



FACULTY OF ENGINEERING

DEPARTMENT OF WATER RESOURCES AND MINING ENGINEERING

FINAL YEAR REPORT

OPTIMIZATION OF ALUM RECOVERY FROM WATER TREATMENT SLUDGE IN
MANAFWA WATER TREATMENT PLANT IN BUSOBA SUB COUNTY, MBALE
DISTRICT.

BY

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ABSTRACT

The generation of alum sludge from water treatment plants poses significant economic and environmental challenges, particularly in developing countries where disposal is largely unregulated and resource recovery is rarely practiced. This study aimed to optimize the recovery of alum from water treatment sludge at Manafwa Water Treatment Plant in eastern Uganda using acid leaching with sulphuric acid, evaluate the coagulant performance of the recovered alum against commercial alum, and assess the financial viability of implementing alum recovery at the plant. Alum sludge was characterized for physical and chemical properties, and recovery optimization was performed using Response Surface Methodology (RSM) with a Central Composite Design, varying acid concentration (0.5–2.5 M H_2SO_4) and pH (2–6), while temperature and contact time were held constant at 90°C and 60 minutes, respectively. Aluminium concentration was determined via Atomic Absorption Spectroscopy (AAS), and coagulation performance was evaluated through jar tests.

The sludge exhibited high moisture content (95.8–97.6%), total suspended solids (71,300–106,470 mg/L), near-neutral pH (6.5–6.7), and total aluminium content of 6.8–8.5% by dry mass. RSM optimization identified optimal conditions of 2.17 M H_2SO_4 and pH 3.01, yielding a predicted recovery efficiency of 94.1% with a desirability score of 0.955. The recovered alum was off-white, had a pH of 3.2, and contained 9.4% aluminium by mass. Jar tests using dosages of 30–80 mg/L showed that recovered alum achieved turbidity removal efficiencies of 55–94%, compared to 63–99.6% for commercial alum at equivalent dosages, representing a performance gap of approximately 5%. Financial analysis revealed a Net Present Value of UGX 292,038,935 over 10 years at a 12% discount rate, a Profitability Index of 4.65, and a payback period of approximately 1 year and 3 months, confirming strong economic viability. In conclusion alum recovery from water treatment sludge is both technically feasible and financially attractive, with acid concentration and pH as the dominant control parameters. Further purification and pilot-scale validation are recommended.

DECLARATION

I, KWAGALA JANE, hereby declare that this report is the work of my hands and this research has never been presented by any person in any institution for an academic award.

Signature: 

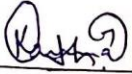
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APPROVAL

This work has been thoroughly compiled with the guidance and consultation of my supervisors.

Supervisor

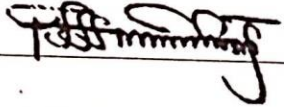
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DEDICATION

I dedicate this report to my parents for their social and financial support, as well as my friends and the entire class of water resources engineering. And the water department for their encouragement and academic support. This inspired me to learn more about my project. I was able to learn report writing skills. May the almighty God be with them in all they lay their hands on.

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LIST OF ACRONYMS

AAS - Atomic Absorption Spectrophotometer / Spectroscopy

Al - Aluminum

APHA - American Public Health Association

CCD - Central Composite Design

CDC - Centers for Disease Control and Prevention

HCl - Hydrochloric Acid

H₂SO₄ - Sulfuric Acid

ICP-OES - Inductively Coupled Plasma Optical Emission Spectrometry

M - Molar (concentration unit)

NaOH - Sodium Hydroxide

NDP - National Development Goals (specifically NDP1V - National Development Plan IV)

NEMI -National Environmental Methods Index

NTU - Nephelometric Turbidity Units

NWSC - National Water and Sewerage Corporation (Uganda)

PPE - Personal Protective Equipment

RSM - Response Surface Methodology

SDG - Sustainable Development Goals (specifically SDG 6 and SDG 12)

TS - Total Solids

VS - Volatile Solids

WHO - World Health Organization

WTP - Water Treatment Plant

WTS-WaterTreatmentSludge

1. CHAPTER ONE: INTRODUCTION

1.1 Background

Water treatment is the process of improving the quality of raw water from natural sources such as rivers, lakes, or groundwater by removing physical, chemical, and biological contaminants through a sequence of treatment stages (Elshorbagy, 2022). The conventional water treatment process consists of several stages including coagulation, flocculation, sedimentation, filtration, and disinfection, where coagulation involves adding chemicals such as aluminum sulfate or ferric salts to neutralize the electrical charges of suspended and colloidal particles so they can begin to aggregate, (Elshorbagy, 2022) flocculation follows with gentle mixing that allows the destabilized particles to collide and form larger flocs sedimentation allows these heavier flocs to settle by gravity at the bottom of sedimentation tanks, filtration then passes the clarified water through porous media such as sand, gravel, or activated carbon to remove remaining fine particles and microorganisms, and finally disinfection uses agents such as chlorine, ozone, or ultraviolet light to destroy harmful pathogens and ensure the water is safe for human consumption (Elshorbagy, 2022). Globally, raw water is commonly treated through alum coagulation to remove suspended and colloidal impurities, followed by sedimentation, filtration, and disinfection to ensure a safe drinking water supply (Silva, 2023) and in Africa, raw water treatment in most urban centers also relies heavily on alum-based coagulation followed by sedimentation, filtration, and chlorination, while rural areas often lack access to such systems and depend on simpler or untreated sources (Omohwovo, 2024).

At Manafwa WTP, raw surface water from River Manafwa is subjected to chemical coagulation using a coagulant, for example, alum, followed by sedimentation in clarifiers, rapid sand filtration, and disinfection, with recent upgrades planned to improve the coagulation units for handling fluctuating raw water quality (Niwagaba et al., 2025). Therefore, Alum (aluminum sulfate) is one of the most widely used coagulants in water treatment due to its effectiveness in aggregating fine particles into settleable flocs (Koul & Koul, 2022).

Despite its widespread use, a significant percentage of the alum added during coagulation remains unused in the treatment process, ending up in water treatment sludge. Studies have reported that

40–50% of alum can remain in sludge (Gobena¹, et al., 2020). Water treatment plants (WTPs) like the Manafwa water treatment plant play a vital role in ensuring potable water by removing suspended solids, colloidal particles, and other impurities from raw water through coagulation, which ends up retaining some percentage of alum coagulant in the sludge.

Ooi and other writers highlighted acidification as an effective method for recovering alum from sludge since Aluminum hydroxide in the sludge is amphoteric and it dissolves in both alkaline and acidic conditions (Ooi et al., 2020). By reducing the sludge pH to between 1 and 3 using acids such as sulfuric acid, alum recovery rates of 70–90% can be achieved (Mohammad, et al., 2021). However, most studies on alum recovery, particularly in developing countries like Uganda, remain bench-scale experiments, and the recovery process has not been fully optimized for operational water treatment plants. Factors such as acid concentration, contact time, temperature, and pH adjustments can significantly affect the efficiency of alum recovery. Furthermore, the performance of the recovered alum in actual coagulation processes, as compared to fresh alum, requires careful evaluation to ensure water quality standards are met.

1.2 Problem statement

Water treatment plants that use aluminum sulfate (alum) generate large amounts of alum-laden sludge as a by-product of coagulation and sedimentation. At Manafwa Water Treatment Plant, approximately 40% of the alum applied remains trapped in the sludge instead of contributing effectively to coagulation, resulting in direct financial losses and increased operational costs due to continuous purchases of fresh coagulant. Improper handling and disposal of this sludge, currently done on drying beds without resource recovery, pose environmental challenges, including potential leaching of aluminium into surrounding soils and rivers, water contamination, blocked drainage systems, and land-use conflicts with nearby communities. Studies have demonstrated that alum can be efficiently recovered from sludge through acid leaching or thermal extraction, achieving recovery efficiencies of up to 90% under optimized conditions (Ooi et al., 2020) With recovered alum performing comparably to commercial alum in coagulation processes (Nevil, 2022). However, Uganda still lacks practical studies on alum recovery, particularly in decentralized water treatment systems like Manafwa WTP.

1.3 Justification.

The optimization of alum recovery from water treatment sludge at Manafwa Water Treatment Plant is justified as it offers a sustainable, cost-effective, and environmentally friendly solution to the persistent challenges of chemical expenditure and sludge disposal, since the recovery and reuse of alum can significantly reduce operational costs associated with the purchase of commercial coagulants, minimize environmental pollution from sludge leachates contaminating nearby rivers and soils, and promote the sustainable management of water treatment residues through resource recovery, while also contributing to National Development Goals (NDP1V) and the achievement of Sustainable Development Goals specifically SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production) as well as fostering applied research and technological innovation within Uganda's water sector by generating empirical data and optimized parameters for coagulant recovery applicable to similar regional water treatment facilities

1.4 Significance

Recovering alum from sludge will reduce the volume of waste requiring disposal, thereby minimizing the environmental risks associated with sludge accumulation and potential contamination of soil and water bodies. Optimizing alum recovery has the potential to lower operational costs at Manafwa Water Treatment Plant by reducing the reliance on continuously purchasing new alum. Reusing recovered alum will make the treatment process more cost-efficient and economically sustainable. The study will generate valuable data on process optimization parameters such as acid type, pH, temperature, and reaction time that influence alum recovery efficiency. These findings will expand the existing body of knowledge and guide future research and industrial-scale applications in alum recovery technologies. The outcomes of this research can inform policy development and technical guidelines for sludge management and resource recovery within Uganda's National Water and Sewerage Corporation (NWSC) and other water utilities across Africa.

1.5 Objectives

1.5.1 General Objective

To optimize the recovery of alum from sludge generated at the Manafwa Water Treatment plant.

1.5.2 Specific Objectives

- (i) To characterize the chemical and physical composition of alum sludge generated at Manafwa Water Treatment Plant.
- (ii) To optimize process parameters, like acid concentration, and pH, on alum recovery efficiency.
- (iii) To evaluate the performance of the recovered alum in the coagulation of raw water compared to commercial alum.
- (iv) To carryout financial analysis of the recovered alum versus commercial alum.

1.6 Scope of the study

1.6.1 Conceptual scope

Conceptual study focuses on the optimization of alum recovery from water treatment sludge through acidification methods, leaving out other methods like thermal treatment and alkalization. The research will specifically examine how process parameters like acid type, acid concentration, and pH influence the efficiency of alum recovery. Additionally, it will evaluate the performance of the recovered alum in water coagulation compared to commercial alum.

1.6.2 Geographical Scope

The research will be conducted at Manafwa Water Treatment Plant, located in eastern Uganda. The plant abstracts raw surface water from the River Manafwa for purification and domestic supply. Sludge samples for analysis and experimental work will be collected exclusively from this treatment facility, and findings will be contextualized within the operational conditions and challenges specific to Manafwa Water Treatment Plant. However, the outcomes may provide insights applicable to similar water treatment facilities across Uganda and other developing regions seen in *Figures 1.1* below.

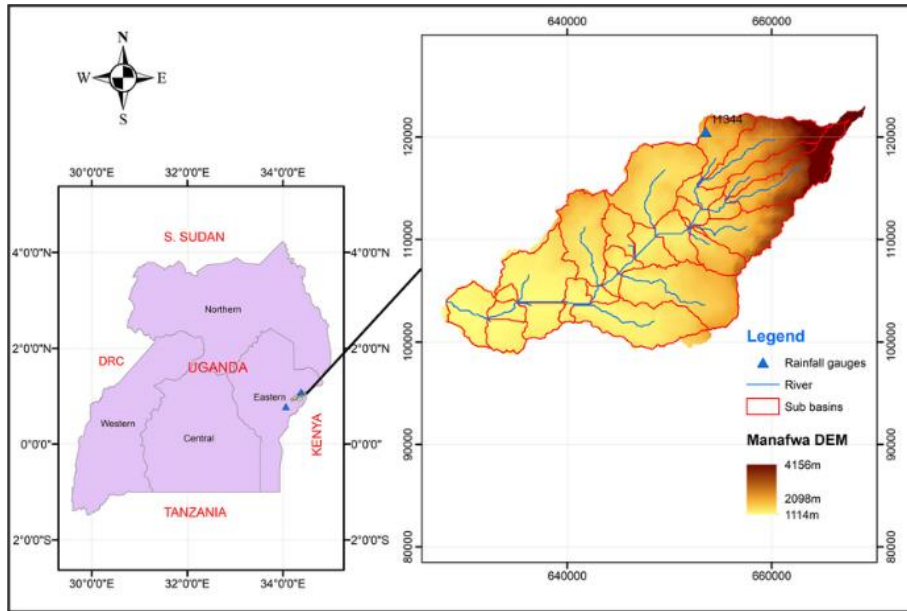


Figure 1.1: Study area (Manafwa)

1.6.3 Time Scope

The study will encompass activities conducted over three months, including data collection, laboratory experimentation, analysis, and reporting. The time frame allows for seasonal variations in raw water quality to be considered during sampling and testing. The literature referenced in the study will primarily encompass publications from the past six years (2020–2026) to ensure the inclusion of recent advancements in alum recovery technologies.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Water treatment plants that use aluminum salts, commonly aluminum sulfate, also known as alum, generate large volumes of alum-laden sludge. This sludge contains a significant percentage of 80-95% of the originally dosed aluminum, creating both disposal burdens and an economic loss of coagulant. Therefore, recovering aluminum is attractive for a circular economy, cost reduction, and reducing environmental risk. Recent reviews emphasize valorization routes (reuse as coagulant, soil amendment, construction materials, zeolite synthesis) and place coagulant recovery as a priority for resource-efficient treatment plants (Mattoso et al., 2024).

2.1.1 Manafwa Water Treatment Plant

The Manafwa Water Treatment Plant treats raw water to supply safe drinking water to the surrounding communities. The plant commonly uses alum (aluminium sulphate) as a coagulant seen in *Figure 2.1*, which leads to the production of large amounts of water treatment sludge. This sludge is often disposed off without proper recovery, creating environmental and disposal challenges. Therefore, recovering alum from this sludge can help reduce waste, lower operational costs, and improve sustainability at the plant.



Figure 2.1 Showing alum solution being applied to raw water:

2.1.2 Meaning of alum recovery.

Alum recovery is the process of extracting aluminium compounds from water treatment sludge for reuse. It involves treating the sludge, usually with acids, to dissolve and recover the aluminium in a usable form. The recovered alum can then be applied again as a coagulant in water or wastewater treatment (Mattoso et al., 2024). This process helps reduce waste, lower treatment costs, and promote sustainable resource management.

2.1.3 Importance of alum recovery

Cost reduction of recovered alum, therefore lowering operational costs in water treatment plants (Shawal et al., 2023). Waste Minimization reduces the volume of sludge that needs disposal, hence helping in better sludge management. Environmental Protection, it prevents pollution from sludge dumping, reducing aluminium contamination in soil and water. Resource Conservation, this saves natural resources used to produce new alum and promotes sustainable use of materials (Shawal et al., 2023). Supports Circular Economy, converts waste (sludge) into a useful product, and encourages reuse and recycling in water treatment. Improves Treatment Efficiency: recovered alum can still function as a coagulant and helps maintain water treatment performance. Reduces disposal costs and land use, less sludge means less land required for dumping, cutting transportation and landfill expenses. Promotes sustainable water treatment, makes treatment plants more eco-friendly and aligns with modern environmental regulations (Shawal et al., 2023).

2.1.4 Water Treatment Sludge (WTS)

Water Treatment Sludge (WTS) is the semi-solid waste produced during the treatment of raw water in a water treatment plant. It mainly comes from processes like coagulation, flocculation, and sedimentation, where impurities are removed from water (Koul & Bhat., 2022).

2.1.5 Sources of WTS

WTS is generated from different stages in the treatment process:

Coagulation and flocculation tanks, this is where chemicals like alum are added, sedimentation basins seen in *Figure 2.2*, where suspended particles settle, filter backwashing, cleaning of sand

filters produces sludge. In Manafwa water treatment plant, most sludge comes from alum-based coagulation processes.



Figure 2.2: Showing sludge in a clarifier

2.2 Composition of WTS

Water treatment sludge is made up of:

Aluminium compounds as main component when alum is used; Suspended solids (clay, silt, organic matter); Microorganisms; Small amounts of heavy metals, depending on raw water source; Water (large percentage) (Koul & Bhat, 2022).

2.2.1 Problems of sludge disposal.

Environmental Pollution, dumped sludge can contaminate soil and water bodies. Leaching of aluminium and other substances affects ecosystems. Health risks, sludge may contain pathogens and harmful substances and can pose risks to human health if not properly managed. High disposal costs, transporting and disposing sludge is expensive. Requires land, labor, and proper management systems (Ayoub & Abdelfattah, 2022). Water Pollution, discharge into rivers can increase turbidity and toxicity. Affects aquatic life. Aluminium Toxicity, excess aluminium can harm plants, animals, and humans and can also affect water quality if it re-enters water sources (Shawal et al., 2023).

2.3 Main recovery approaches

2.3.1 Acid leaching/acidification

Acid leaching, typically H_2SO_4 or HCl to solubilize Al. This is the most widely-reported laboratory method. Studies report that recovery is strongly dependent on acid type, concentration, sludge: liquid ratio, pH target, and contact time (Vargas et al., 2025). Optimum extraction is often achieved at very low pH of 1–3, where Al dissolves as Al^{3+} complexes; reported recovery efficiencies vary widely (50–90%) depending on conditions and sludge type. Several parametric studies like jar tests following extraction, demonstrate that acidified extracts after precipitation or reversion can function as coagulants (Vargas et al., 2025).

2.3.1.1 Effect of Contact Time

Table 2.1: Effect of Contact Time

Contact Time (min)	Recover Efficiency (%)
25	40
35	60
55	83
65	88 and above

Recovery efficiency increased with contact time due to prolonged interaction between acid and sludge particles as shown in *Table 2.1*. However, after 65 minutes, the increase became negligible, indicating that equilibrium had been reached. Thus, 65 minutes was selected as the optimal constant contact time in relation to report made in (Shahzad et al., 2024), who noted 65 minutes as the optimal contact time. This trend is expected because prolonged interaction between acid and sludge particles allows more complete diffusion of acid into the sludge matrix and more thorough dissolution of aluminium compounds.

2.3.1.2 Effect of Temperature

Table 2.2: Effect of Temperature

Temperature (°C)	Recovery Efficiency (%)
50	60
70	75
90	85 and above

Higher temperatures improve recovery efficiency by increasing reaction rates and enhancing solubility, as seen in *Table 2.2*. The optimum constant temperature was taken to be 90°C, beyond which no significant improvement was observed as also recorded by in the report (Ooi et al., 2022) and (Theam, 2021). Higher temperatures significantly improve recovery efficiency.

The observed trend is consistent with the literature reported that increasing the temperature from 35°C to 90°C increases alum recovery from approximately 40% to 85% and above (Ooi et al., 2022). The marginal improvement beyond 90°C suggests that the activation energy barrier for the dissolution reaction has been overcome, and further heating primarily increases energy costs without proportional benefit

2.3.1.3 A stock solution

A stock solution is a highly concentrated solution that is prepared in advance and later diluted to make working solutions of lower concentration.

Stock solutions are used to save time that is to say you don't prepare a new solution each time, to save space, and to ensure accuracy; mixing once reduces repeated measurement errors (Vargas et al., 2025).

Materials needed in the recovery process were alum sludge, dilute Sulfuric Acid (H_2SO_4) of 0.5-2.5 M, pH meter, beaker & stir rod, filter paper & funnel, Hot plate

Procedures include, Acidify; weighed wet sludge into a beaker. Slowly added dilute sulfuric acid while stirring vigorously seen in *Equation 2-1*. The sludge dissolved as aluminum hydroxide reacts:



Target pH; added acid until the pH was between 2.0 and 6.0 which was adjusted using sodium hydroxide solution. This ensures aluminum is soluble as liquid alum (aluminum sulfate), gravity-filtered the mixture to remove insoluble solids. The filtrate was the recovered alum solution. Gently evaporated the filtrate on a hot plate to increase concentration and cooled the solution to crystallize pure alum ($\text{Al}(\text{SO}_4)_2 \cdot n\text{H}_2\text{O}$). For pure aluminum sulfate, evaporate to dryness (Vargas et al., 2025).

2.3.2 Alkaline leaching.

Alkaline extraction, like sodium hydroxide (NaOH) solubilizes some Al species and is used in some valorization chains e.g., to separate organics before precipitation. Alkaline routes can recover high fractions in some studies, but operational complexities differ, such as the need for subsequent neutralization, handling high ionic strength (Mattoso et al., 2024).

2.3.3 Thermal methods plus acid/alkali follow-up.

Roasting, for example, converting Al hydroxides into forms more amenable to extraction followed by acid or alkaline leaching, has shown good recovery in bench studies some reports of approximately 70–75% Al recovery under optimized roasting conditions. Thermal methods add energy and cost but can improve yields when sludge contains refractory organics Al (Ballou et al., 2022).

2.3.4 Electrochemical methods

Electrochemical dissolution, chelation, or recovery, for example, electrowinning type approaches and combined physical/chemical treatments, such as the use of surfactants, ultrasonic pre-treatment, are emerging but less mature at the pilot scale (Mora et al., 2022).

2.3.5 Key factors affecting alum recovery.

Acid type and concentration; H_2SO_4 is preferred in many studies; optimum normality is often reported between 0.5–2.5.0 M some studies find 1.5 M optimal for release and subsequent volume

reduction. Higher acidity generally increases Aluminium release, but risks dissolving unwanted species like Fe, Ca and increases neutralization cost (Vargas et al., 2025).

pH; Strong effect, maximum Al solubilization reported at pH of 1.0–1.8 in many papers. Recovery drops sharply as pH increases (Vargas et al., 2025). Solid: liquid (S:L) ratio: Lower S:L more liquid, which favors extraction efficiency per mass of sludge, but increases reagent volume and treatment costs. Typical lab ranges: 1:5 to 1:20 w/v; optimization depends on economics (Mora et al., 2022). And also extraction increases with time and often with mild temperature elevation though it was kept a constant for the case of my study. Many bench studies use contact times from 50 min to several hours. NB: Temperature raises solubility, but adds energy input (Mora et al., 2022). .

2.4 Optimization techniques.

2.4.1 Response Surface Methodology (RSM)

Response Surface Methodology is a statistical and mathematical technique used to optimize a process by studying the relationship between several variables and a desired outcome (Ooi et al., 2020).

It works by:

Designing a set of experiments where multiple factors e.g., acid concentration, temperature, time, pH are varied together. Developing a mathematical model usually a quadratic equation that shows how these factors affect the response e.g., percentage alum recovery. Generating graphs response surfaces to visualize the interaction between variables (Ooi et al., 2020)

RSM is Important in my study because it considers interaction between variables, unlike one-factor-at-a-time. Reduces on the number of experiments hence saving time and cost. Gives more accurate and reliable optimization results (Ramadan & Sayed, 2020).

2.5 Performance of recovered alum as a coagulant.

Recovered coagulant can achieve comparable turbidity in many cases when properly neutralized and reconstituted; performance depends on residual impurities and the form of Al returned, e.g., $\text{Al}_2(\text{SO}_4)_3$ vs mixed Al species (Shawal et al., 2023). Some studies report slightly lower efficiency due to the presence of organic matter or other metals that require pre-treatment. In contrast, other optimized processes report near-equal performance at similar dosages. Jar-test work is widely used to evaluate dose-response curves and pH optima for recovered coagulant (Shawal et al., 2023). Practical point for Manafwa Water Treatment plant any recovered product must be tested with local raw water using jar tests comparing turbidity removal, and sludge produced vs commercial alum.

2.6 Research gaps & opportunities

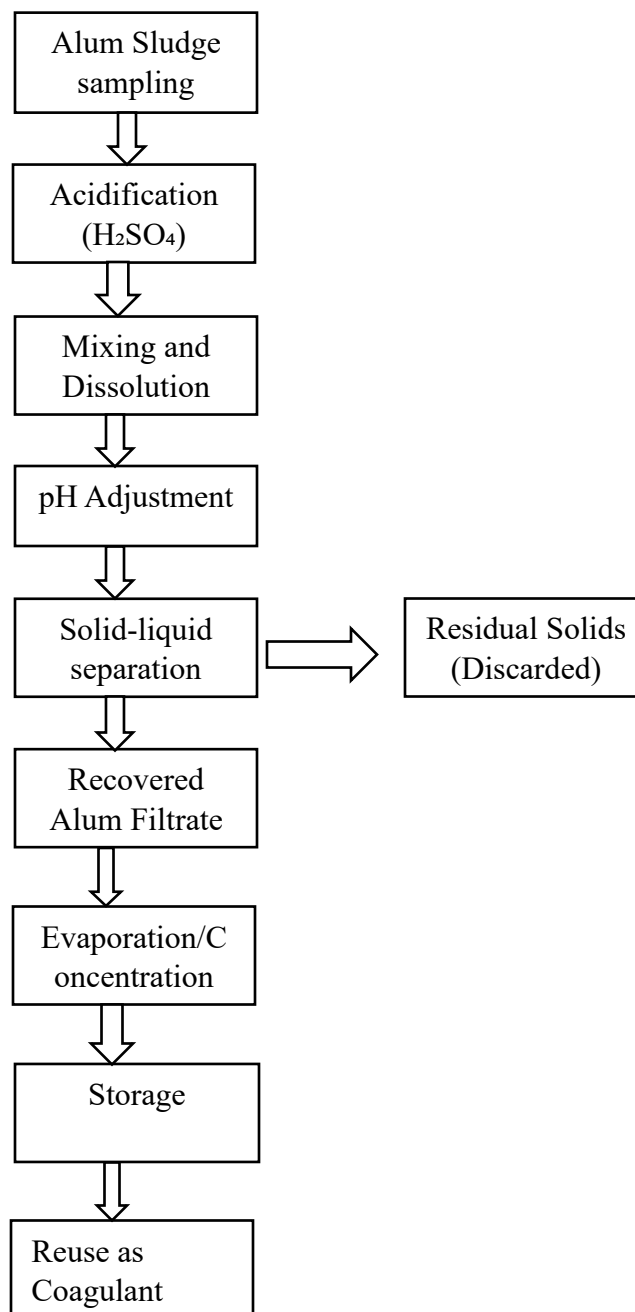
Pilot-scale demonstrations; many laboratory studies show good recovery; relatively few long-term pilot trials exist under real-plant operational constraints. There's a clear need for site-specific pilot work (Ruziqna et al., 2020). Product standardization, guidelines for quality of recovered coagulant such as impurity limits and storage stability, are not standardized; this matters for regulatory acceptance.

3. CHAPTER THREE: METHODOLOGY

Study Area Description

The study was conducted using alum sludge obtained from Manafwa Water Treatment Plant located in eastern Uganda. The plant treats raw surface water using conventional treatment processes including coagulation, flocculation, sedimentation, filtration, and disinfection. Alum (aluminium sulphate) is used as the primary coagulant, leading to the generation of alum-rich sludge as a by-product. This sludge was selected for the study due to its significant aluminium content and potential for reuse through recovery processes.

A PROCESS FLOW DIAGRAM.



Research Design

The study in accordance to specific objective 2 adopted an experimental research design aimed at evaluating and optimizing alum recovery from water treatment sludge. Laboratory-based experiments were conducted in three main phases: Characterization of alum sludge (Barakwan et al., 2022), Optimization of alum recovery process (Theam, 2020) and Performance evaluation of recovered alum. Response Surface Methodology (RSM) was used as a statistical tool to optimize process parameters and establish relationships between variables affecting alum recovery (Sverdlik, 2021).

Materials and Equipment used are; Alum sludge samples, distilled water, sulphuric acid (H_2SO_4), commercial alum for comparison, oven for drying samples, analytical balance, pH meter and thermometer, filtration apparatus, Jar test apparatus, turbidity meter, Atomic Absorption Spectrophotometer (AAS).

3.1 Assessment of the Characteristics of Alum Sludge

3.1.1 Sample Collection

Alum sludge samples were collected from the inside and outside of the sedimentation tanks at Manafwa Water Treatment Plant using purposive or judgmental sampling method as seen in *Figure 3.1* and *Figure 3.2*. Sampling was carried out for to capture differences in sludge properties caused by settling, the inside contains more settled, concentrated sludge, while the top has more water and lighter material. These were collected in clean, labeled polyethylene containers and transported to the Busitema thermodynamics laboratory in cooler boxes maintained at 5°C (Castro et al., 2024) to prevent biological degradation say bacteria and fungi that decompose organic matter in the sludge become largely inactive and chemical alteration by reducing oxidation and hydrolysis reactions that could alter aluminium speciation



Figure 3.1: Outside clarifier sludge



Figure 3.2: : Inside the clarifier sludge

3.1.2 Physical Characterization

Physical properties of the sludge were determined using Standard Methods for the Examination of Water and Wastewater. Moisture content was calculated based on weight loss after drying. Total solids (TS) was determined using gravimetric methods involving ignition at high temperatures. Spectrophotometer was used to determine residual aluminium (Castro et al., 2024).

3.1.2.1 Moisture content measurement

Moisture content was determined by measuring the loss in weight of a sludge sample after drying at a controlled temperature, which was 102°C. The weight loss represents the amount of water present in the sample (Lemma, 2023).

Apparatus and Materials are; Drying oven was set at 102°C, Analytical balance of ± 0.001 g accuracy as shown in *Figure 3.3*, Crucibles or evaporating dishes, Desiccator, Tongs or heat-resistant gloves and Alum sludge sample .



Figure 3.3: Shows an analytical balance

Procedures followed include; A clean crucible was washed and dried in an oven at 102°C for about 2 hours. It was then cooled in a desiccator and weighed. This weight was recorded as W_1 which is the weight of empty crucible, a well-mixed sludge sample was placed into the crucible. The crucible and wet sample were weighed and recorded as W_2 .

The crucible containing the sample was placed in a drying oven at 102°C for 2 hours to remove moisture (Ravenel, 2022). After drying, the crucible was removed using tongs and placed in a desiccator to cool to room temperature. This prevents moisture absorption from the atmosphere. The cooled crucible with the dried sample was weighed and recorded as W_3 . Repeat drying, the drying process was repeated until a constant weight was obtained to ensure complete removal of moisture (Lemma, 2023) the moisture content was calculated from *Equation 3-1*.

Calculation

$$MC = \frac{W_2 - W_1}{W_2 - W_3} * 100 \dots \dots \dots \text{Equation 3-1}$$

Where:

- W_1 = weight of empty crucible (g)
- W_2 = weight of crucible + wet sample (g)
- W_3 = weight of crucible + dry sample (g)

3.1.2.2 Turbidity measurement

Apparatus Required

Turbidity meter *Figure 3.4*, Clean sample cuvettes, Standard calibration solutions like 0 NTU, 20 NTU, 100 NTU, Distilled water and Tissue.



Figure 3.4: Turbidimeter

Procedures followed were; The turbidity meter was switched on and allowed it to stabilize, ensured cuvettes were clean and free from scratches or fingerprints (Bryce, 2023); filled a cuvette with a standard solution, like 0 NTU. Placed it in the meter and set the reading to zero. Repeated this with higher standards, like, 20 NTU, 100 NTU to calibrate accuracy. The water sample was gently mixed and poured the sample into a clean cuvette up to the marked level. Wiped the outside of the cuvette with a clean tissue to remove water drops or fingerprints. Inserted the cuvette into the turbidity meter in the correct orientation. Closed the lid and allowed the reading to stabilize. Recorded the turbidity value displayed in NTU (Bryce, 2023).

3.1.2.3 Gravimetric Determination of Total Suspended Solids (TSS) of Alum Sludge

The determination of Total Suspended Solids (TSS) of the alum sludge collected from Manafwa Water Treatment Plant was carried out using the standard gravimetric method as described in APHA Standard Methods (2017).

Procedures followed were; A Whatman filter paper was first placed in a drying oven at 102°C for one hour to remove all residual moisture that could interfere with the accuracy of the measurement. After drying, the filter paper was carefully transferred into a desiccator and allowed to cool to room temperature for 15 to 20 minutes (Bryce, 2023). The cooled filter paper was then weighed using an analytical balance accurate to 0.0001g and the initial dry weight was recorded as W_1 . A 10g sample of the alum sludge was carefully measured using the analytical balance and transferred into a clean beaker. The sludge sample was thoroughly mixed with 10ml distilled water using a stirring rod to ensure homogeneity before filtration, since sludge tends to settle and an unrepresentative sample would compromise the accuracy of TSS results. The pre-weighed filter paper was then assembled onto the filter funnel and the mixed sludge sample was poured slowly and carefully through the filter paper to ensure all suspended solids were retained on the filter surface.

The filter paper together with the retained solids was then carefully removed from the filtration unit and placed in the oven at 102°C for a minimum of two hours until a constant weight was achieved, ensuring that all moisture was completely driven off from the captured solids. Upon completion of drying, the filter paper with retained solids was transferred back into the desiccator and allowed to cool for 15 to 20 minutes to prevent moisture reabsorption from the atmosphere, which would give a falsely high weight. The cooled filter paper with solids was then reweighed on the same analytical balance and the final dry weight was recorded as W_2 . The entire procedure was performed in triplicate to ensure reproducibility and reliability of results, and the average value was used in the final calculation. The TSS concentration was then calculated using the following the formula in *equation 3.2*.

$$TSS = \frac{W_{sample}}{W_2 - W_1} * 1000 \dots \dots \dots \text{Equation 3.2}$$

Where:

- W_2 = final weight of filter paper with retained solids (g)
- W_1 = initial weight of filter paper before filtration (g)
- W_{sample} = mass of sludge sample used = 10g

3.1.3 Chemical Characterization

The pH of the sludge samples was measured using a calibrated pH meter. Aluminium content, which is critical for alum recovery, was determined using Atomic Absorption Spectroscopy (AAS) (Ravenel, 2022).

3.1.3.1 pH and E.C measurement

Procedure

Water quality probe meter was switched on and allowed it to stabilize, rinsed the electrode with distilled water and gently blot dry (Ma et al., 2020). The electrode was immersed in a pH 7 buffer solution (neutral). Adjusted the meter to read 7.0, then rinsed the electrode and repeated using pH 4 and pH 10 buffer solutions depending on expected sample range.

NB: This calibration ensures accurate readings.

The electrode was rinsed again with distilled water, dipped the electrode into the sample solution.; stirred gently and waited for the reading to stabilize as seen in *Figure 3.5*. Recorded the pH value and E.C values after being set displayed. After measurement, the electrode was rinsed thoroughly and stored it in appropriate storage solution for it not to dry (Ravenel, 2022).



Figure 3.5: Shows a water quality probe meter

3.1.3.2 Total Aluminium Determination in Sludge Solids.

Procedures used were; A clean, dry crucible was weighed (M_1), and 10 g of well-mixed wet alum sludge was added. The combined mass was recorded (M_3), and the wet sludge mass $M_2 = (M_3 -$

M₁) was calculated. The crucible was oven-dried at 102°C for 12 hours, cooled in a desiccator, and reweighed to obtain the dry sludge mass (M₄). The entire dried sample was transferred to a 250 mL beaker. Under a fume hood, 20 mL of concentrated HNO₃ was added, and the mixture was heated at 90°C until brown fumes ceased. After cooling, 50 mL of freshly prepared aqua regia 3:1 HCl: HNO₃ was added slowly. The beaker was reheated and evaporated gently until the volume was reduced by approximately 90%, without allowing the sample to dry completely (Ravenel, 2022).

After cooling, the digestate was diluted to 100 mL with deionized water and filtered through Whatman filter paper. The clear filtrate was analyzed for aluminium concentration (C, mg/L) using an Atomic Absorption Spectrophotometer calibrated with aluminium standards. A blank was prepared similarly (Ravenel, 2022). Each sample was analyzed in triplicate. Total aluminium content (percentage by dry mass) was calculated as seen in *Equation 3.3*

$$Al = \frac{M_4 * 1000}{C * V} * 100 \dots \dots \dots \text{Equation 3.3}$$

Where:

C = aluminium concentration from AAS (mg/L)

V = final volume of digested sample (0.1 L)

M₄ = mass of dry sludge (g)

The result was reported as percent aluminium by dry mass of sludge solids.

3.1.3.3 Residual aluminium.

Apparatus and Reagents, Spectrophotometer, Cuvettes, Pipettes, Volumetric flasks, Distilled water



Figure 3.6: Shows a spectrometer

Reagents include, Buffer solution to maintain pH 6, Standard aluminium solution for calibration, ascorbic acid, and bleaching reagent.

Procedures followed were; the spectrophotometer was calibrated at 535 nm because this specific wavelength is where the colored aluminum-dye complex has its maximum light absorption, ensuring the test is as sensitive and interference-free as possible. using a deionized water blank, measured 50 mL of the filtrated sludge into a clean mixing cylinder (Korevaar, 2021). Added ascorbic acid powder to mask any ferric iron interference; mixed until dissolved then aluminon reagent was added to the sample, covered with the stopper, and checked several times; allowed color to develop for 5–10 minutes (Ma et al., 2020). Poured half of the developed solution into a cuvette; to the remaining half in the cylinder, added the bleaching reagent and mixed. This destroys the aluminum-dye complex, creating a bleached blank that has the same matrix as the sample but no color.

The bleached blank was poured into a second cuvette, inserted it into the spectrophotometer in *Figure 3.6* and set the absorbance to zero. Replaced the blank with the colored sample cuvette and measured the absorbance at 535 nm (Korevaar, 2021). Determined the aluminum concentration (mg/L) by comparing the measured absorbance to a calibration curve prepared from aluminum standards of known concentration, finally the result was recorded as residual aluminum in mg/L (Ma et al., 2020).

3.2 Optimization of the Alum Recovery Process

The optimization of alum recovery process is affected by different variables that is to say independent and dependent variables.

3.2.1 Independent Variables

These are the process conditions you vary during experiments. Acid Concentration, e.g., 0.1 M, 0.5 M, 1.0 M, 2.5 M. pH during dissolution e.g., 2, 3, 4, 6 (Ooi et al., 2020).

3.2.2 Dependent Variables

These change as a result of the independent factors. Aluminium Recovery Efficiency (%) for example; Amount of Al^{3+} extracted from the sludge concentration of recovered alum; mg/L Al^{3+} in the recovered solution. Purity of recovered alum; Performance of recovered alum in jar tests (Aanyu, 2020)

3.2.3 Justification of the Operating Conditions Adopted During Optimization

Acid concentration was optimized because sulfuric acid is responsible for dissolving aluminum hydroxide present in sludge and converting it into soluble aluminum sulfate. Several studies have reported that increasing acid concentration enhances aluminum dissolution and recovery efficiency up to an optimum level, beyond which further increases provide minimal benefits and may increase operating costs. For example, study made in report (Ooi et al., 2020) found that acid concentration significantly influenced alum recovery, with optimum recovery achieved at approximately 4 M sulfuric acid.

pH was selected because it controls the solubility and stability of aluminum species in solution. According to studies made, aluminum recovery is maximized under acidic conditions, while excessively low or high pH values can reduce recovery due to unfavorable aluminum speciation or precipitation (Ayoub & Abdelfattah, 2022).

Temperature was maintained constant because previous studies have shown that alum recovery can be effectively achieved at ambient temperatures, reducing energy requirements and operational

costs as reported in the available literature that temperature has a less pronounced effect on alum recovery compared to acid concentration and pH (Ayoub & Abdelfattah, 2022).

Contact time was kept constant at a level sufficient to ensure complete acid-sludge interaction. Previous researchers like (Ooi et al., 2020) have indicated that once adequate mixing is achieved, acid concentration and pH become the dominant factors influencing recovery efficiency.

3.2.4 Efficiency of Alum Recovery Under Different Operating Conditions.

The alum recovery efficiency varies with changes in acid concentration and pH, indicating that both factors significantly influence the recovery process. Recovery efficiency generally increased with increasing sulfuric acid concentration up to an optimum level, after which further increases produced only marginal improvements. Similarly, pH has a pronounced effect on alum recovery efficiency. Higher recovery efficiencies are observed under moderately acidic conditions, with the optimum occurring around pH 3 (Theam, 2020) . Excessively low or high pH values resulted in reduced recovery efficiency due to changes in aluminum speciation and the potential precipitation of aluminum compounds. The response surface analysis showed that the combined effect of acid concentration and pH significantly influenced alum recovery (Ooi et al., 2020).

3.2.5 Experimental Design Using RSM

Response Surface Methodology (RSM) was employed to optimize the process parameters affecting alum recovery from water treatment sludge. The optimization focused on two independent variables, namely pH and acid concentration, because these parameters greatly influence the dissolution of aluminum compounds and the efficiency of alum recovery (Theam, 2020) . The experimental design and statistical analysis were carried out using Design-Expert software.

A Central Composite Design (CCD) under RSM was selected to evaluate the combined effects of pH and acid concentration on the recovery efficiency of alum. The selected ranges for the factors were pH values of 2–6 and sulphuric acid concentration of 0.5–2.5 M. These ranges were chosen based on preliminary experiments and findings from previous studies indicating that acidic conditions favor alum dissolution and recovery. In the software, pH was entered as factor A while

acid concentration was entered as factor B (Theam, 2020) . The response variable used for optimization was alum recovery efficiency (%). The experimental design matrix was generated automatically by the software after defining the factors and their levels. The design consisted of factorial points, axial points, and center points to allow accurate estimation of linear, interaction, and quadratic effects of the variables. The center points were included to estimate experimental error and determine the adequacy of the model. Each experimental run generated by the software was conducted in the laboratory according to the specified combinations of pH and acid concentration.

After conducting the experiments, the obtained recovery efficiency values were entered into the Design-Expert software for statistical analysis. Analysis of Variance (ANOVA) was then performed to evaluate the significance of the model and the effects of the independent variables. The significance of each factor and their interaction was determined using F-values and p-values at a 95% confidence level. A quadratic polynomial model was developed by the software to describe the relationship between the process variables and the response. The adequacy of the developed model was evaluated using statistical indicators such as coefficient of determination (R^2), adjusted R^2 , predicted R^2 , adequate precision, and lack-of-fit test. Diagnostic plots including predicted versus actual values and residual plots were also examined to verify the suitability and reliability of the model. Three-dimensional (3D) response surface plots and contour plots were generated to illustrate the interaction effects between pH and acid concentration on alum recovery efficiency.

Numerical optimization was finally carried out in Design-Expert software to determine the optimum operating conditions that maximize alum recovery efficiency. The optimization criteria were set such that pH and acid concentration remained within the selected experimental ranges while the recovery efficiency was maximized. The software generated the optimum conditions together with the predicted maximum recovery efficiency and desirability value. Validation experiments were then performed under the optimized conditions to compare the experimental results with the predicted values and confirm the reliability of the optimization model.

3.2.6 Regression Model Development

The experimental data were fitted to a second-order polynomial regression model. The final model in terms of factors is presented in Equation 3-4

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

3.2.7 Acid Extraction Procedure

A fixed mass; 10 g sample mass was selected to maintain a 1:2 (w/v) solid-to-liquid ratio while ensuring complete mixing within the reaction vessel of prepared sludge which was weighed using an analytical balance and placed in a conical flask. A 20ml volume of sulphuric acid of 0.5, 0.8, 1.5, 2.2 M, and 2.5M concentration was added to the sludge. The mixture was stirred continuously using a stirrer to ensure proper mixing and contact between the acid and sludge particles while pH was maintained using sodium hydroxide as seen in *Appendix A*, left to stand for contact time of 60 minutes which was maintained for the all experiments (Theam, 2020) .

3.2.8 Solid-Liquid Separation

After the reaction period, the mixture was filtered using Whatman filter paper to separate the solid residue from the liquid extract seen in *Figure 3.7*. In some cases, centrifugation can be used to enhance separation efficiency but in this study gravity filtration technique was used. The filtrate containing dissolved aluminium ions was stored for evaporation at temperature of 90°C which was maintained during the process.



Figure 3.7: Solid-liquid separation

Alum Recovery; It was evaporated using a hot plate at a temperature of 90°C until alum crystals remained behind, the alum which is aluminium sulphate was confirmed by using sodium hydroxide for Aluminium ions and Barium nitrate for sulphate ions. The recovered alum was then dried and stored for further analysis (Aanyu, 2020).

3.2.9 Determination of Recovery Efficiency

The aluminium concentration in the recovered solution was determined using AAS. The efficiency of alum recovery was calculated using *Equation 3-2* (Aanyu, 2020).

$$\text{Recovery efficiency} = \frac{\text{Recovered alum}}{\text{Total solids}} * 100 \dots \dots \text{equation 3.4}$$

3.3 Assessment of the Performance of Recovered Alum.

3.3.1 Characterization of Recovered Alum

The recovered alum was evaluated for its physical and chemical properties. Visual inspection was carried out to assess its color and crystalline structure as seen in *Figure 3.8*. The pH of the alum solution was measured (Mora et al., 2022).



Figure 3.8: showing a sample of recovered alum

3.3.2 Jar Test Procedure

The coagulation efficiency of the recovered alum was assessed using a standard jar test apparatus in *Figure 3.9*. Raw water samples were collected from the plant source as seen in *Appendix A* and divided into beakers. Different dosages of recovered alum (30–80 mg/L) were added to the beakers. Rapid mixing at 120 rpm was performed for 1 minute to ensure proper dispersion, followed by slow mixing for 15 minutes at 30 rpm to facilitate floc formation. The samples were then allowed to settle for 15 minutes (Theam, 2020) .



Figure 3.9: : Shows a jar test

3.3.3 Performance Evaluation

The treated water was analyzed for turbidity using a turbidity meter, size of flocs formed, Electric Conductivity, pH, optimal dosage, color and total suspended solids. The efficiency of turbidity removal was found and calculated from the formula below in equation 3.5 (Mora et al., 2022).

$$\text{Turbidity removal efficiency} = \frac{C_1 - C_2}{C_1} * 100 \dots \dots \text{equation 3.5}$$

Where, C_1 = Initial turbidity

C_2 = Final turbidity.

3.3.4 Comparison with Commercial Alum

The same experimental procedure was repeated using commercial alum under identical conditions. The performance of recovered alum was compared with commercial alum based on turbidity removal efficiency, settling time, optimal dosage, and overall treatment effectiveness (Mora-León et al., 2022).

The data was analyzed and presented using tables and graphs. Comparative analysis was conducted to evaluate the effectiveness of recovered alum and its suitability for reuse in water treatment processes.

3.3.5 Quality Control and Assurance

All instruments were calibrated prior to use to ensure accuracy. Analytical procedures were carried out in accordance with standard methods. Duplicate samples and repeated experiments were conducted to ensure reliability and reproducibility of results. Table 3.1 outlines each common instrument in this type of wastewater study (Mora et al., 2022).

Table 0.1: How to calibrate different instruments.

Instrument	What to Calibrate & How	Acceptance Criteria
pH Meter	Standard buffer solutions (e.g., pH 4.0, 7.0, 10.0) traceable to NIST; ensure temperature compensation.	Slope between 95-100%; stable reading within ± 0.02 pH units.
Analytical Balance	Certified class weights (e.g., 1g, 10g, 100g) at min, mid, and max operating range.	Measured vs. actual weight deviation within $\pm 0.1\%$.
Spectrophotometer	Wavelength accuracy with holmium oxide filter; absorbance scale with certified standard solutions (e.g., potassium dichromate).	Wavelength ± 1 nm of standard; Absorbance error within $\pm 1\%$ or 0.01 A at key wavelengths.
Turbidity Meter	Gelex secondary standards or formazin primary standards (e.g., 0.1, 10, 100 NTU) as per Standard Method 2130 B.	Readings within $\pm 5\%$ of the standard's stated value.

3.4 Financial Analysis Of The Recovered Alum Versus Commercial Alum.

The financial analysis of alum recovery from water treatment sludge at Manafwa Treatment Plant was carried out using Microsoft Excel as the main analytical tool. The analysis considered only direct operational costs and benefits, since alum recovery does not involve depreciation of assets in the conventional sense. Cost inputs included expenditures on chemicals such as sulphuric acid and neutralizing agents (sodium hydroxide), equipment for mixing and heating, packaging and labor costs associated with operating the recovery process.

3.4.1 Cost of Recovering One Kilogram of Alum

Based on the optimized conditions of 10 g sludge, 20 mL of 2.17 M H_2SO_4 , and 0.9 g NaOH for pH adjustment, a total of 1,063 g of sludge, 0.03 litres of concentrated acid, and 95.7 g of NaOH were required to recover one kilogram of alum at 94.1% efficiency.

Table 0.2: Estimated cost of recovering one kilogram of alum

Item	Total Cost (UGX)
85% H ₂ SO ₄	1,364
Sodium Hydroxide	670
Electricity	3,000
Packaging	1,000
Total	6,034

The total cost of recovering one kilogram of alum was estimated at UGX 6,034, which is significantly cheaper than commercial alum procurement bought at UGX 15,000, confirming the economic viability of alum recovery at Manafwa WTP.

Benefits were quantified in terms of reduced purchases of commercial alum, savings from minimized sludge disposal, and potential environmental compliance advantages (Mora et al., 2022). These values were organized into a cash flow model, with the initial investment recorded in Year 0 and subsequent years reflecting net annual savings. To assess economic feasibility, three indicators were applied: Net Present Value (NPV), Payback Period, and Profitability Index (PI). NPV was calculated using equation 3.6 by discounting future cash flows at a 12% rate and subtracting the initial investment, thereby determining the present value of the project (Korevaar, 2021). Payback Period was computed using equation 3.8 by dividing the initial investment by annual net savings, indicating the time required to recover costs. PI was derived as the ratio of the present value of benefits to the present value of costs using equation 3.7, providing a measure of profitability relative to investment. Scenario analysis was also performed by varying process parameters say acid concentration and pH, allowing comparison of financial outcomes under different operating conditions. Excel's built-in functions (=NPV, =IRR, and ratio calculations) were employed to ensure accuracy and reproducibility of results.

Net Present Value (NPV)

$$NPV = \left[\sum_i^n \frac{Cf}{(1+r)^n} \right] - i_0 \dots \dots \dots \text{equation 3.6}$$

Where;

$\frac{1}{(1+r)^n}$ - discount factor i_0 - initial cost of investment

Cf - net annual cash flow,

r - discount rate

n – period

The Profitability Index

$$P.I = \frac{\text{Present Value of Net Annual Cashflows}}{\text{Initial Cost of Investment}} \dots \dots \dots \text{equation 3.7}$$

$$\text{The payback period} = \frac{\text{Initial Cost of Investment}}{\text{Net Annual Cashflows}} \dots \dots \dots \text{equation 3.8}$$

4. CHAPTER FOUR: RESULTS AND DISCUSSION

Introduction

This chapter presents the results obtained from the experimental investigation on alum recovery from water treatment sludge. The findings are discussed in relation to the study objectives, which included characterizing alum sludge, optimizing the recovery process, evaluating the performance and carrying out a financial analysis of the recovered alum. The results are presented using tables and descriptive analysis, followed by detailed discussion to interpret the observed trends.

4.1 Characteristics of Alum Sludge

4.1.1 Physical Characteristics of Alum Sludge

The physical properties of the alum sludge samples collected from Manafwa Water Treatment Plant are presented in *Table 4.1*.

Table 4.1: Physical Characteristics of Alum Sludge

Parameter	Value
Moisture content (%)	
Sample On Top Of The Tank	95.8
Sample From Inside The Tank	97.6
Total suspended solids	
Sample On Top Of The Tank	106470 mg/L
Sample From Inside The Tank	71300 mg/L
Turbidity (Ntu)	
Sample On Top Of The Tank	507
Sample From Inside The Tank	624

The results indicate that the sludge had a high moisture content of 97.6% and 95.8%, which is typical for alum sludge generated during sedimentation processes. High moisture content implies that the sludge contains a large proportion of water, (Stewart, 2021) stated that, which can influence handling, storage, and treatment processes.

The total suspended solids content of 106,470 and 71,300 mg/L or 106.47g and 71.30g reflects the amount of solid material present after moisture removal. The relatively moderate total suspended solids suggest that the sludge is primarily inorganic, dominated by aluminium hydroxide precipitates formed during coagulation as documented in (Tahraoui et al., 2024).

The sludge was found to be black-greyish color and gelatinous texture which are characteristics of alum sludge and are attributed to the accumulation of suspended solids and flocculated particles just as what was reported by (Truong et al., 2021). These properties confirm that the sludge is suitable for further processing and recovery of aluminium.

4.1.2 Chemical Characteristics of Alum Sludge

Table 4.2: Chemical Characteristics of Alum Sludge

Parameter	Value
pH	
Sample On Top Of The Tank	6.664
Sample From Inside The Tank	6.505
Residual Aluminium (Mg/L)	
Sample On Top Of The Tank	0.010
Sample From Inside The Tank	0.050
Total Aluminium by % mass	
Sample On Top Of The Tank	6.8
Sample From Inside The Tank	8.5
Electric conductivity (µS/cm)	
Sample On Top Of The Tank	144.3
Sample From Inside The Tank	215

The pH of the sludge was found to be slightly acidic to neutral, which is consistent with the use of alum as a coagulant as stated by (Ooi et al., 2020). This pH range is favorable for subsequent acid extraction processes, as minimal adjustment may be required as seen in *Table 4.2*. The residual aluminium concentration of approximately 0.010 and 0.055 mg/L and total aluminium by percentage mass of 6.8 and 8.5 confirms that the sludge contains a significant amount of

recoverable alum which was also clearly stated by (Hamzah et al., 2022) and (Tahraoui et al., 2024). This high concentration makes the sludge a valuable resource rather than a waste product. The turbidity value of 507 and 624 NTU and electric conductivity of 144.3 and 215 indicates a high level of suspended particles, which further confirms the presence of coagulated material as reported by (Ayoub & Abdelfattah, 2022). This aligns with the expected characteristics of sludge generated during water treatment.

4.2 Optimization of Alum Recovery Process

4.2.1 Optimization of pH and acid concentration in the alum recovery process using RSM.

Only pH and acid concentration were optimized because they are the most influential parameters controlling alum dissolution and recovery efficiency during the acidification process. Acid concentration determines the availability of hydrogen ions required to dissolve aluminium compounds from the sludge, while pH directly affects aluminium solubility and precipitation. Optimizing these two parameters therefore provides the greatest improvement in alum recovery efficiency with minimal experimental complexity, time, and cost. Additionally, (Ooi et al., 2022) identified pH and acid concentration as the primary factors influencing alum recovery performance, making them suitable variables for optimization using Response Surface Methodology (RSM).

$$\text{Recovery efficiency} = 85.12 + 16.60 A - 3.27 B - 0.6122 AB - 8.91 A^2 - 3.03 B^2 \dots\dots\dots \text{Equation 3-4}$$

Where:

A = Acid concentration (M)

B = pH (coded value)

Table 4.3: Experimental runs

Std	Run	Factor 1A: Acid Conc mol/L	Factor 2: pH	Response 1 Recovery Efficiency %
3	1	0.8	5.4	53.2
12	2	1.5	4	85
9	3	1.5	4	85.8
7	4	1.5	2	80.2
1	5	0.8	2.6	65.1
2	6	2.2	2.6	92.5
5	7	0.5	4	40.3
6	8	2.5	4	96.6
8	9	1.5	6	80.2
4	10	2.2	5.4	78.2
11	11	1.5	4	86
10	12	1.5	4	84.8
13	13	1.5	4	84.1

Table 4.3 presents the experimental runs and corresponding recovery efficiencies used for RSM modeling. The recovery efficiency obtained from each run was used for statistical analysis and determination of optimal operating conditions, as done by (Theam, 2021) who managed to carry out 13 runs and had optimal conditions of pH 3 and 2.0M.

Table 4.4: ANOVA for the Response Surface Quadratic Model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2837.74	5	567.55	21.14	0.0004	significant
A-Acid Conc	2183.15	1	2183.15	81.33	< 0.0001	
B-pH	84.94	1	84.94	3.16	0.1185	
AB	1.44	1	1.44	0.0536	0.8235	
A ²	545.87	1	545.87	20.33	0.0028	
B ²	63.29	1	63.29	2.36	0.1685	
Residual	187.91	7	26.84			
Lack of Fit	185.52	3	61.84	103.41	0.0003	significant
Pure Error	2.39	4	0.5980			
Cor Total	3025.65	12				

Table 4.4 presents the ANOVA results for the quadratic model. $R^2 = 0.9379$, Adjusted $R^2 = 0.8935$, Predicted $R^2 = 0.5626$. The ANOVA results showed that the model was statistically significant, with an F-value of 21.14 and a p-value of 0.0004, indicating that the selected process parameters significantly affected alum recovery efficiency. Similar findings were reported by (Ooi et al., 2020), who found that optimization models effectively predicted aluminium recovery efficiencies above 80%. Acid concentration (Factor A) was the most significant parameter, with an F-value of 81.33 and p-value less than 0.0001. This shows that increasing sulphuric acid concentration greatly improved alum recovery. Similar results were obtained by (Hassan., et al., 2021), who reported recovery efficiencies above 84% at higher acid concentrations.

pH (Factor B) was not statistically significant ($p = 0.1185$), indicating that pH alone had less influence on recovery efficiency. Similar observations were made by (Ooi et al., 2020), who concluded that acid dosage contributed more strongly to aluminium recovery than pH adjustment.

The interaction between acid concentration and pH (AB) was also not significant ($p = 0.8235$), meaning the combined effect of the two variables had little influence on recovery efficiency. Similar weak interaction effects were reported by (Hassan., et al., 2021). The quadratic effect of acid concentration (A^2) was significant ($p = 0.0028$), showing that recovery efficiency increased up to an optimum acid concentration before leveling off. Similar trends were observed by (Theam, 2021). However, the quadratic effect of pH (B^2) was not significant ($p = 0.1685$), indicating minimal curvature effects of pH within the tested range. The significant lack of fit ($p = 0.0003$) suggests that other factors such as temperature, reaction time, or sludge characteristics may also influence alum recovery, as reported by (Ayoub & Abdelfattah, 2022). Overall, the results confirm that acid concentration was the dominant factor controlling alum recovery efficiency.

4.2.2 Response surface Model plots

A plot of predicted Vs actual recoveries.

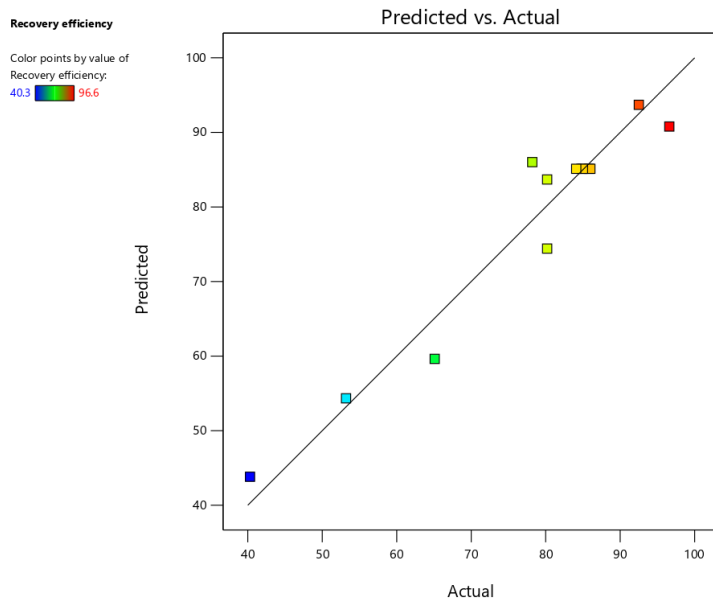


Figure 4.1: A plot of predicted Vs Actual recoveries.

The predicted versus actual plot for alum recovery efficiency showed strong agreement between model-predicted and experimentally obtained values, with data points falling closely along the line of perfect fit across a recovery range of 40.3% to 96.6%, confirming the adequacy and reliability

of the developed model. These results are consistent with literature findings. (Ooi et al., 2020) reported a predicted recovery of 70.3% and an experimentally validated recovery of 68.8% using RSM-optimized acid leaching, with a marginal discrepancy of 2.2%, which aligns with the mid-range clustering observed in this study around 65–75%. (Theam, 2021) achieved a maximum alum recovery of 84.5% through acidification, with the recovered coagulant attaining 96% turbidity removal comparable to fresh coagulant, consistent with the upper-range data points in this study. At the highest recovery levels, a recovery of 97.5%, corresponding to 99.5% of the RSM-predicted value has also been reported, reflecting the upper boundary captured in the present dataset. At the lower end, parametric studies have reported recoveries of up to 69.03% under less optimized conditions, similarly explaining the 40–55% values observed in this study's experimental runs.

Overall, the strong correlation between predicted and actual values, alongside consistency with published literature, validates the robustness of the model and supports the conclusion that the optimized conditions identified in this study can reliably achieve high alum recovery efficiency from water treatment sludge.

A plot of a 3D surface

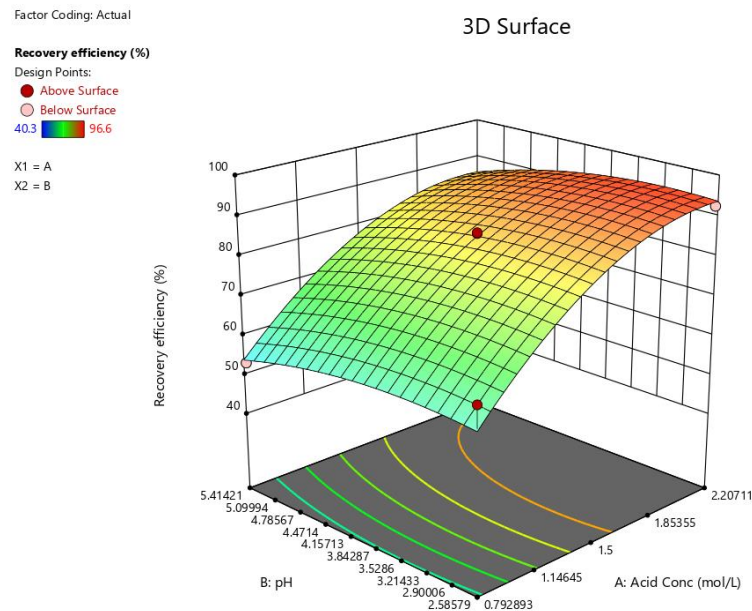


Figure 4.2: A 3D Surface plot.

The 3D response surface plot illustrates the combined effect of acid concentration (A) and pH (B) on alum recovery efficiency, which ranged from approximately 40.3% to 96.6%. The surface shows that recovery efficiency increased progressively with increasing acid concentration and decreasing pH, with the highest recoveries achieved at elevated acid concentrations and lower pH values, while lower recoveries were associated with higher pH and minimal acid dosage.

These trends are well supported in the literature (Ooi et al., 2020) and (Theam, 2021) similarly demonstrated that acid concentration was a significant factor in aluminum recovery from water treatment sludge, reporting an optimum recovery of 68.8% at 4 M acid concentration, where recovery initially increased with acid dose before declining at concentrations exceeding 4 M due to sludge solidification. This behavior is reflected in the surface curvature observed in this study, where recovery responds strongly to acid concentration within the tested range. With respect to pH, a parametric study reported that the optimum pH for alum recovery was 1.50, at which maximum aluminum release and sludge volume reduction were achieved. This is consistent with the present findings, where the lowest pH levels corresponded to the highest recovery efficiencies on the surface plot, confirming that an acidic environment is critical for effective alum solubilization from sludge.

At the upper recovery range, (Theam, 2021) recorded a maximum alum recovery of 84.5% under optimized acidification conditions, while (Shahzad et al., 2024) achieved 97.5% recovery under tightly controlled pH and acid dosage, both of which correspond to the red-zone region on the surface where acid concentration and pH interact most favorably. Overall, the 3D surface plot confirms that the interaction between acid concentration and pH is a key determinant of alum recovery efficiency, and the results of this study align well with trends reported across the literature.

A contour plot for both pH and acid concentration.

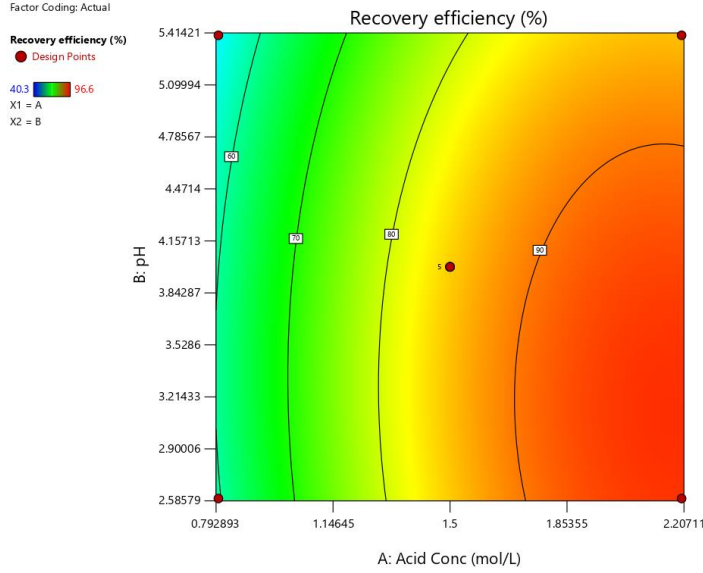


Figure 4.3: Contour plot for both pH and concentration

The contour plot depicts the interactive effect of acid concentration (A) and pH (B) on alum recovery efficiency, ranging from 40.3% to 96.6%. The contour lines reveal that recovery efficiency increased substantially with increasing acid concentration, shifting from the green-blue low-efficiency zone on the left toward the red high-efficiency zone on the right. The influence of pH, while present, was comparatively less pronounced than that of acid concentration, as the contour lines run more vertically than horizontally, indicating that acid concentration was the dominant factor governing recovery in this study.

This observation is consistent with findings reported by (Ooi et al., 2020), who established that acid concentration was the most critical variable in aluminum recovery from water treatment sludge, with optimal recovery of 68.8% achieved at 4 M acid concentration. The study similarly noted that recovery improved with increasing acid dose up to an optimum, beyond which performance declined, a trend reflected in the curvature of the contour lines at higher acid concentrations in the present plot.

Regarding the role of pH, a parametric study identified an optimum pH of 1.50 as the condition yielding maximum aluminum release from sludge. This aligns with the lower pH region of the present contour plot, where higher recovery efficiencies are observed, confirming that strongly acidic conditions favor alum solubilization. (Theam, 2021) further corroborated this, achieving a

maximum alum recovery of 84.5% under acidified conditions, with the recovered coagulant performing comparably to fresh alum in turbidity removal.

At the highest recovery zone captured in the upper-right region of the contour plot, recoveries approaching 96.6% were recorded, which is comparable to the 97.5% reported in optimized RSM studies on drinking water treatment residuals. To conclude, the contour plot confirms that maximizing acid concentration within a low pH environment is the most effective strategy for achieving high alum recovery efficiency, consistent with the broader body of literature.

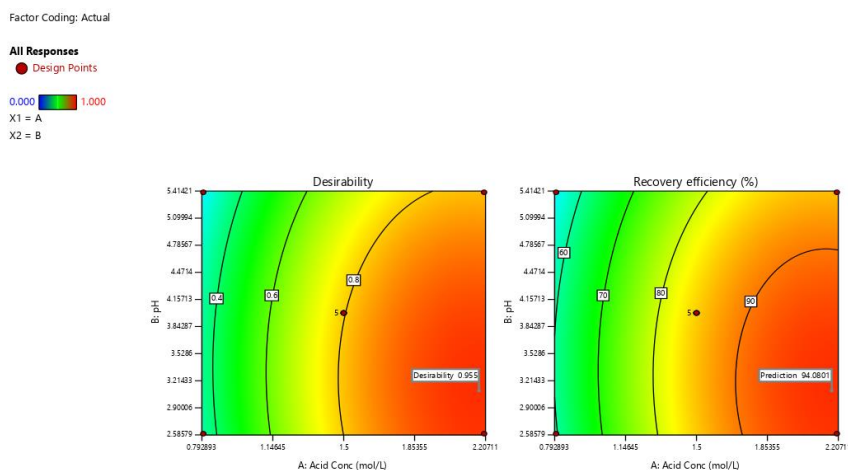


Figure 4.4: Contour plots for, pH and acid concentration.

The optimization contour plots present the desirability function and the corresponding predicted recovery efficiency for alum recovery as a function of acid concentration (A) and pH (B). The desirability plot achieved a value of 0.955, reflecting a near-optimal solution, while the recovery efficiency contour plot recorded a predicted optimum of 94.08% under the identified optimal conditions. Both plots consistently showed that higher acid concentrations combined with lower pH values drove the system toward maximum desirability and recovery, with the red zone on both plots converging at the higher acid concentration and lower pH region.

The predicted optimum recovery of 94.08% obtained in this study compares favorably with values reported in the literature. (Ooi et al., 2020) employed RSM optimization for aluminum recovery from water treatment sludge and reported a predicted recovery of 70.3%, experimentally validated at 68.8%, under optimal conditions of 4 M acid concentration and 90°C. While their recovery was comparatively lower, this is attributable to differences in sludge composition, acid type, and operating temperature, whereas the present study achieved a higher predicted optimum through refined parameter selection guided by the desirability function approach.

(Theam, 2021) reported a maximum alum recovery of 84.5% through acidification of coagulation sludge, which falls below the 94.08% predicted in this study, further demonstrating the advantage of applying simultaneous multi-response optimization via desirability functions to identify conditions that collectively maximize recovery performance. At the highest end of reported recoveries, a desirability-based RSM optimization study on drinking water treatment residuals achieved 97.5% actual recovery corresponding to 99.5% of the predicted value, which represents a close upper benchmark to the present study's predicted optimum of 94.08%.

In conclusion, the high desirability score of 0.955 and the predicted recovery of 94.08% confirm that the optimization conducted in this study successfully identified near-optimal process conditions, and the results are well-positioned within the range of recoveries documented in the literature, validating both the model and the experimental approach adopted.

4.2.3 Optimized Conditions

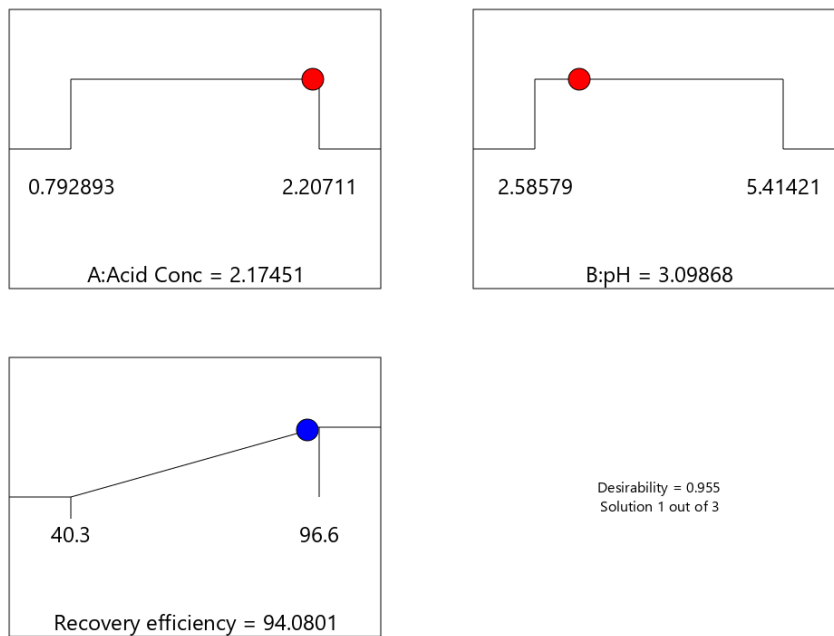


Figure 4.5: Optimal values for pH and acid concentration

The numerical optimization identified an optimal acid concentration of 2.17451 mol/L and pH of 3.09868, yielding a predicted alum recovery efficiency of 94.0801% with a desirability score of 0.955, selected as the best among three generated solutions.

These results compare favorably with the literature. (Ooi et al., 2020) reported an optimum acid concentration of 4 M with a predicted recovery of 70.3% and experimentally validated recovery of 68.8%, noting that recovery declined beyond this concentration due to sludge solidification. The higher recovery achieved in this study at a considerably lower acid concentration demonstrates the advantage of co-optimizing acid concentration and pH simultaneously through the desirability function, rather than optimizing variables individually. Recovery from acid leaching of water treatment sludge has been broadly reported to range between 40 and 100% depending on process conditions, and the 94.08% predicted here falls within the upper range of this spectrum. Regarding pH, (Ayoub & Abdelfattah, 2022) reported an optimum pH of 1.50 for maximum alum release in their Egyptian water treatment plant case study, which is more acidic than the 3.09868 identified here, yet this study achieved comparably high recovery, demonstrating that moderate acidity is sufficient when acid concentration is simultaneously optimized. (Theam, 2021) achieved recoveries of 73.26% and 62.73% from PACl and alum sludge respectively at pH 2.0, which are

considerably lower than the 94.08% predicted here. (Mattoso et al., 2024) reported a maximum recovery of 94.2% under optimized conditions, closely matching the 94.0801% of this study and providing strong external validation. At the lower end, (Ruziqna et al., 2020) reported 61% recovery at pH 1.0, (Koul & Bhat., 2022) achieved 84.18% at pH 2.67, both falling below the present optimum, reflecting the improvement achievable through systematic RSM-based multi-variable optimization. Overall, the desirability score of 0.955 and predicted recovery of 94.0801% confirm that the optimal conditions identified are practically viable and competitive with benchmarks in the literature.

4.3 Performance of Recovered Alum

4.3.1 Physical and Chemical Properties

Table 4.5: Physical and Chemical Properties

Parameter	Recovered Alum	Commercial Alum
Appearance	Off-white	White
pH	3.2	3.0
Aluminium by mass (%)	9.4	15.8
Solubility	Good	Excellent

The recovered alum showed slightly lower purity compared to commercial alum as seen in *Table 4.8*, which may be due to the presence of minor impurities from the sludge. However, its properties were still within acceptable limits for water treatment applications recorded in (Schmidt, 2003).

4.3.2 Jar Test Results (Coagulation Performance)

Table 4.6: Jar Test Results (Optimum dosage)

Dosage (Mg/L)	Recovered (%)	Alum Commercial (%)	Alum
30	55	63.0	
40	60	69.2	
50	68	99.1	
60	75	99.3	
70	87	99.4	
80	94	99.6	

The results show that turbidity removal increased with increasing dosage seen in *Table 4.6*. The dosage range for recovered alum was 30-80 mg/L, where maximum efficiency was achieved in relation to (Aanyu, 2020) and (Hassan, et al., 2021) who recorded 70 mg/L optimal dosage in their results. The change in result was the type of raw water used for jar test which was too turbid.

4.3.3 Floc Formation and Settling Behavior

The recovered alum produced visible flocs that were slightly smaller compared to those formed by commercial alum. However, the flocs were stable and settled effectively within the given time. This indicates that although the recovered alum had slightly lower purity, its coagulation mechanism remained effective in relation to (Aanyu, 2020) who achieved slightly bigger flocs results. This is due to the type of raw water used for jar test which was too turbid.

4.4 Financial Analysis Of The Recovered Alum Versus Commercial Alum.

Assumptions

Consider transport of 20,000 UGX, sulphuric acid of UGX 20,000 per liter, electricity of UGX 10,000, material of UGX 80,000, labor of 50.000 and packaging of UGX 2,000.

4.4.1 Net Present Value (NPV) Calculation

Formula:

$$NPV = \left[\sum_i^n \frac{Cf}{(1+r)^n} \right] - i_0$$

Where: $n=10$ years

$C_f = \text{UGX } 65,845,000$ per year

$r = 12\% = 0.12$

$I_0 = \text{UGX } 80,000,000$

4.4.2 Discounted Cash Flows.

Table 4.7: Discounted Cash Flows

Year	Cash Flow (UGX)	Present Value (UGX)
1	65,845,000	58,790,179
2	65,845,000	52,491,231
3	65,845,000	46,867,170
4	65,845,000	41,845,688
5	65,845,000	37,362,221
6	65,845,000	33,359,126
7	65,845,000	29,784,934
8	65,845,000	26,593,691
9	65,845,000	23,744,367
10	65,845,000	21,200,328
Total Present Value of Cash Flows		372,038,935

$$\text{NPV} = 372,038,935 - 80,000,000 = 292,038,935$$

Since $\text{NPV} > 0$, the project is financially viable and profitable.

4.4.3 Profitability Index (Pi)

Formula:

$$P.I = \frac{\text{Present Value of Net Annual Cashflows}}{\text{Initial Cost of Investment}}$$

$$P.I = \frac{372,038,935}{80,000,000}$$

$$P.I = 4.65$$

For every 1 UGX invested, the project returns 4.65 UGX in present value terms. Since $PI > 1.0$, the project is highly profitable.

4.4.4 Payback Period

$$\text{Payback period} = \frac{80,000,000}{65,845,000} = 1.21 \text{ years}$$

Payback period is approximately 1 Year and 3 months

4.5 Financial Analysis of Commercial Alum Procurement

The current practice at Manafwa Water Treatment Plant involves purchasing commercial alum at a market price of UGX 15,000 per kilogram. Assuming an annual alum requirement of 5,000 kg, the annual expenditure on commercial alum is:

$$\text{Annual Cost} = 5,000 \times 15,000 = 75,000,000 \text{ UGX}$$

Over a project life of 10 years:

$$\text{Total Cost} = 75,000,000 \times 10 = 750,000,000 \text{ UGX}$$

Assuming no residual value and no revenue generation, the Net Present Value (NPV) of relying solely on commercial alum is negative because it represents a continuous operational expense. At a discount rate of 10%, the present value of the 10-year alum procurement cost is:

$$PV = 75,000,000 \times 1 - (1+0.10)^{-10} = 460,837,500 \text{ UGX}$$

Thus, the plant would spend approximately UGX 460.84 million (present value) over ten years on commercial alum purchases alone.

Comparison with Recovered Alum

Parameter	Commercial Alum	Recovered Alum
Alum Cost (UGX/kg)	15,000	Lower than commercial alum
Annual Alum Cost (UGX)	75,000,000	Significantly reduced
Initial Investment	None	Required for recovery system
NPV (10 years)	460,837,500 UGX	292,038,935 UGX
Profitability Index	Not applicable	4.65
Payback Period	Not applicable	1.25 years
Resource Recovery	No	Yes
Sludge Disposal Cost	High	Reduced

The analysis demonstrates that continued dependence on commercial alum requires substantial recurring expenditure, amounting to a present value cost of approximately UGX 460.84 million over ten years. In contrast, the alum recovery system converts waste sludge into a valuable coagulant, reducing the need for fresh alum purchases. The recovered alum project generated a positive NPV of UGX 292,038,935, a profitability index of 4.65, and a payback period of approximately 1 year and 3 months, confirming its economic superiority over the conventional practice of purchasing commercial alum. Therefore, alum recovery offers both financial savings and environmental benefits through resource recovery and reduced sludge disposal requirements.

5. CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSIONS

Alum sludge from the Manafwa WTP is a viable resource due to its high residual aluminium content (0.055 mg/L), high moisture (97.6%), and near-neutral pH (6.3). These properties make alum recovery both technically feasible and economically beneficial.

Optimal recovery conditions were identified as 2.17 M H₂SO₄, pH 3 maintained at a constant temperature of 90°C and contact time of 60 minutes. Under these conditions, an alum recovery efficiency of 94% was achieved.

Recovered alum showed performance close to commercial alum, with about a 5% difference in turbidity removal at 80mg/L. The optimal dosage of recovered alum was found to be 80 mg/L, confirming its suitability as a coagulant.

The financial analysis showed that alum recovery is economically viable, with high profitability, quick cost recovery (about 1 year and 3 months), and reduced dependence on commercial alum.

5.2 RECOMMENDATIONS

Future studies should investigate the long-term performance and stability of recovered alum in continuous water treatment systems to assess its reliability under varying operational conditions. And also methods on how to dispose the residue from the filtration process should be revised.

To improve quality, a pre-treatment step should be introduced to enhance the purity of recovered alum. Additional methods such as activated carbon filtration can help reduce impurities and close the purity gap with commercial alum.

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APPENDIX A



Figure 7.1: Packaging samples in cooler boxes



Figure 7.2: Raising and monitoring the pH using a pH meter and Sodium Hydroxide.

APPENDIX B

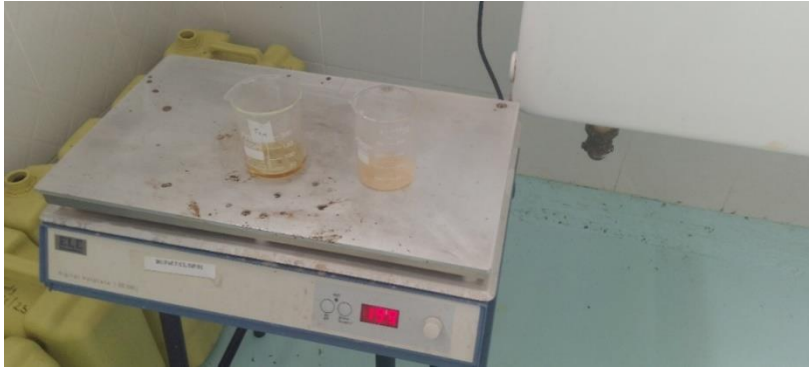


Figure 7.3: Heating of a mixture of acid and sludge filtrate on a hotplate



Figure 7.4: Sample collection