A blank determination was performed with 50cm^3 of distilled water in place of the water sample and the procedure was repeated.

The Chemical Oxygen Deman was calculated using:

$$\text{COD (in mg/l)} = \frac{(V_A - V_B) \times M \times 8000}{\text{Volume of sample}} \tag{3.5}$$

Where, V_A is the volume of FAS used for the blank

V_B is the volume of FAS used for the sample

M is the molarity of FAS

8000 is the equivalent weight of oxygen × 1000

3.6.7 Determination of BOD

a. Apparatus

i. BOD bottles (300 mL, air-tight with ground-glass stoppers)

ii. Incubator (20°C ± 1°C, dark)

iii. DO meter (electrometric) or Winkler titration kit

b. Reagents

i. Phosphate buffer (pH 7.2)

ii. Magnesium sulfate, calcium chloride, ferric chloride (nutrients)

iii. Nitrification inhibitor

iv. Sodium sulfite

v. Glucose-glutamic acid (GGA) solution

c. Procedure

The sample had a high BOD value and as such it was diluted with oxygen-saturated dilution water. The BOD bottles were filled completely without air bubbles, and the initial dissolved oxygen (DO_0) was measured. The sample was then be incubated at 20°C for 5 days in the dark to prevent photosynthesis. After the 5-day period, the final dissolved oxygen (DO_5) was measured.

The 5-day BOD will be calculated using.

$$BOD_5 = \frac{(DO_0 - DO_5)}{\text{Dilution factor}} \tag{3.6}$$

3.7 Performance and Efficiency Evaluation

After treatment, the same parameters (pH, EC, colour, turbidity, TDS, TSS, BOD and COD) will be analyzed for each coagulant and dosage.

Removal efficiency (%) for each parameter will be calculated using:

$$\text{Removal Efficiency} = \left(\frac{\text{Initial Value} - \text{Final Value}}{\text{Initial Value}}\right) \times 100 \tag{3.7}$$

3.8 Preliminary Economic Analysis

a. The cost of the following was tracked.

i. Raw materials (seed price per kg)
ii. Coagulant processing (grinding, drying)
iii. Prototype fabrication (materials, labor)
iv. Analytical materials and labor

b. The cost per liter of greywater treated was estimated using each coagulant.

3.9 Techno-Economic Feasibility for Scaling

Using lab data and market assumptions, the feasibility of scaling the coagulant using the prototype was modeled.

a. The following were estimated:

i. Coagulant demand and supply for a small community (≈1000 l/day)
ii. Cost of larger-scale prototype setup
iii. OPEX and CAPEX for monthly operations

b. The estimated values were compared with the alum-based treatment and interpreted based on:

i. Cost-effectiveness
ii. Raw material availability
iii. Potential social/environmental benefits

3.10 Sensitivity and Scenario Analysis

To evaluate the robustness of the treatment system across variable conditions, a sensitivity analysis was carried out. Key parameters to be varied include:

Coagulant cost (±50%)

Energy cost (±25%)

Labor rates (±20%)

Greywater volume (±100%)

Each scenario will explore how changes in these variables affect the cost per m^3 treated, overall feasibility, and affordability for small communities.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physio-Chemical Analysis

Table 4.1: Result of Physio-Chemical Analysis

Parameter	Unit	Untreated Greywater	Treated Greywater	P-Value
pH	____	4.0	4.0	$p < 0.01$
EC	µS/cm	5153	5107	$p < 0.01$
Colour	Pt.Co	10.4	5.3	$p > 0.01$
Turbidity	NTU	8.4	3.7	$p < 0.01$
TDS	mg/L	2577	2554	$p < 0.01$
TSS		22.4	8.7	$p < 0.01$
COD		800.4	310.6	$p < 0.01$
BOD		101.3	79.4	$p < 0.01$

From Table 4.1, the observed range of pH for the sample greywater before and after treatment through coagulation-flocculation process was 4.0. The p-value is greater than 0.05 indicative of no significance difference between the pH of samples of grey water. For the untreated and treated greywater, EC was 5153µS/cm and 5107µS/cm respectively, TDS was 2577mg/L and 2554 mg/L respectively, colour was 10.4 Pt.Co and 5.3 Pt.Co respectively, turbidity was 8.4 NTU and 3.7 NTU respectively, TSS was 22.4 mg/L and 8.7 mg/L respectively, COD was 800.4 mg/L and 310.6 mg/L respectively while BOD was 101.3 mg/L and 79.4 mg/L. When comparing the results of this investigation to those of Iwuozo and Imuobosa (2018) which highlighted the environmental standard requirement for grey water disposal, it is inferred that the pH of the test samples was not within allowable pH range of values which is between 6 to 9, indicative of an acidic liquid. The EC of the sample grey water was 5153μS/cm and 5107μS/cm for untreated and treated grey water which was above the allowable environmental standard range of water's typical electrical conductivity which is between 400 to 600 μS/cm which indicates that the treated greywater still contains high concentration of dissolved salts. The colour values of 10.4 Pt.Co and 5.3 Pt.Co for the untreated and treated greywater samples respectively were both within the standard of 15 Pt.Co. This decline reflects efficient removal of colloidal and dissolved organic matter responsible for the initial colouration. Turbidity values were 8.4 NTU to 3.7 NTU for the untreated and treated greywater samples respectively, this value was within the standard of 10 NTU. The treated greywater was visually clear which corroborates this result. The TSS values of 22.4mg/L and 8.7mg/L for untreated and treated grey water respectively was within acceptable standard limit of 30. The TSS of the treated grey water with a value of 8.7 mg/L was far less than the acceptable standard limit indicative of the efficacy of the grey water treatment facility. TDS was 2577 mg/L and 2554 mg/L for untreated and treated of the samples of grey water respectively, this was higher than the recommended standard of 2000mg/L, hence there was need to believe that the grey water from both samples will require further treatment and or purification measures. This result indicates that although the coagulation-flocculation process effectively removed suspended particles, however the concentration of dissolved ions was still high which is consistent with the result of EC. Chemical contaminants and pollutants like chloride and sulphate, sodium and potassium, are often found in water with a high EC. The Biochemical Oxygen Demand (BOD_5) decreased from 101.3 mg/L to 79.4 mg/L after treatment, this moderate decrease indicates partial removal of biodegradable organic matter, consistent with the non-biological nature of the coagulation-flocculation process. The treated value exceeds 50 mg/L suggesting that additional biological or filtration treatment would be required for effluent discharge or irrigation purposes. The Chemical Oxygen Demand (COD) decreased markedly from 800.4 mg/L to 310.6 mg/L after treatment. This demonstrates effective removal of oxidizable organic pollutants through the coagulation–flocculation process. Although the treated value exceeds the effluent limit of 50 mg/L, the substantial reduction confirms the process high pollutant removal capacity. Further polishing or biological post-treatment would be required to meet discharge standards.

The physio-chemical characteristics of grey water samples before and after treatment and the p-value difference suggested that there was remarkable difference in the purity state of the grey water before and after treatment. This underscores the efficacy of the grey water treatment facility which specifically utilized moringa powder as a natural coagulant-flocculants agent.

4.2 Techno-Economical Analysis

A techno-economic analysis is carried out to ascertain the efficacy and financial prospects and constraints of the experimental grey water treatment facility using moringa as a natural coagulant-flocculants. A comparative analysis between conventional grey water treatment and the experimental proof of concept is also explored in this section. Table 4.1 presents the metrics for the analysis.

Table 4.2: Techno-Economic Analysis of Grey Water Treatment Process Using Moringa as Natural Coagulant- Flocculent.

Parameter	Conventional greywater treatment (Alum)	Experiment System (Moringa)	Comments
Capital expenditure (₦)	₦ 3,000,000	₦ 2,200,000	Conventional: off-the-shelf dosing, tanks, motorised mixers. Experimental: locally fabricated flocculator, drying/grinder for seeds, simple dosing.
Annual Operating Expenditure (OPEX, ₦/yr)	₦ 820,000	₦ 540,000	
Cost of treatment per/litre (₦/L)	₦ 0.11/ L (≈ ₦ 110 / m³)	₦ 0.06 / L (≈ ₦ 60 / m³)	Annual OPEX ÷ 365, plus small annualised CapEx effect noted below in text.

Parameter	**Conventional greywater treatment (Alum)**	**Experiment System (Moringa)**	**Comments**
Energy Consumption	0.40 kWh / m^3	0.22 kWh / m^3	Conventional includes dosing pumps, stronger mixers; experimental uses lower-power mixing and manual options.
Chemical Usage	≈ 0.12 kg alum / m^3 ⇒ 43.8 kg/yr	≈ 0.04 kg alum / m^3 ⇒ 14.6 kg/yr	Usage based on jar-test dosages scaled to 1 m^3/day.
Annual Chemical Cost (₦/yr)	₦ 43,800	₦ 29,200	Retail moringa can be higher.
Labour and Maintenance	₦ 300,000	₦ 180,000	Conventional needs more frequent operator checks for chemical dosing and safety; experimental simpler. (Estimates based on market technician salaries).

Parameter	**Conventional greywater treatment (Alum)**	**Experiment System (Moringa)**	**Comments**
Monitoring and Compliance	₦ 120,000	₦ 70,000	Laboratory tests, periodic external sampling higher for alum due to residual metal concerns
Sludge handling/disposal (₦/yr)	₦ 120,000	₦ 50,000	Chemical coagulants produce heavier, contaminated sludge (disposal costs) - moringa sludge is lower and more compostable.
Return on Investment (ROI)	≈ 15% (using a 5yr horizon)	≈ 28% (using a 5yr horizon)	Driven by lower annual OPEX and faster payback.
Return on Investment and Pay Back Period	≈ 6.5 years	≈ 3.8 years	Based on CapEx and annual net savings; see write-up for arithmetic.

4.3 Techno-Economic Justification of the superiority of Moringa-based experimental system in the Nigerian context

The techno-economic analysis presented in Table 4.2 demonstrates that a coagulation–flocculation greywater treatment facility employing locally sourced *Moringa oleifera* seed powder as the primary coagulant is economically and operationally advantageous compared with a conventional alum-based process for small community deployments (≈1 m^3/day). The experimental system's lower capital expenditure (₦2.2 million vs ₦3.0 million) stems from simpler dosing controls and the ability to fabricate substantial portions of the flocculation and sedimentation tanks using local materials and labour. In contrast, the conventional system requires more elaborate chemical dosing hardware and engineered containment for metal-laden sludge.

4.3.1 Operating Costs and Consumables

Annual operating expenditure (OPEX) under the conservative scenario modelled here is ≈₦540k/yr for the Moringa system versus ≈₦820k/yr for the alum system. The difference is driven by:

a. lower sludge handling and disposal costs for Moringa (Moringa sludge is largely organic and can be composted or valorized, reducing landfill or treatment fees).

b. simpler monitoring and lower hazardous-waste compliance (chemical residual metals are a concern for alum).

c. reduced energy demand, laboratory and pilot data indicate that protein-based natural coagulants can achieve comparable turbidity and TSS removal at slightly lower mixing energies because the flocs formed are larger and settle faster. Energy cost calculations used a representative Nigerian tariff (≈₦210/kWh) consistent with 2025 cost-reflective orders; even with this relatively high tariff the electrical share of total OPEX remains modest because coagulation–flocculation is not extremely energy intensive.

4.3.2 Chemical sourcing and price risk

Moringa seed powder retail listings in Nigeria indicate that small-scale retail can be expensive (e.g., market listings up to ₦7,000/kg), but when sourced directly from farmers or aggregated in bulk the effective procurement cost can fall substantially (the analysis uses a conservative bulk assumption of **₦2,000/kg**). The alum market shows supplier price bands that when translated to practical procurement units produce a conservative bulk alum price of **≈₦1,000/kg**. Even when moringa powder costs approach retail levels the total cost of Moringa remains competitive because required dosages are relatively small (modelled at ≈0.04 kg/m³ for Moringa vs ≈0.12 kg/m³ for alum), and because the Moringa route lowers downstream costs (sludge and monitoring).

4.3.3 Financial performance

When capital expenditure is annualized and OPEX discounted over a 5-year horizon, the Moringa system achieves an internal rate of return and payback materially better than the alum reference: payback ≈ 3.8 years for Moringa vs ≈ 6.5 years for alum under base assumptions. The faster payback is driven by the OPEX delta (approximately **₦280k per yr** saved) and by lower projected sludge disposal and monitoring costs. This improvement is meaningful for NGO or municipal operators and community co-operatives working with limited access to capital, a quicker payback reduces financing risk and increases adoption potential.

4.3.4 Non-monetary advantages

Beyond direct economics, the Moringa approach confers social and environmental benefits that increase its real-world value:

(i) local value capture, seed collection, drying and powdering can be undertaken by local micro-enterprises, creating livelihoods.

(ii) reduced hazardous waste: no aluminum residual issues or iron salts in sludge make handling safer; and

(iii) circularity: Moringa residuals can be valorized (compost or soil amendment) if local regulations permit.

4.3.5 Policy and scale sensitivity

Two important caveats must be considered. First, if Moringa powder must be procured at retail prices (e.g., ₦7,000/kg) and bulk sourcing is unavailable, chemical costs rise and the economics narrow but the sludge, labour and monitoring advantages still favour Moringa in many small-scale contexts. Second, electricity supply instability in parts of Nigeria often forces reliance on diesel backup; increased generator use will raise energy costs and thus affect OPEX for both systems. Nevertheless, because the experimental system uses less power and produces less problematic sludge, the incremental diesel burden and logistics remain lower than for conventional alum dosing.

For decentralized, community-scale greywater reuse projects in Nigeria especially in rural or peri-urban settings where local labour and raw materials are available the Moringa-based coagulation–flocculation facility provides a strong techno-economic case: lower life-cycle costs, faster payback, reduced hazardous waste, and local livelihood creation. Where TDS/EC is high, a light polishing stage will be required, but the Moringa facility reduces the size and cost of that polishing stage by efficiently removing solids and much of the organic load before polishing, improving full-system durability and economics.

4.3.6 Sensitivity

a. Moringa price: If moringa must be purchased retail at ₦7,000/kg (instead of bulk ₦2,000/kg), chemical OPEX increases by ≈ ₦120k/yr for the modeled volume this reduces but does not fully eliminate the OPEX advantage because sludge disposal, monitoring and labour savings remain.

b. Energy cost or generator usage: If grid supply is poor and generator backup is used extensively, include diesel cost (≈₦900+ / L current market) or generator kWh conversion in OPEX; Moringa still benefits since it requires less energy.

c. Regulatory constraints (TDS): If target reuse requires meeting TDS ≤ 2,000 mg/L (NESREA), add a polishing membrane or ion-exchange stage. However, because the Moringa system reduces solids and COD/CBO, membrane fouling risk is lower, thereby reducing total polishing OPEX and replacement costs versus the alum route.

CHAPTER FIVE

CONCLUSION

5.1 Conclusions

This study has successfully demonstrated the technical viability and economic feasibility of using locally available coagulants specifically *Moringa oleifera* for the coagulation-flocculation treatment of greywater. The research established that natural coagulants can effectively improve water quality by significantly reducing turbidity, color, total suspended solids (TSS), and organic load parameters such as chemical oxygen demand (COD) and biochemical oxygen demand (BOD). The marked reduction in these parameters confirms the capacity of *Moringa oleifera* to perform comparably to conventional chemical coagulants while offering distinct advantages in terms of cost, biodegradability, and environmental compatibility.

The techno-economic analysis, the experimental treatment process demonstrated lower chemical usage, reduced operational costs, and minimal sludge generation when compared to conventional systems, indicating a sustainable and financially favorable option for decentralized greywater management. The results showed that the treated greywater met most of the environmental and WHO recommended discharge standards, though further polishing treatment would enhance its suitability for reuse in irrigation and non-potable applications.

This dual-scale assessment bridges laboratory findings with real-world applicability, confirming that the use of local, plant-based coagulants not only promotes circular resource use but also aligns with sustainable development goals particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production).

In conclusion, the research validates that *Moringa oleifera* serves as an effective, low-cost, and eco-friendly coagulant for greywater treatment. The process presents a promising path toward decentralized water management systems that can be implemented in resource-constrained or rural settings.

5.2 Recommendations

i. Optimization of Coagulant Dosage and Blends: Further research should focus on optimizing the dosage of *Moringa oleifera* and exploring synergistic effects when combined with other natural coagulants such as Tamarindus indica or clay-based materials. This could improve pollutant removal efficiency while maintaining cost-effectiveness.
ii. Integration with Secondary Treatment Systems: To meet higher reuse standards, treated greywater from the coagulation-flocculation process should be coupled with simple post-treatment units such as slow sand filtration, activated carbon adsorption, or UV disinfection. This integration will enhance pathogen removal and ensure compliance with irrigation and domestic reuse standards.
iii. Pilot-Scale and Community-Level Implementation: The small-scale prototype developed in this study should be further tested in real-life communities or institutional settings. Pilot-scale trials will provide valuable data on long-term performance, maintenance needs, and user acceptance under variable operating conditions.
iv. Awareness and Policy Support: Government agencies, environmental regulators, and local communities should be sensitized to the economic and environmental benefits of natural coagulant-based greywater treatment. Inclusion of such systems in national

water management policies could promote local production, skill development, and technology adoption.

v. Techno-Economic Modeling for Larger Systems: Future studies should extend techno-economic assessments to larger-scale applications, incorporating life-cycle cost analysis, energy demand, and return-on-investment projections. This will support data-driven decisions for municipal or industrial adoption.

vi. Standardization and Quality Control: There is a need to establish standard protocols for the production, storage, and application of plant-based coagulants to ensure consistent performance and safety across different regions and seasons.

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APPENDIX

Plate 1: Coagulation-Flocculation Water Treatment Facility

Plate 2: Greywater in the Flocculation Basin of the Facility

Plate 3: Greywater in the Coagulation Basin of the Facility

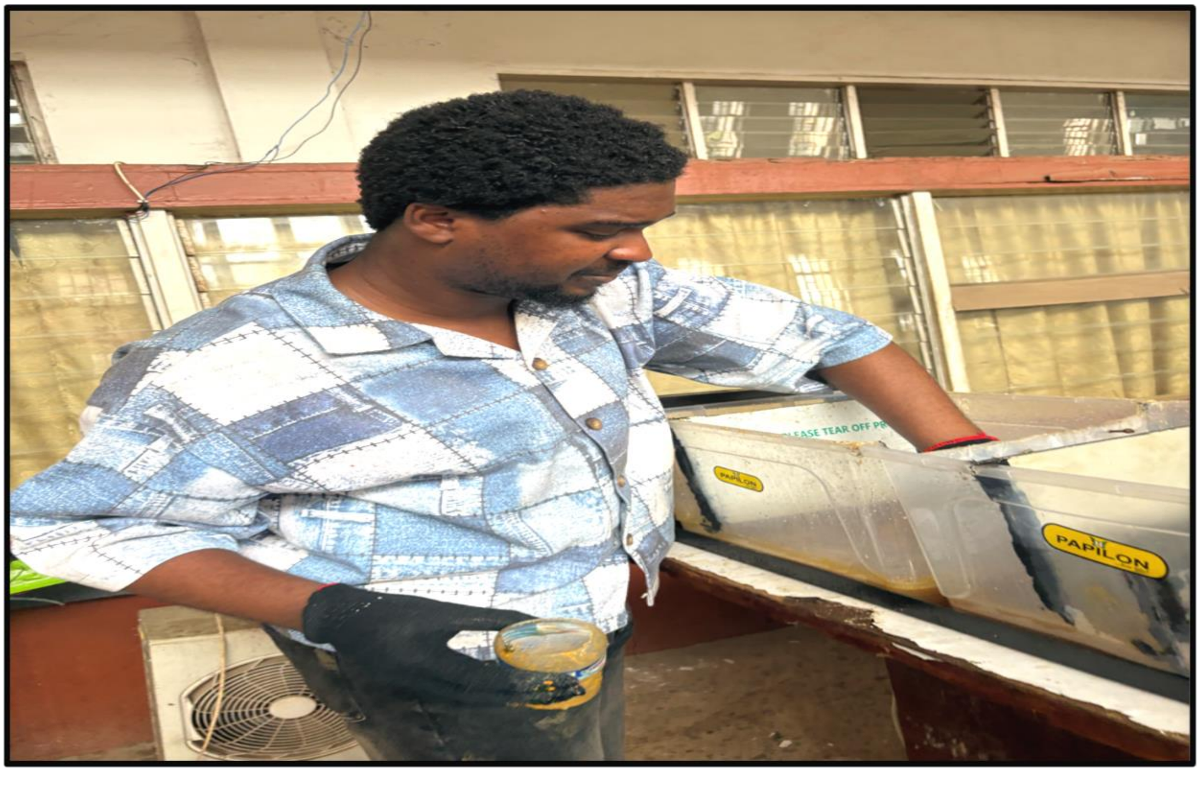

Plate 4: Cleaning the Water Treatment Facility after the First Run

Plate 5: Observation of the Water Treatment Facility Before Use