UGANDA CHRISTIAN UNIVERSITY

A Centre of Excellence in the Heart of Africa

POTENTIAL OF ALUM SLUDGE FROM KATOSI DRINKING WATER TREATMENT PLANT FOR REDUCTION OF PHOSPHORUS IN WASTEWATER TREATMENT PLANT EFFLUENT IN UGANDA

SHARON ANNEYS NAAYO

RM22M45/008

PROJECT SUPERVISOR: ELEANOR WOZEI (PhD)

A DISSERTATION SUBMITTED TO THE FACULTY OF ENGINEERING, DESIGN, AND TECHNOLOGY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF A DEGREE OF MASTER OF SCIENCE IN WATER AND SANITATION OF UGANDA CHRISTIAN UNIVERSITY

MUKONO, UGANDA.

FEBRUARY 2024

ABSTRACT

In response to the global surge in wastewater production due to population growth and economic development, improving wastewater treatment is crucial. The presence of excess nutrients, particularly phosphorus (P), in wastewater effluent poses a significant threat of eutrophication. This study, therefore, set out to assess the potential of reusing alum sludge from the Katosi Drinking Water Treatment Plant (KDWTP) as a phosphorus adsorbent in wastewater effluent, aiming at finding a more sustainable and effective alum sludge disposal solution while reducing environmental and health risks associated with P-contamination.

Effluent samples were analysed for total phosphorus, temperature, pH, and turbidity. Alum sludge was characterized using a variety of methods (pH, moisture content, FTIR, XRF, and SEM analyses). Phosphorus reduction was evaluated using alum sludge granules (ASG) prepared by binding oven-dried alum sludge with Carboxymethyl cellulose (CMC) in batch experiments. The effect of varying contact time and ASG masses on phosphorus reduction was investigated. The adsorption behaviour was described by the Langmuir and Freundlich models, and statistical tests were used to determine model suitability and group differences.

The alum sludge exhibited favourable characteristics for phosphorus adsorption, with a maximum adsorption capacity of 0.3 mg/g. The highest reduction, 86 %, was achieved at 24 hours of contact at an ASG mass of 9 g. The Langmuir isotherm model, with a coefficient of determination, R^2, of 0.743, provided the best fit for total phosphorus adsorption onto ASG, demonstrating the potential of reusing alum sludge from the Katosi Drinking Water Treatment Plant for phosphorus reduction in wastewater effluent in Uganda.

Further field testing, pilot studies, and exploration of granulation techniques are recommended for real-world applications.

DECLARATION

I, SHARON ANNEYS NAAYO, declare that all the material portrayed in this dissertation is original and has never been submitted for the award of any degree, certificate, or diploma to any university or institution of higher learning. For any other information obtained from the literature of previously published work, the origin has been duly noted and referenced.

SHARON ANNEYS NAAYO

Signature: …….

Date: ……/……/…….

ACKNOWLEDGEMENTS

I am profoundly grateful to the Almighty God for granting me the gift of life and the opportunities that have shaped my journey. My heartfelt appreciation goes to my steadfast parents, whose support has been a constant presence throughout every step of my life.

I also extend a special note of appreciation to Professor Eleanor Wozei, my dedicated supervisor, for her invaluable guidance and relentless encouragement throughout my academic journey. Her mentorship has been instrumental in shaping my research and personal growth.

I also extend sincere thanks to Mr. Innocent Twinomujuni, Mr. Collins Taremwa, Mr. Paul Kiberu, the Quality Control Team from the Katosi Drinking Water Treatment Plant in Mukono District, and Mr. Robert Katesh Bayo from the Central Laboratory – National Water and Sewerage Corporation (NWSC). Their insights, support, and expertise greatly enriched my work.

Lastly, I am deeply thankful to Mrs. Elizabeth Kamaliza, Quality Control Officer at the Lubigi Faecal Sludge and Wastewater Treatment Plant in Kampala, for her unwavering guidance throughout my research. Her expertise has been indispensable to my work.

APPROVAL

This is to certify that this dissertation has been done by SHARON ANNEYS NAAYO, and is ready for submission with approval.

Project supervisor: ELEANOR WOZEI (PhD)

Signature: ……

Date: ……/……../……..

TABLE OF CONTENTS

ABSTRACT i
DECLARATION ii
ACKNOWLEDGEMENTS iii
APPROVAL iv
TABLE OF CONTENTS v
LIST OF TABLES viii
LIST OF FIGURES ix
LIST OF APPENDICES xi
LIST OF ACRONYMS xii
CHAPTER ONE: INTRODUCTION 1
1.1. Background 1
1.2. Problem Statement 4
1.3. Objectives 6
1.3.1. Main Objective 6
1.3.2. Specific Objectives 6
1.4. Research Questions 6
1.5. Justification 6
1.6. Significance 7
1.7. Scope of Study 8
1.8. Theoretical Framework 8
CHAPTER TWO: LITERATURE REVIEW 9
2.1. Introduction 9
2.1.1. Wastewater characteristics 9
2.1.2. Wastewater treatment challenges 9
2.2. Phosphorus removal technologies and their limitations 10
2.3. Adsorption 11
2.3.1. Mechanisms of phosphorus adsorption 11
2.3.2. Factors affecting phosphorus removal 12

2.3.3. Adsorbents used for phosphorus removal 13
2.4. Alum sludge 14
2.4.1. Alum sludge production and management 16
2.4.2. Sludge production and management at the Katosi Drinking Water Treatment Plant 17
2.5. Alum sludge as an adsorbent 19
2.5.1. Composition and properties of alum sludge 21
2.5.2. Methods used for physicochemical characterisation of alum sludge .. 23
2.5.3. Alum sludge reuse in phosphorus reduction 24
2.6. Benefits of alum sludge for phosphorus reduction 25
2.7. Alum sludge reuse pathways after phosphorus adsorption 25
2.8. Conclusion to the Literature Review 26
CHAPTER THREE: METHODOLOGY 27
3.1. Introduction 27
3.2. Research Design 27
3.3. Area of Study 27
3.4. Information Sources 28
3.5. Methods for achieving specific objectives 28
3.5.1. Characterisation of the wastewater effluent 28
3.5.2. Characterisation of alum sludge 30
3.5.3. Evaluation of phosphorus reduction efficiencies of alum sludge 33
3.5.4. Assessment of phosphorus adsorption capacity of alum sludge 36
3.6. Quality Control 39
CHAPTER FOUR: RESULTS AND DISCUSSION 41
4.1. Wastewater treatment plant effluent characteristics 41
4.2. Alum sludge characteristics 42
4.2.1. Chemical composition of alum sludge 42

4.2.2. FTIR characterisation 44
4.2.3. Morphological characterisation 45
4.3. Adsorption of TP onto ASG 47
4.3.1. Effect of the mass of alum sludge granules 47
4.3.2. Effect of contact time 50
4.3.3. The combined effect of the mass of ASG and contact time 55
4.4. Suitable Isotherm Model 56
CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS 59
5.1. Conclusion 59
5.2. Limitations to the study 61
5.3. Recommendations 61
REFERENCES 63
APPENDICES 79

LIST OF TABLES

Table 2-1: Overview of various phosphorus removal technologies, their advantages, and limitations 10
Table 2-2: Adsorbents that have been used for phosphorus removal 14
Table 2-3: Alum sludge quantification for the KDWTP for a 12-month period (1st January 2022 to 31st December 2022) 19
Table 2-4: Chemical composition of water treatment plant alum sludge from different studies 22
Table 4-1: Comparison of effluent quality (grab sample) with Maximum Permissible Limits 41
Table 4-2: Chemical composition of alum sludge from XRF analysis 43
Table 4-3: Summary of parameters of the adsorption isotherms on adsorption of TP by ASG for the experimental group 57

LIST OF FIGURES

Figure 2-1: Adsorption process (Rudi *et al.*, 2020) 11
Figure 2-2: Adsorption mechanisms (Rudi *et al.*, 2020) 11
Figure 2-3: Dissolved Air Floatation process (Mecham, 2018) 16
Figure 2-4: KDWTP alum sludge production block diagram 17
Figure 2-5: Summary of water treatment residue modifications for wastewater treatment (Sharma and Ahammed, 2023) 20
Figure 2-6: Preparation process of granular alum sludge adsorbent using a binding agent (Wu et al., 2019) 21
Figure 3-1: Effluent sample acidification (left and next center), packing for transportation and refrigeration (sample with ice packs and later placed in the fridge at 4ºC) 29
Figure 3-2: Potassium hydroxide solution and nitrification inhibitor used (left) the test bottle rack placed in the thermostat cabinet (middle) and, 500 mL BOD brown glass test bottles with BOD sensor screw caps (right) 30
Figure 3-3: Alum sludge sample placed in an oven (left) and sludge sample left to cool at room temperature (right) 31
Figure 3-4: Grinding of oven-dried alum sludge sample using a Universal Mill Electric Powder Grinder (left and center) and sieving using a Vibratory Sieve Shaker AS 300 (right) 31
Figure 3-5: Coating ASG and alum sludge powder samples with chromium using a Q150T ES splutter coater (left) and prepared samples transferred to the Vapour Pressure Sigma 300 High-Resolution Scanning Electron Microscope for detailed surface characterisation (right) 33
Figure 3-6: Alum sludge granulation process; weighing of alum sludge powder and CMC (A), formation of a wet mixture (B), wet mixture put in a silicon mould (C), mixture left to dry for 48 hours (D), and alum sludge granules formed (E and F) . 34
Figure 4-1: FTIR spectrum of the powdered alum sludge sample 44
Figure 4-2: SEM micrographs of the oven-dried alum sludge powder at magnifications of 500 and 3000 45
Figure 4-3: SEM micrographs showing the surface of the alum sludge granule at magnifications of 76 and 222 46

Figure 4-4: SEM micrograph of alum sludge granule showing the compact areas (A) as well as the pores (B) 46
Figure 4-5: Effect of mass of ASG on the Total Phosphorus concentration for the experimental group with an initial TP concentration of 22.581 mg/L and the positive control with an initial concentration of 32.107 mg/L compared against the MPL of 10 mg/L 48
Figure 4-6: Effect of contact time on the TP concentration for 3 g, 6 g, and 9 g of ASG..... 51
Figure 4-7: Effect of contact time on the TP reduction for 3 g, 6 g, and 9 g of ASG 52
Figure 4-8: Total phosphorus percent reduction for respective ASG masses and contact times..... 55
Figure 4-9: Langmuir (a) and Freundlich (b) models fitting TP adsorption for the experimental group..... 56

LIST OF APPENDICES

Appendix 1: Results from the alum sludge XRF analysis 79
Appendix 2: Results from the alum sludge FTIR analysis 80
Appendix 3: Effluent characterisation and adsorption experiment results 81

LIST OF ACRONYMS

ASG	Alum Sludge Granules
CMC	Carboxymethyl Cellulose
DGAL	Directorate of Government Analytical Laboratory
FTIR	Fourier Transform Infrared
KDWTP	Katosi Drinking Water Treatment Plant
MWE	Ministry of Water and Environment
NWSC	National Water and Sewerage Corporation
P	Phosphorus
SEM	Scanning Electron Microscopy
TP	Total phosphorus
WTS	Water Treatment Sludge
XRF	X-ray Fluorescence

CHAPTER ONE: INTRODUCTION

1.1. Background

Global wastewater production is on the rise, primarily attributed to factors like population growth, improved water supply systems, elevated living standards, and economic development (European Investment Bank, 2022; Pratap *et al.*, 2023). Annually, an estimated 380 billion m^3 of wastewater is generated worldwide (Pratap *et al.*, 2023). Projections indicate that wastewater production will surge by 24 % by 2030 and 51 % by 2050 (European Investment Bank, 2022).

Wastewater, itself, is water whose physical, chemical, and/or biological properties have been altered due to the introduction of substances rendering it unsafe (Manasa and Mehta, 2020). Comprising about 99.9 % water and 0.1 % inorganic and organic compounds, including sodium, copper, lead, zinc, fats, oils, grease, pathogens, and nutrients like phosphorus and nitrogen, wastewater originates from sources like domestic, industrial, commercial, and agricultural activities, as well as surface runoff, storm water, and sewer inflow or infiltration through damaged sewer systems (Manasa and Mehta, 2020; Koul *et al.*, 2022). The organic fraction primarily encompasses human waste, proteins, fats, and organic materials originating from anthropogenic activities (Manasa and Mehta, 2020). After treatment, wastewater transforms into effluent, which can be either released into the environment or reused, underscoring the significance of effective contaminant removal for both environmental preservation and public health (Manasa and Mehta, 2020; Koul *et al.*, 2022; Pratap *et al.*, 2023).

Globally, it is estimated that more than 80 % of all generated wastewater is discharged into the environment without adequate treatment, albeit with regional variations (European Investment Bank, 2022). The situation is mirrored in Uganda, where compliance with national wastewater effluent discharge standards remains notably low, with an average compliance rate of 30 % (Ministry of Water and Environment Water, 2020). The Water and Environment Sector Performance Report of 2020, emphasizes that key wastewater dischargers, including the facilities managed by the National Water and Sewerage Corporation (NWSC), still fall short of complete adherence to the National Standards for wastewater discharge onto land, particularly concerning specific parameters (Ministry of Water and Environment

Water, 2019, 2020). These challenges often revolve around the inefficiencies and limitations within wastewater treatment facilities, stemming from financial constraints, inadequate workforce capacity, and operational efficiency issues (Ministry of Water and Environment Water, 2019; National Water and Sewerage Corporation, 2020). Moreover, the NWSC Annual Report (National Water and Sewerage Corporation, 2020), highlights that the deteriorating quality of raw water in Lake Victoria – a source of domestic water supply - is largely attributed to source pollution resulting from unregulated discharges of industrial effluent, domestic wastewater, and unsustainable agricultural practices. This deterioration not only impacts the quality of the raw water but also escalates the demand for water treatment chemicals required to purify the same volume of water (Muisa *et al.*, 2020; National Water and Sewerage Corporation, 2020).

One of the prevalent components of wastewater is phosphorus (P) which originates from various sources including domestic and agricultural wastewater, as well as urban storm water run-off (Wu *et al.*, 2019; Alwan and Rashid, 2021; Nguyen *et al.*, 2022a). Improper treatment of P-rich wastewater can lead to water pollution, especially when released into the environment (Bunce *et al.*, 2018; Muisa *et al.*, 2020; Akinnawo, 2023). One of the most significant consequences of excessive P is eutrophication in surface water sources such as rivers, lakes, and other aquatic systems (Kabenge, Wang and Li, 2016; Bunce *et al.*, 2018; Bacelo *et al.*, 2020; Muisa *et al.*, 2020; Nguyen *et al.*, 2022a; Akinnawo, 2023; Sharma and Ahammed, 2023).

In Uganda, over the past few decades, Lake Victoria has experienced a concerning increase in eutrophication, primarily stemming from heightened nutrient inflows (Kabenge, Wang and Li, 2016; Olokotum *et al.*, 2020, 2021; Njagi *et al.*, 2022). The repercussions of this eutrophication pose a significant threat to the social welfare of more than 42 million people residing in the countries surrounding the Lake Victoria basin (Olokotum *et al.*, 2020; Njagi *et al.*, 2022; Obuya *et al.*, 2023). Lake Victoria is a distinctive and indispensable resource in East Africa, providing sustenance through food and access to safe drinking water (Njagi *et al.*, 2022; Obuya *et al.*, 2023). However, its progressive eutrophication has led to substantial alterations in the fish community, and contributed to the recurrent outbreaks of

water hyacinth and cyanobacteria (Kabenge, Wang and Li, 2016; Olokotum *et al.*, 2020; Akinnawo, 2023).

It is, therefore, crucial to eliminate phosphorus through advanced treatment methods, especially in regions with stringent effluent standards (Bacelo *et al.*, 2020; Muisa *et al.*, 2020). However, biological treatments can be challenging to manage in practical settings, with inconsistent processing effects (Bunce *et al.*, 2018; Muisa *et al.*, 2020). On the other hand, chemical treatments necessitate a substantial amount of chemicals, resulting in extremely high operational costs (Wu *et al.*, 2019; Muisa *et al.*, 2020).

Adsorption is favoured because of its low cost, high efficiency, and simple operation (Bacelo *et al.*, 2020; Nguyen *et al.*, 2022a; Usman *et al.*, 2022; Pająk, 2023). In recent years, several materials have been tested for P-adsorption such as fly ash (Zhang *et al.*, 2020), slag (Vu *et al.*, 2021), silver nanocomposites (Nyakairu, Usman and Ntale, 2023), and zeolite (Wang *et al.*, 2021). Due to its effective adsorption properties with phosphorus, alum sludge has emerged as a cost-effective alternative for use as an adsorbent in phosphorus removal (Ren *et al.*, 2020b). As a result, the utilization of alum sludge for phosphorus removal in water has garnered considerable attention (Wu *et al.*, 2019).

Large volumes of alum sludge are produced in the drinking water treatment industry from Aluminium Sulphate ($Al_2(SO_4)_3$), a common coagulant salt used in the production of safe and clean drinking water (Dassanayake *et al.*, 2018; Basri *et al.*, 2019; Muisa *et al.*, 2020; Nguyen *et al.*, 2022b). The proportion of alum sludge produced is estimated to represent 1 % - 3 % (in m^3/day) of the treated water of a drinking water treatment plant where alum is used (Ren *et al.*, 2020b; Zhao *et al.*, 2021). Since the demand for clean drinking water grows with increasing population and urbanization (Turner *et al.*, 2019; Sharma and Ahammed, 2023), more alum sludge is produced from water treatment with time, raising concerns about how to manage it sustainably and cost-effectively (Ren *et al.*, 2020b).

In developing countries, alum sludge from drinking water treatment plants is typically managed by landfilling or discharge into natural waterbodies and wetlands (Abd EL- Razek, Elgendy and Fouad, 2016; Muisa *et al.*, 2020; Sharma and Ahammed,

2023). Landfill disposal encounters major setbacks due to increased disposal costs and decreased landfill capacity (Muisa *et al.*, 2020). Meanwhile, the direct discharge of alum sludge into waterbodies is strongly discouraged due to its potential adverse effects on the aquatic environment such as habitat smothering as well as aluminium toxicity (Ackah *et al.*, 2018; Turner *et al.*, 2019; Hussein *et al.*, 2021).

The Katosi Drinking Water Treatment Plant, located in Mukono, Uganda, employs dissolved air flotation technology along with alum as a coagulant to treat raw water with high turbidity. This process generates approximately 1,576 m^3/day of alum sludge, which is presently manually removed and disposed of on open land (SOGEA SATOM and SUEZ, 2019). The plant was designed with a capacity of 160,000 m^3/day of treated water, with provisions for future expansion to 240,000 m^3/day. As the plant prepares for expansion (phase 2), alum sludge production is expected to increase, highlighting the need for a more sustainable and effective disposal method.

In modern societies, such waste is managed with the help of the 5 R's principle; "Reduce, Reprocess, Reuse, Recycle and Recover", a criterion introduced to utilize waste material and support a sustainable environment (Zhao *et al.*, 2021; Tony, 2022). By adopting this criterion, societies can work towards establishing *"a circular economy"* that facilitates sustainable resource management (Geissdoerfer *et al.*, 2017; Valavanidis, 2018; Dias *et al.*, 2021; Velenturf and Purnell, 2021; Nguyen *et al.*, 2022b).

1.2. Problem Statement

Eutrophication is a critical global issue affecting waterbodies due to the influx of nutrients (Njagi *et al.*, 2022; Akinnawo, 2023). In Uganda, deteriorating water quality is often attributed to eutrophication (Njagi *et al.*, 2022). Lake Victoria, for instance, experienced a substantial deterioration of water quality from the 1960s to the 1990s, primarily attributed to eutrophication (Deirmendjian *et al.*, 2021). By 2005, the levels of phosphorus in the L. Victoria basin had surged by a factor of 2 to 3 as reported by Mugidde, Hecky and Ndawula, (2005). A limnology assessment conducted from 2018 to 2019 revealed that Lake Victoria remained phosphorus-saturated (Deirmendjian *et al.*, 2021), indicating the persistent challenge of eutrophication. Eutrophication results in challenges such as the proliferation of algal

biomass, harmful algal blooms leading to fish mortality, shifts in algal communities, loss of desirable fish species, and seasonal depletion of oxygen in bottom waters (Njagi *et al.*, 2022; Usman *et al.*, 2022; Akinnawo, 2023).

To address these environmental issues, the Ugandan government established the Lubigi Faecal Sludge and Wastewater Treatment Plant in 2014. Phosphorus removal at this plant currently relies on anaerobic and facultative stabilisation ponds. However, this method faces several challenges, including inconsistent removal efficiencies, the re-release of nutrients, limited removal of dissolved phosphorus, spatial constraints, and long retention times, especially in systems characterized by high influent flow rates (Bunce *et al.*, 2018; Ho and Goethals, 2020). Although there have been several studies in Uganda on the use of alum sludge as a phosphorus adsorbent (Kabenge *et al.*, 2018; Nyakairu, Usman and Ntale, 2023). The abundant stocks available at the Katosi Drinking Water Treatment Plant have not been utilised for this purpose, given that there are considerable variations among alum sludge generated by different water treatment plants (Odimegwu *et al.*, 2018; Muisa *et al.*, 2020).

At the Katosi plant, dewatered alum sludge is manually removed from drying beds and openly disposed of on land (SOGEA SATOM and SUEZ, 2019), a practice with severe environmental and public health consequences (Krupinska, 2020). This unsustainable method poses risks including soil contamination, fire hazards due to the combustibility of alum sludge, water contamination through pollutant runoff, and limited available land for dumping (Ackah *et al.*, 2018; Dassanayake *et al.*, 2018; Niwagaba *et al.*, 2019; Zhao *et al.*, 2021). These pressing environmental and health concerns underscored the need for an investigation into "the potential of reusing alum sludge from the Katosi Drinking Water Treatment Plant for phosphorus reduction." Furthermore, as the plant prepares for expansion in its second phase, sludge production is expected to increase, highlighting the urgency of finding more sustainable and effective disposal solutions.

1.3. Objectives

1.3.1. Main Objective

The main objective of this study, therefore, was to assess the potential of alum sludge from the Katosi Drinking Water Treatment Plant as an adsorbent for phosphorus reduction in wastewater effluent in Uganda.

1.3.2. Specific Objectives

The specific objectives were:

1. To determine the physicochemical characteristics of the effluent from the Lubigi Faecal Sludge and Wastewater Treatment Plant.
2. To identify the physical and chemical characteristics of the discarded alum sludge from the Katosi Drinking Water Treatment Plant.
3. To evaluate the phosphorus reduction by the alum sludge from the Katosi Drinking Water Treatment Plant.
4. To assess and characterise the phosphorus adsorption capacity of the alum sludge from the Katosi Drinking Water Treatment Plant.

1.4. Research Questions

1. What are the key physicochemical properties of the effluent from the Lubigi Faecal Sludge and Wastewater Treatment Plant?
2. What are the physicochemical properties of the discarded alum sludge from the Katosi Drinking Water Treatment Plant?
3. How effective is this alum sludge from the Katosi Drinking Water Treatment Plant in reducing phosphorus in wastewater effluent?
4. What is the adsorption capacity of the alum sludge from the Katosi Drinking Water Treatment Plant for phosphorus in wastewater effluent?

1.5. Justification

The project aimed to investigate the potential of using alum sludge as an adsorbent for phosphorus removal in wastewater treatment. This research can contribute to the development of sustainable practices in the water treatment industry and address the current knowledge gap regarding the effectiveness and optimization of alum sludge reuse for water pollution control (Wu *et al.*, 2019). The utilisation of discarded alum sludge offers various advantages, including the reduction of solid

waste in water treatment plants and the creation of a low-cost adsorbent for phosphorus reduction (Wu *et al.*, 2019; Everaert *et al.*, 2021; Nguyen *et al.*, 2022a).

1.6. Significance

Uganda Vision 2040, is "conceptualized around strengthening the fundamentals of the economy to harness the abundant opportunities around the country and these fundamentals include infrastructure for energy, transport, water, oil, and gas" (NPA, 2012). This dissertation contributes to this vision in the aspect of improving the resilience of drinking water treatment plants by providing a possible solution for one of their major drawbacks, the alum sludge production footprint.

The dissertation findings also contribute to the achievement of Sustainable Development Goals;

SDG 6: Clean Water and Sanitation

a) Target 6.3: *'By 2030, improve water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.'*

The study supports this target by proposing a method for phosphorus reduction in wastewater effluent, which contributes to pollution reduction and water quality improvement.

SDG 12: Responsible Consumption and Production

b) Target 12.5: *'By 2030, substantially reduce waste generation through prevention, reduction, recycling, and reuse.'*

The study supports this target by proposing a method for reusing discarded alum sludge, which is a waste product from the drinking water treatment process. By reducing the amount of alum sludge that is sent to landfills, the study helps to reduce waste generation.

1.7. Scope of Study

This study, which investigated the potential for the reuse of alum sludge, was geographically limited to the Katosi Drinking Water Treatment Plant. This plant is one of the drinking water treatment plants operated by the National Water and Sewerage Corporation (NWSC), a public utility company managed by the government in Uganda The plant is located in Mukono – Uganda. This research, conducted over nine months, focused on the potential of discarded alum sludge from drinking water treatment plants for phosphorus reduction in wastewater effluent.

1.8. Theoretical Framework

The theoretical framework for alum sludge reuse for phosphorus reduction utilises concepts related to wastewater treatment, phosphorus reduction, alum sludge characteristics (Ackah *et al.*, 2018; Hou *et al.*, 2018; Ren *et al.*, 2020c), adsorption of phosphorus onto alum sludge (Bunce *et al.*, 2018; Hou *et al.*, 2018; Zhao *et al.*, 2021), and reuse options (Ackah *et al.*, 2018; Dassanayake *et al.*, 2018; Turner *et al.*, 2019; Dias *et al.*, 2021; Hussein *et al.*, 2021; Nguyen *et al.*, 2022a). This framework provides a foundation for further research and development of innovative and sustainable solutions for phosphorus removal in wastewater treatment.

This study addresses the global challenge of wastewater management by focusing on the pressing issue of phosphorus in wastewater and its environmental impact. With a substantial proportion of wastewater being discharged untreated and/or inadequately treated, particularly in Uganda where compliance is at 30 %, the study centred on the potential of alum sludge from the Katosi Drinking Water Treatment Plant, as an adsorbent for phosphorus reduction. Embracing the 5 R's principle for waste management, the study aimed to contribute to sustainable water treatment practices, aligning with Uganda Vision 2040 and supporting key Sustainable Development Goals, notably SDG 6 and SDG 12. The theoretical framework encompassed vital concepts related to wastewater treatment, phosphorus removal, alum sludge characteristics, adsorption processes, as well as alum sludge reuse strategies.

In the following chapter, the literature review delves into the existing knowledge and research on wastewater treatment, phosphorus removal methods, and the utilisation of alum sludge for environmental sustainability.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

The worldwide production of wastewater is undergoing a notable uptrend owing to factors such as population growth, advancements in water supply systems, and economic progress (European Investment Bank, 2022; Pratap *et al.*, 2023). Approximately 380 billion m^3 of wastewater is generated every year (Pratap *et al.*, 2023). Projections indicate an expected 24 % surge by 2030 and a substantial 51 % increase by 2050 (European Investment Bank, 2022).

2.1.1. Wastewater characteristics

Wastewater, composed of 99.9 % water and 0.1 % diverse contaminants, originates from various sources, including residential, industrial, commercial, and agricultural activities (Koul *et al.*, 2022). Contaminants include but not limited to; inorganic and organic compounds, including sodium, copper, lead, zinc, fats, oils, grease, pathogens, and nutrients like phosphorus and nitrogen (Manasa and Mehta, 2020). The wastewater poses environmental and public health challenges (Manasa and Mehta, 2020; Koul *et al.*, 2022; Pratap *et al.*, 2023). Therefore, effective wastewater treatment is of utmost importance to safeguard the environment and public well-being.

2.1.2. Wastewater treatment challenges

Globally, over 80 % of generated wastewater is inadequately treated before discharge (European Investment Bank, 2022). This is also a concern shared by Uganda where the compliance to the national wastewater effluent discharge standards is at a 30 % average (Ministry of Water and Environment Water, 2020). Non-compliance primarily results from inefficiencies, financial constraints, and limited workforce capacity within wastewater treatment facilities (Ministry of Water and Environment Water, 2019, 2020; National Water and Sewerage Corporation, 2020).

Phosphorus, a common element in wastewater, is sourced from domestic, agricultural, and urban runoff (Nguyen *et al.*, 2022a). Inadequate treatment of phosphorus-rich wastewater can lead to water pollution, with eutrophication being a major consequence (Bunce *et al.*, 2018; Muisa *et al.*, 2020; Akinnawo, 2023). In Uganda, over the past few decades, Lake Victoria has experienced a concerning

increase in eutrophication, primarily stemming from heightened nutrient inflows (Kabenge, Wang and Li, 2016; Olokotum *et al.*, 2020, 2021; Njagi *et al.*, 2022). This has led to a decline in the water quality of Lake Victoria, intensifying the demand for treatment chemicals (National Water and Sewerage Corporation, 2020; Njagi *et al.*, 2022).

In light of these challenges, this section reviews the current phosphorus removal technologies, with a focus on adsorption and the use of alum sludge from the Katosi Drinking Water Treatment Plant (KDWTP) as an adsorbent for phosphorus removal.

2.2. Phosphorus removal technologies and their limitations

Effective wastewater treatment is vital to combat eutrophication caused by excessive phosphorus discharge. To tackle this, various phosphorus removal technologies have been devised each with unique strengths and limitations. Table 2-1 presents an overview of phosphorus removal techniques, emphasizing their characteristics, merits, and constraints.

Table 2-1: Overview of various phosphorus removal technologies, their advantages, and limitations

Phosphorus Removal Technology	Description	Advantages	Limitations
Chemical Precipitation (Usman *et al.*, 2022)	Addition of chemicals to precipitate phosphorus	Effective, widely used	Generates large volumes of sludge, costly
Biological Phosphorus Removal (Usman *et al.*, 2022)	Utilizes specific microbes to store phosphorus	Environmentally friendly, reduces sludge	Sensitive to operational changes, requires monitoring
Membrane Filtration (Ali, 2015)	Utilizes membranes to filter out phosphorus	Effective, produces high-quality effluent	Energy-intensive, expensive to operate
Constructed Wetlands (Ho and Goethals, 2020)	Natural or engineered wetlands for treatment	Sustainable, promotes biodiversity	Effectiveness influenced by environmental conditions
Ion Exchange (Usman *et al.*, 2022)	Resins exchange phosphorus ions with other ions	Efficient removal can recover phosphorus	Resins require regeneration, creating a waste stream
Electro-coagulation (Hu *et al.*, 2023)	Electricity to destabilize and remove phosphorus	Effective, applicable to various wastewaters	Energy-intensive, requires precise control
Adsorption (Koul *et al.*, 2022; Usman *et al.*, 2022)	Use of adsorbents to capture phosphorus	Versatile, some materials are reusable	Adsorbents can become saturated, need regeneration or replacement, affected by coexisting ions

2.3. Adsorption

This is a process in which molecules or ions from a liquid or gas are attracted and adhere to the surface of a solid material (Sreeremya, 2017; Rudi *et al.*, 2020; Pourhakkak *et al.*, 2021; Abin-Bazaine, Trujillo and Olmos-Marquez, 2022).

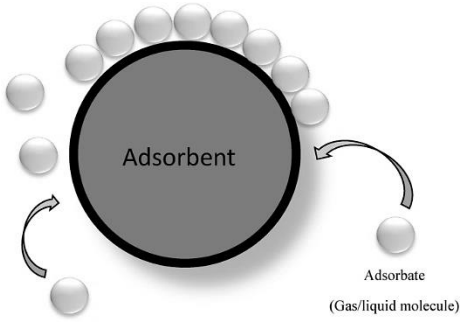


Figure 2-1: Adsorption process (Rudi *et al.*, 2020)

The need for more effective removal of nutrients like phosphorus in wastewater effluent has driven the discovery of advanced treatment methods, see Table 2-1. Among these methods, adsorption stands out as the top choice for phosphorus removal. This preference is due to its high efficiency, cost-effectiveness, ability to effectively remove phosphate from water, even at low concentrations, ease of operation, simple design, high capacity, and the potential to minimize the generation of by-products (Koul *et al.*, 2022; Usman *et al.*, 2022).

2.3.1. Mechanisms of phosphorus adsorption

Phosphorus adsorption mechanisms can be broadly categorized into physical and chemical adsorption (Muisa *et al.*, 2020; Rudi *et al.*, 2020; Usman *et al.*, 2022), as shown in Figure 2-2.

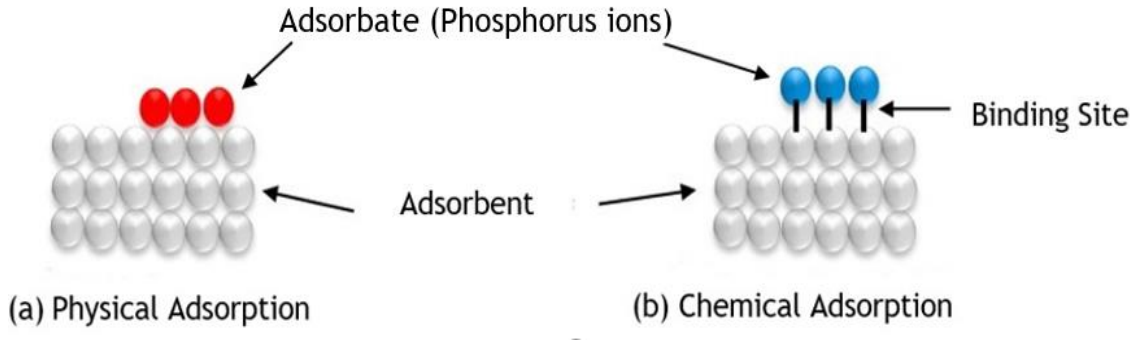


Figure 2-2: Adsorption mechanisms (Rudi *et al.*, 2020)

a) Physical adsorption

This form of adsorption occurs when the adsorbate attaches to the surface solely via relatively weak intermolecular forces known as Van der Waals forces, see Figure 2-2(a), and it occurs at lower temperatures and is reversible (Rudi *et al.*, 2020; Aljamali, Khdur and Alfatlawi, 2021).

b) Chemical adsorption

This process occurs when phosphorus molecules or ions create strong covalent or ionic bonds with the surface of a solid or liquid, see Figure 2-2 (b) (Aljamali, Khdur and Alfatlawi, 2021; Du *et al.*, 2022). This type of adsorption involves the transfer of electrons between the phosphorus ions (the adsorbate, or substance being adsorbed) and the material's surface (the adsorbent where adsorption occurs) (Muisa *et al.*, 2020). Unlike physical adsorption, it's less reversible and often requires specific conditions like reactants, catalysts, or elevated temperatures (Ali, 2015; Muisa *et al.*, 2020; Rudi *et al.*, 2020).

In practice, a combination of physical and chemical adsorption mechanisms can occur simultaneously, depending on the nature of the adsorbent material, the environmental conditions, and the concentration of phosphorus in the system (Muisa *et al.*, 2020; Usman *et al.*, 2022).

2.3.2. Factors affecting phosphorus removal

a) Mass of adsorbent

The amount of phosphorus reduced by adsorption is directly proportional to the mass of the adsorbent (Muisa *et al.*, 2020; Usman *et al.*, 2022). Increasing the adsorbent mass can enhance P-reduction as it increases the number of active sites and total surface area for adsorption (Wu *et al.*, 2019; Muisa *et al.*, 2020; Zhang *et al.*, 2020; Alwan and Rashid, 2021). However, this improvement in P-reduction is only observed up to a certain mass threshold (Wu *et al.*, 2019; Muisa *et al.*, 2020; Trinh *et al.*, 2020; Alwan and Rashid, 2021). This is because when an excessive amount of adsorbent is introduced, particle aggregation can occur, reducing the active surface area and sites available for phosphorus adsorption (Muisa *et al.*, 2020; Trinh *et al.*, 2020).

b) Contact time

Contact time, the duration of interaction between an adsorbent and phosphorus-containing water, directly impacts phosphorus removal (Muisa *et al.*, 2020; Trinh *et al.*, 2020; Alwan and Rashid, 2021). For a given dose, longer contact times lead to better phosphorus binding to the adsorbent, as more phosphorus ions attach to active sites on the adsorbent's surface and shorter contact times result in incomplete phosphorus removal because the process doesn't have enough time to reach its full potential (Muisa *et al.*, 2020; Usman *et al.*, 2022). Summarily, phosphorus removal is directly linked to contact time, but there's often an optimal duration where further improvements in removal are negligible (Trinh *et al.*, 2020).

c) Initial phosphorus concentration

Phosphorus removal has an inverse relationship with the initial phosphorus concentration. This happens because, at lower concentrations, nearly all phosphorus ions engage with the accessible binding sites (Trinh *et al.*, 2020; Alwan and Rashid, 2021). However, when the initial phosphorus concentration is higher, these binding sites become saturated, resulting in a reduction in the percentage of removed phosphorus (Trinh *et al.*, 2020).

d) Presence of other ions

Anions in the environment typically coexist, and the same holds for phosphorus and their competing anions in wastewater (Muisa *et al.*, 2020). These substances, sharing the same charge, naturally compete for binding sites on a positively charged metal surface creating competition that interferes with phosphorus adsorption (Muisa *et al.*, 2020; Usman *et al.*, 2022). Real wastewater samples are typically complex and contain various dissolved constituents that can also vie for adsorption sites, impacting the removal of phosphorus (Usman *et al.*, 2022).

2.3.3. Adsorbents used for phosphorus removal

Several adsorbents have been studied for their ability to remove phosphorus from aqueous solutions as well as wastewater effluent. The table below presents some of the adsorbents used for phosphorus adsorption.

Table 2-2: Adsorbents that have been used for phosphorus removal

Adsorbent Type	Examples
Metal-Based	Aluminium-modified bio char (Usman *et al.*, 2022), aluminium-doped magnetic nanoparticles (Xu, Luu and Tang, 2017), alum sludge (Maqbool, Khan and Asghar, 2016; Ojha, Sharma and Amatya, 2019; Wu *et al.*, 2019; Alwan and Rashid, 2021; Everaert *et al.*, 2021; Nguyen *et al.*, 2022a; Kuldeyev *et al.*, 2023), Zinc Oxide coated ball-milled Magnetic Sphere (Zhang *et al.*, 2020), iron-coated sand (Chardon *et al.*, 2022)
Carbon-Based	Synthesized Silver/Calcium Oxide-Activated Carbon Nanocomposite (Nyakairu, Usman and Ntale, 2023), orange peel-based bio char activated by Ca/Zn composite (Chen *et al.*, 2022), Silver Nanoparticles-Loaded Activated Carbon derived from Tea Residue (Trinh *et al.*, 2020)
Natural Sorbents	Clay minerals (Elgarhy *et al.*, 2022), peat (Robalds *et al.*, 2016)
Modified Adsorbents	Lanthanum-modified zeolite (Wang *et al.*, 2021), ion exchange resins (Guida *et al.*, 2021)

Inadequate treatment of phosphorus-rich wastewater underscores the critical need for phosphorus removal (Bunce *et al.*, 2018; Muisa *et al.*, 2020; Akinnawo, 2023). Alum sludge, due to its cost-effectiveness and phosphorus affinity, has gained significant attention as a P-adsorbent (Wu *et al.*, 2019; Ren *et al.*, 2020b). Given the diversity in the composition of alum sludge due to different treatment methods at different treatment plants, it is crucial to thoroughly investigate its specific physical and chemical properties before considering reuse (Odimegwu *et al.*, 2018; Usman *et al.*, 2022). As such, this study investigated the potential of using alum sludge from the Katosi Drinking Water Treatment Plant to reduce phosphorus from wastewater effluent in Uganda.

2.4. Alum sludge

Alum sludge is a by-product of water treatment processes produced when Aluminium salts are used as coagulants to form Aluminium hydroxide and sulphuric acid – see Equation 2-1 (Basri *et al.*, 2019; Muisa *et al.*, 2020). It is worth noting that the term "alum sludge" is also informally employed to describe waste generated from water treatment facilities using Aluminium salts other than Aluminium Sulphate (Muisa *et al.*, 2020).

However, within the scope of this study, "alum sludge" specifically pertains to the sludge originating from water treatment plants where Aluminium Sulphate is used as the primary coagulant.

Alum: also known as Aluminium Sulphate, $Al_2(SO_4)_2$, is a coagulant used in water treatment plants to remove impurities from raw water (Basri *et al.*, 2019; Muisa *et al.*, 2020). The alum is dissolved in water and the aluminium ions (Al_3^+) that form, have a high capacity to neutralize the negative charges which are carried by the colloidal particles and which contribute to particle stability. The aluminium ions hydrolyse and in the process form aluminium hydroxide, $Al(OH)_3$ which precipitates as a solid. During flocculation when the water is slowly stirred the aluminium hydroxide flocs trap the small colloidal particles. The flocs settle readily and most of them can be removed in the proceeding stages of treatment (Basri *et al.*, 2019).

$$Al_2(SO_4)_3 + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2SO_4$$

Equation 2-1

At the Katosi Drinking Water Treatment Plant, alum is the commonly used coagulant for drinking water treatment. Coagulation and flocculation, at this plant, are carried through the dissolved air floatation process, Figure 2-3.

Dissolved Air Floatation: this is a separation process that is similar to sedimentation but the main target is to achieve small-uniform flocs that will readily float rather than settle out. This is done by injecting pressurized water (microbubbles) into the water to ensure particle (floc) attachment to the microbubbles. The DAF process, Figure 2-3, was designed especially for treating waters laden with algae and moderate levels of suspended solids (up to 30 NTU in turbidity) (Mecham, 2018; Wong and Hess, 2019). The sludge floats at the top and is hydraulically removed by flooding the chamber to overflow the sludge into a desludging trough as is the case for the Katosi Drinking Water Treatment Plant.

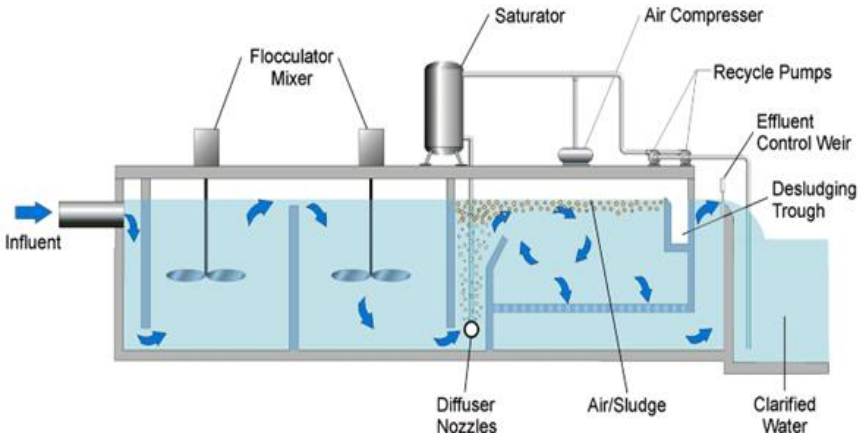


Figure 2-3: Dissolved Air Floatation process (Mecham, 2018)

2.4.1. Alum sludge production and management

The amount of alum sludge generated is around 1 % - 3 % (in m^3/day) of the raw water in drinking water treatment plants using alum (Ren *et al.*, 2020b; Zhao *et al.*, 2021). Alum sludge is generated in most water treatment plants through two main processes: sedimentation following coagulation and flocculation, and the other during the filter backwashing process. Both sludge streams undergo thickening before dewatering to produce solid cakes for final disposal (Zhao *et al.*, 2021). However, getting accurate global or regional data is difficult due to the way local authorities categorize waste statistics, alum sludge is often mistaken for wastewater treatment plant sludge (Turner *et al.*, 2019; Ren *et al.*, 2020b; Zhao *et al.*, 2021), making it challenging to obtain precise production figures. Despite recent research efforts, information on alum sludge production and cost estimates remains limited (Dassanayake *et al.*, 2018; Ren *et al.*, 2020b; Tony, 2022).

According to Ren *et al.*, (2020b), Muisa *et al.*, (2020), and Dassanayake *et al.*, (2018), most countries worldwide still heavily rely on landfilling or incineration after drying as an alum sludge disposal method. Integrating landfill costs into tap water pricing raises consumer expenses, but landfilling faces limitations due to land use and environmental regulations, while incineration, though efficient for low-moisture sludge, is costly and environmentally unpopular (Muisa *et al.*, 2020).

Several studies have demonstrated that alum sludge can be considered a valuable resource rather than a waste (Dassanayake *et al.*, 2018; Ren *et al.*, 2020a; Ren *et al.*, 2020b; Ren *et al.*, 2020c; Zhao *et al.*, 2021). Currently, there are four main categories of beneficial reuse for alum sludge. These categories include using it for

wastewater treatment (Wu *et al.*, 2019; Everaert *et al.*, 2021; Hien *et al.*, 2021; Zhao *et al.*, 2021; Pająk, 2023), incorporating it into building and construction materials (Tony, 2022), agricultural applications (Dassanayake *et al.*, 2018; Tolofari *et al.*, 2022) and recovering and reusing it as a coagulant (Abd EL- Razek, Elgendy and Fouad, 2016; Basri *et al.*, 2019).

2.4.2. Sludge production and management at the Katosi Drinking Water Treatment Plant

At the Katosi Drinking Water Treatment Plant (KDWTP), the alum sludge produced originates from both the water clarifiers (Aquadaf™[1]) and the filters (Aquazur® V[2]) as shown in the block diagram, Figure 2-4; Alum sludge from the clarifiers is extracted and conveyed to the sludge balancing tanks and to the sludge thickeners to remove more water for recycling.

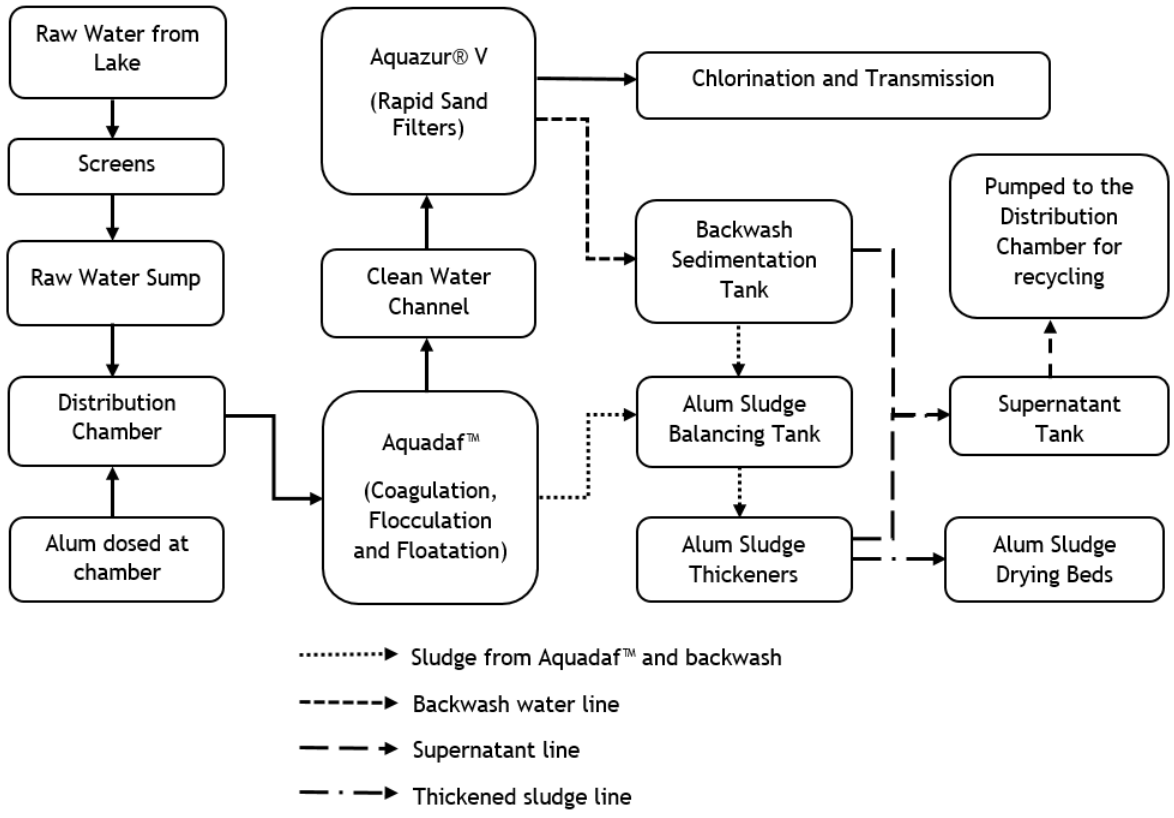


Figure 2-4: KDWTP alum sludge production block diagram

[1] Aquadaf™ is a patented High Speed Dissolved Air Floatation Technology of SUEZ, a multinational company operating in water treatment, waste management, and recycling.

[2] Aquazur® V is also a patented Down Flow Open Rapid Sand Filtration Technology of SUEZ.

Alum sludge from the filters, also known as the backwash water line is sent to the backwash sedimentation tank. This tank allows for the settlement of the sludge and also the extraction of supernatant into the supernatant tank to be pumped back to the distribution chamber. This settled sludge is then pumped to the sludge thickeners. The sludge from the thickeners is collected in hoppers, conveyed to the thickened sludge pump station, and then sent to the drying beds for dewatering. The principle of operation of the drying beds is based on the dewatering of sludge by evaporation of water and also drainage of water through porous media, this makes it possible to remove at least 50 % of the water present in the sludge (SOGEA SATOM and SUEZ, 2019). The dried sludge (solid) is then manually removed and dumped on land in an open space.

From the mass balance equation, the mass of the sludge disposed of per day from the KDWTP was calculated as shown in Table 2-3. The data used was attained over the year 2022 from January to December, all chemicals and processes were the same hence the data gives representative information assuming a steady state.

$$Mass\ in = Mass\ out\ + accumulation\ (assuming\ a\ steady\ state)$$

$$QC_{1(IN)} + QC_{2(IN)}\ \equiv\ QC_{1(OUT)} + M\ Sludge$$

$$M\ Sludge\ \equiv Q(C_{1(IN)} +\ C_{2(IN)} -\ C_{1(OUT)})$$

Where; $Q \rightarrow$ Flow rate of raw water, $C_{1(IN)} \rightarrow$ Dose rate of coagulant, $C_{2(IN)} \rightarrow$ Raw water Total Suspended Solids, $C_{1(OUT)} \rightarrow$ Effluent Total Suspended Solids and $M\ Sludge \rightarrow$ Sludge generated

Table 2-3: Alum sludge quantification for the KDWTP for a 12-month period (1st January 2022 to 31st December 2022)

Month	Pumped Daily	Average Flow Rate	Average Flow rate (Q)	Dose rate ($C_{1(IN)}$)	Raw water TSS ($C_{2(IN)}$)	Effluent TSS ($C_{1(OUT)}$)	Sludge
	m^3	(m^3/hr)	m^3/s	mg/L	mg/L	mg/L	m^3/day
January	74,739	3,114	0.87	4.7	5	1	650.23
February	77,541	3,231	0.90	3.4	5	1	535.03
March	80,981	3,374	0.94	4	6	1	728.83
April	78,467	3,269	0.91	22.1	6	1	2126.46
May	81,353	3,390	0.94	23.9	6	1	2351.1
June	85,265	3,553	0.99	15	6	1	1705.3
July	102,503	4,271	1.19	11	5	1	1537.55
August	93,653	3,902	1.08	8.2	4	1	1048.91
September	93,177	3,882	1.08	8.5	5	1	1164.71
October	93,653	3,902	1.08	8.2	4	1	1048.91
November	92,634	3,860	1.07	9	6	1	1296.88
December	91,886	3,829	1.06	9	6	1	1286.4

Note: The figures shown in the table were monthly averages and the daily amount pumped (column 2) was obtained from the daily readings taken from the SCADA (Supervisory Control and Data Acquisition) application of the pump readings.

2.5. Alum sludge as an adsorbent

Alum sludge, a by-product of drinking water treatment, has been identified as a potential adsorbent due to its large specific surface area and pore volume (Wu *et al.*, 2019; Everaert *et al.*, 2021; Nguyen *et al.*, 2022a). Therefore, it can be utilized as an effective adsorbent in wastewater treatment (Muisa *et al.*, 2020). To understand its adsorbency, Wu *et al.*, (2019), Everaert *et al.*, (2020), Zhao *et al.*, (2021), and Nguyen *et al.*, (2022a) conducted studies on the morphology of aluminium compounds present in alum sludge, which were believed to be the key factors contributing to its adsorption capabilities. Studies conducted by different researchers; Kim *et al.*, (2012), Hien *et al.*, (2021), Abba *et al.*, (2022), Djekoune *et al.*, (2022) Nguyen *et al.*, (2022a), and Pająk, (2023) revealed that alum sludge possesses adsorption capacity for certain contaminants in water such as phosphorus, zinc, copper, arsenic, lead, dyes, hydrogen sulphide, mercury, nickel, and vanadium.

Alum sludge has been shown to effectively remove phosphorus from wastewater (Wu *et al.*, 2019; Muisa *et al.*, 2020; Alwan and Rashid, 2021; Nguyen *et al.*, 2022a). Typically, the sludge is reused in a powdery form after drying, grinding, and sieving

procedures (Ren *et al.*, 2020b). However, according to Wu *et al.*, (2019), Everaert *et al.*, (2020), Ren *et al.*, (2020b), and Sharma and Ahammed, (2023), the utilization of powdered alum sludge in engineering applications poses significant challenges. This is due to its tendency to generate colloidal suspensions during treatment, leading to elevated turbidity levels and decreased adsorption efficiency. Additionally, separating and settling powdered sludge after use is difficult, making its recycling challenging (Sharma and Ahammed, 2023). Water treatment residuals (WTRs) are subjected to a variety of modifications to make them a viable material and Figure 2-5 presents a summary of these methods, as reported in the review by Sharma and Ahammed, (2023).

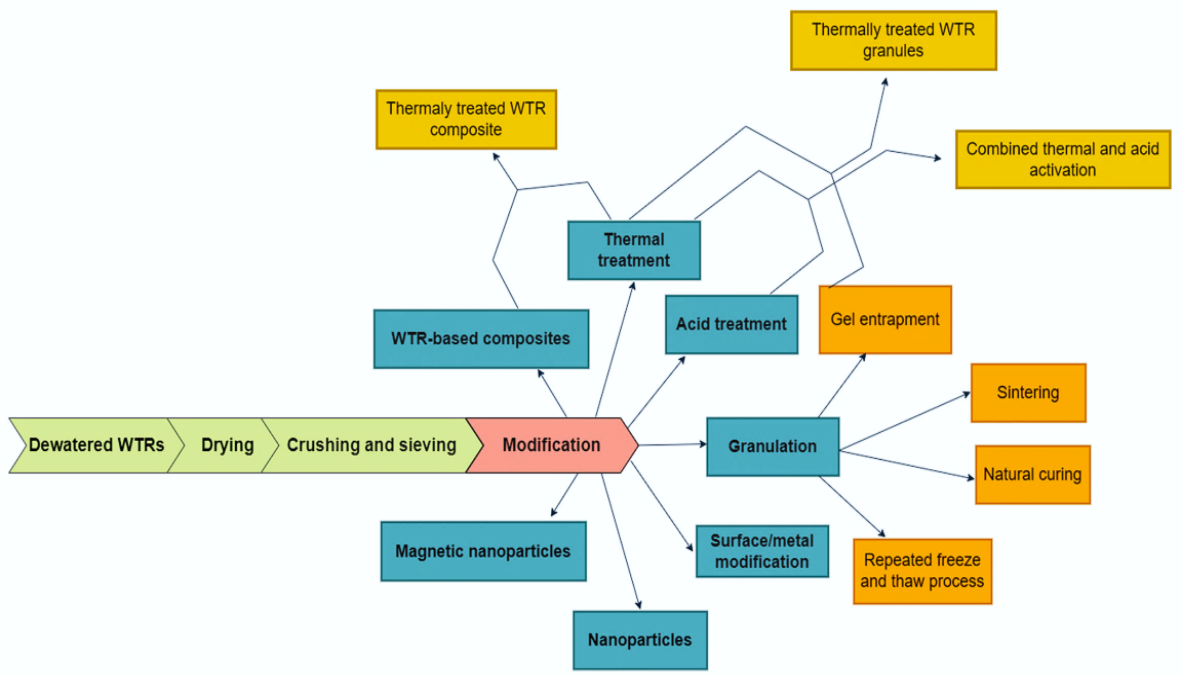


Figure 2-5: Summary of water treatment residue modifications for wastewater treatment (Sharma and Ahammed, 2023)

Wu *et al.*, (2019), Ren *et al.*, (2020b), and Sharma and Ahammed, (2023), suggested granulation, an agglomeration-based particle enlargement technique, as a promising strategy to improve the engineering application of alum sludge, as shown in Figure 2-6.

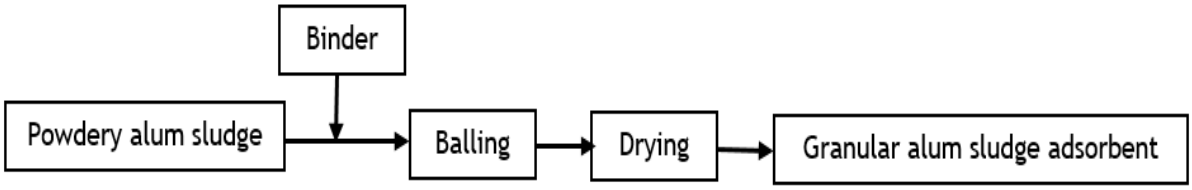


Figure 2-6: Preparation process of granular alum sludge adsorbent using a binding agent (Wu et al., 2019)

According to Ren *et al.*, (2020b), who did a review on the recent advances and prospects of Alum sludge granulation, only 14 studies were classified, at the time, as dealing with the presented topic, and some of the binders used included; sodium alginate, polyvinyl alcohol (PVA), Carboxymethyl cellulose, water glass, sodium hydroxide, aluminium chloride, and molasses. They also pointed out that the choice of binder should consider the potential impact of the binder on the adsorption capacity of the granules as well as the cost, availability, and environmental impact. Wu *et al.*, (2019) suggested that aluminium chloride was the optimum binder compared to other binders. However, the review done by Ren *et al.*, (2020b), revealed that phosphorus is at a neutral to slightly alkaline pH. However, the use of $AlCl_3$ as a binder makes the solution more acidic, decreasing the adsorption capacity of the granules for phosphorus. Moreover, $AlCl_3$ is not commonly used as a binder in granulation processes due to its corrosive nature, safety concerns, and environmental impact. Polymer binders such as polyvinyl alcohol (PVA) or Carboxymethyl cellulose (CMC) were also suggested since they provide good binding strength and do not interfere with the adsorption process (Ren *et al.*, 2020b).

2.5.1. Composition and properties of alum sludge

Alum sludge's composition can vary based on the raw water quality, treatment processes, and chemical dosages used for treatment (Turner *et al.*, 2019; Zhao *et al.*, 2021), but the sludge usually contains aluminium hydroxide, iron hydroxide, organic matter, and impurities removed from the water being treated (Ackah *et al.*, 2018; Barakwan, Trihadiningrum and Bagastyo, 2019; Zhao *et al.*, 2021; Nguyen *et al.*, 2022a). The properties of alum sludge depend on its composition and dewatering/disposal methods, with a moisture content of 60 % - 90 %, pH range of 6.5 - 8.5, colour ranging from light grey to dark brown, and a variable consistency from liquid to solid (Dassanayake *et al.*, 2018; Barakwan, Trihadiningrum and

Bagastyo, 2019; Basri *et al.*, 2019; Zhao *et al.*, 2021; Nguyen *et al.*, 2022a). The composition of the sludge typically consists predominantly of SiO_2 followed by Al_2O_3. Other oxides such as Fe_2O_3, CaO, MgO, Na_2O, K_2O, and P_2O_5 may also be present, albeit in smaller proportions (Ren *et al.*, 2020b; Ren *et al.*, 2020c; Zhao *et al.*, 2021; Sharma and Ahammed, 2023).

The deviations in alum sludge composition data, Table 2-4, highlight the considerable variations among sludge generated by different water treatment plants. This makes it impractical to draw general conclusions or establish typical benchmarks for these parameters without specifying the particular water treatment facility in question as noted by Odimegwu *et al.*, (2018) and Muisa *et al.*, (2020) in their reviews. Similarly, the effectiveness of different water treatment plant alum sludge in removing various environmental pollutants will vary (Muisa *et al.*, 2020). Therefore, suggesting universal beneficial reuse applications for water treatment sludge is challenging without first evaluating the specific characteristics and phosphorus adsorption capacity of each alum sludge.

Table 2-4: Chemical composition of water treatment plant alum sludge from different studies

Chemical	**Percentage composition (%)**						
	Ahmad, Ahmad and Alam, (2016)	Breesem, Abood and Rahman, (2016)	Breesem, Faris and Abdel-Magid, (2016)	El-Tokhy *et al.*, (2020)	Alwan and Rashid, (2021)	Djekoune *et al.*, (2022)	Sharma and Ahammed, (2023)
SiO_2	52.78	43.29	42.32	38	10.80	42.09	39.02
Al_2O_3	14.38	32.19	35.03	23.50	40.10	19.73	34.84
Fe_2O_3	5.20	5.52	4.94	3.63	21.70	5.57	4.76
CaO	4.39	0.17	0.13	4.42	6.40	8.21	4.64
MgO	3.08	0.33	0.30	1.37	3.50	1.34	1.30
Na_2O	0.97	0.13	0.10	0.50	4.60	0.52	0.54
SO_3	-	0.22	0.14	0.52	1.30	0.34	-
K_2O	3.62	2.08	1.87	0.50	5.30	1.74	1.37
P_2O_5	0.17	-	-	-	0.80	0.18	0.59
MnO	0.08	-	-	-	-	0.06	
TiO_2	0.61	-	-	1.20	-	0.59	0.62
Cl	-	-	-	0.88	-	0.06	

2.5.2. Methods used for physicochemical characterisation of alum sludge

The pH and moisture content of alum sludge has been determined by the use of a pH meter and moisture content analyser respectively (Abd EL- Razek, Elgendy and Fouad, 2016; Ahmad, Ahmad and Alam, 2016; Dan *et al.*, 2018). The structure and surface morphology, mineralogy, and chemical composition of the alum sludge have been examined by the methods described below.

a) Fourier Transform Infrared spectroscopy

FTIR (Fourier Transform Infrared) spectroscopy is a widely used analytical technique for identifying and characterising organic and inorganic compounds based on their infrared absorption spectra (Khan *et al.*, 2018; Nandiyanto, Oktiani and Ragadhita, 2019). It provides valuable information about the functional groups and molecular structure of a sample (Khan *et al.*, 2018; Everaert *et al.*, 2021; Abba *et al.*, 2022).

b) X-Ray Fluorescence

X-ray fluorescence (XRF) is an analytical technique used by different researchers to determine the elemental composition of a sample (Shafii, Ling and Shaffie, 2019; Turner *et al.*, 2019; Everaert *et al.*, 2021; Garg *et al.*, 2021; Nguyen *et al.*, 2022a). It works by irradiating the sample with high-energy X-rays, which cause the atoms in the sample to emit characteristic X-ray fluorescence radiation (Garg *et al.*, 2021). By analysing the emitted X-rays, it is possible to identify and quantify the elements present in the sample. The principal asset of the X-ray fluorescence method over other elemental analysis techniques is its non-destructiveness, simultaneous multi-elemental capability, ingenuous sample preparation, and high resolution for trace elements (Garg *et al.*, 2021).

c) Scanning Electron Microscopy

SEM (Scanning Electron Microscopy) analysis of alum sludge can provide valuable information about the morphology and composition of the sludge (Wu *et al.*, 2019; Abba *et al.*, 2022). The SEM gives magnified images of the size, shape, composition, crystallography, and other physical and chemical properties of a specimen (Ural, 2021). During SEM analysis, a sample of the alum sludge is prepared and placed under the electron microscope. The sample is typically coated with a thin layer of conductive material, such as gold or chromium, to enhance the conductivity and

imaging quality (El-Tokhy *et al.*, 2020; Singh and Singh, 2022). The SEM instrument scans the sample with a focused electron beam, and the interaction between the electrons and the sample surface produces various signals that are detected and used to create an image (Ural, 2021; Singh and Singh, 2022).

2.5.3. Alum sludge reuse in phosphorus reduction

In the exploration of alum sludge reuse for phosphorus reduction, several studies have provided valuable insights. Ojha, Sharma and Amatya, (2019) delved into the alum sludge from the Mahankal Water Treatment Plant in Nepal, utilising batch tests with synthetic phosphorus solutions. Their findings demonstrated effective phosphorus reduction, reaching 98.4 % for a dosage 40 g/L and followed the Freundlich isotherm. However, their study was limited by its focus on synthetic phosphorus solutions, potentially not fully capturing the complexities of real-world wastewater compositions.

Expanding on this, Alwan and Rashid, (2021) explored the use of alum sludge from the Baqubah Treatment Plant in Iraq, which was oven-dried and finely ground, for phosphorus reduction from synthetic phosphorus solutions. Their study revealed optimal phosphorus reduction at a dose of 10 g/L and a contact time of 180 minutes, achieving percent reductions of 98 to 99 %. While powdered alum sludge increases the surface area for adsorption, factors such as alum sludge age have been shown to be of no real significance on P-adsorption (Nguyen *et al.*, 2022a). However, Alwan and Rashid, (2021) observed that powdered alum sludge increases the turbidity of water and cannot be easily recovered after adsorption. Therefore, they recommended exploring alternative forms of alum sludge for phosphorus adsorption.

Taking a broader perspective, Zhao *et al.*, (2021) provided a comprehensive overview of recent developments in the use of alum sludge for wastewater treatment processes. Their review highlighted reuse strategies such as low-cost adsorbents, substrates in constructed wetlands, primary coagulants for high-strength wastewater treatment, conditioners for co-conditioning sewage sludge, and novel materials for hydrogen sulphide/odour gas purification. They found that alum sludge has good adsorption ability for contaminants, making it a promising material for wastewater treatment. They, therefore, recommended expanding the scope of

research and development on alum sludge to further explore its widespread application as a raw material in wastewater treatment.

The foregoing studies were reliant on batch tests with synthetic water/wastewater or phosphorus solutions. Sharma and Ahammed, (2023) emphasized the significance of conducting studies using real wastewater to accurately evaluate the genuine potential of such sludge and the need for additional tests to optimize operating conditions. Their study showed the limitations associated with the application of the water treatment sludge powder. They, therefore, recommended the modification of this sludge powder into granules to enhance its application.

Collectively, these studies contributed to a comprehensive understanding of alum sludge's potential and highlighted the need for further exploration in real-world scenarios.

2.6. Benefits of alum sludge for phosphorus reduction

Alum sludge reuse offers several advantages, including cost-effectiveness as it provides a viable alternative to traditional methods of phosphorus removal, such as chemical precipitation or biological treatment (Everaert *et al.*, 2021; Zhao *et al.*, 2021; Nguyen *et al.*, 2022a). Moreover, due to the presence of aluminium ions, alum sludge is an efficient adsorbent of phosphorus (Alwan and Rashid, 2021; Nguyen *et al.*, 2022a). This process promotes sustainability and a closed-loop system by facilitating the reuse of spent resources (Dassanayake *et al.*, 2018; Abd EL-Razek, Elgendy, and Fouad, 2019; Niwagaba *et al.*, 2019).

2.7. Alum sludge reuse pathways after phosphorus adsorption

After the adsorption of phosphorus, if not properly managed, the alum-phosphate sludge produced can also become a nuisance. The growing world population and subsequent increase in food demand have created a need for additional sources of phosphorus (Tolofari *et al.*, 2022). According to Chapagain, (2016), Nguyen *et al.*, (2022b), and Tolofari *et al.*, (2022), Aluminium-Phosphorus (Al-P) sludge, which is generated during wastewater treatment, can be a beneficial source of phosphorus.

Tolofari *et al.*, (2022) tested the response of maize to Al-P sludge. Maize was chosen as the test crop due to its prevalent use as human and animal food and as a source of biofuel. The objective of the study was to investigate Al-P sludge as a source of

P compared to a commercial fertilizer (mono ammonium phosphate, MAP). The results showed that Al-P sludge was as effective as MAP in supplying enough P for the desired biomass yield. They, therefore, concluded that Al-P sludge could be an alternative source of P, especially for growing maize as feedstock for bioenergy.

2.8. Conclusion to the Literature Review

From the foregoing sections, it is evident that as the volume of alum sludge generated from drinking water treatment plants grows, sustainable and valuable reuse options have to be explored. While existing literature highlights the potential of alum sludge in various applications, including phosphorus reduction from wastewater, critical knowledge gaps persist. Many studies are based on synthetic phosphorus solutions and alum sludge powder tests, leaving uncertainties about the feasibility of alum sludge granules and challenges of implementing alum sludge-based methods in real-world wastewater treatment facilities. The wide-ranging variations in alum sludge compositions among different drinking water treatment plants underscore the necessity for specific evaluations before suggesting reuse applications.

This study takes a step in bridging these knowledge gaps by conducting a plant-specific evaluation and investigating the potential of granulation for phosphorus reduction in real-world wastewater effluent. This research study aims to provide insights into the suitability of the Katosi Drinking Water Treatment Plant alum sludge for phosphorus reduction.

CHAPTER THREE: METHODOLOGY

3.1. Introduction

This chapter encompasses the different procedures and methods that were used during the research process to attain data and information that aided in answering the earlier mentioned research questions, as well as implementing the specific objectives.

3.2. Research Design

The methodological research design for this research was based on the quantitative research design. To determine the potential for alum sludge reuse in wastewater treatment, the quantitative research design was followed because this type of research design focuses on "the organized inquiry about a phenomenon through the collection of numerical data and execution of statistical, mathematical or computational techniques (Opoku, Ahmed and Akotia, 2016). Quantitative research design is sourced from the "*positivism paradigm*", which is objective and is based on precise observation and verifiable measurement, and also the purpose of research under this paradigm is to test a theory or find the strength of relationships between variables (Ugwu, Ekere and Onoh, 2021). Therefore, the dissertation focused on experimental research, which relied on laboratory tests and statistical analysis to achieve the specific objectives as well as answer the research questions.

3.3. Area of Study

The wastewater effluent samples for this study were collected from the Lubigi Faecal Sludge and Wastewater Treatment Plant in Namungona, Kampala, Uganda. This facility, operational since May 2014, treats 400 m^3 of faecal sludge and 5,000 m^3 of wastewater daily. It employs waste stabilisation ponds for treatment and is located in Lubigi Wetland, Kawempe Division, Kampala District, about 5 km from Kampala city square. The plant serves areas including Kawempe, Bwaise, Katanga, Makerere, Nsooba, Mulago Hospital, Public Service, and Wandegeya, and is the second wastewater treatment plant in Kampala. It handles wastewater from the piped network and faecal sludge brought by private cesspool emptying trucks (Kyayesimira *et al.*, 2019).

The alum sludge samples utilised in this study were picked from the Katosi Drinking Water Treatment Plant. This facility is situated in the lakeside town of Katosi, within

the Ntenjeru Sub-county of Mukono District. The plant's coordinates are approximately 0° 07' 02.0" N and 32° 46' 37.0" E. Ownership of the Katosi Drinking Water Treatment Plant rests with the National Water and Sewerage Corporation, a government-owned entity entrusted with the responsibility of delivering safe drinking water and sewerage services across Uganda. The plant commenced operations in 2021, boasting an initial daily water treatment capacity of 160,000 m^3 of treated water per day, with plans for future expansion to accommodate up to 240,000 m^3 of water daily. This significant infrastructure development anticipates serving an estimated population of 4.5 million individuals by 2025 and a projected 7 million residents by the year 2040 (SOGEA SATOM and SUEZ, 2019).

3.4. Information Sources

For this study, data was collected from both primary and secondary sources. Primary sources included laboratory tests, experiments, and observations, while secondary sources consisted of books, journals, articles, reports, and manuals.

3.5. Methods for achieving specific objectives

3.5.1. Characterisation of the wastewater effluent

a) Effluent sample collection and preservation

The effluent sample was collected from the Lubigi Faecal Sludge and Wastewater Treatment Plant on 15th July 2023 at midday as a grab sample to attain representative results (Ren *et al.*, 2020c). The effluent grab sample was picked using a 10-litre plastic jerry can at about 0.4 m below the surface of the water at the exit (weir) of the facultative ponds before discharge into the Lubigi Wetland.

Following collection, the sample was preserved by adding 2 mL of concentrated sulphuric acid per litre to attain a pH<2 (APHA, 1999; Smith, 2016), see Figure 3-1. The sample was then transferred into ten replicate 1000 ml sample-rinsed white HDPE wide-mouthed bottles with screw caps. These bottles were carefully placed inside a cooler box, alongside ice packs, to maintain a low temperature during transportation to the laboratory. Upon arrival at the laboratory, the samples were stored at 4°C, following the U.S. EPA guidelines (United States Environmental Protection Agency, 1983), as depicted in Figure 3-1.

Figure 3-1: Effluent sample acidification (left and next center), packing for transportation and refrigeration (sample with ice packs and later placed in the fridge at 4ºC)

b) Effluent sample analysis

The sample (from one of the sample-filled 1000 mL white HDPE wide-mouthed bottles with screw caps) was then analysed in the laboratory to determine the total phosphorus concentration following the US EPA Method 365.3 (United States Environmental Protection Agency, 1983) using the HACH DR6000 UV-VIS laboratory spectrophotometer at a wavelength of 880 nm.

The temperature, pH, and electrical conductivity were determined using the HACH Sension+ MM374 GLP 2-channel Laboratory meter. The turbidity was measured using a HI-88713-02 ISO turbidity meter.

For the Chemical Oxygen Demand (COD), the sample was digested using the RD010 heating reactor at 150°C for 120 minutes, left to cool, and then analysed in the Lovibond SpectroDirect single-beam spectrophotometer following the US EPA Method 410.4, (O'Dell, 1993). The true colour was analysed using the same spectrophotometer following the Lovibond method 203. The Total Suspended Solids (TSS) were also determined using the gravimetric method, US EPA Method 160.2 (O'Dell, 1999).

The 5-day Biochemical Oxygen Demand (BOD_5) of the effluent sample was determined using the Lovibond® BD 600 BOD measurement system following the Lovibond BD 600 Instruction Manual (Lovibond® Water Testing Tintometer® Group, 2015). Initially, a 244 mL overflow measuring flask was used to measure the sample, which was then transferred into 500 mL BOD brown glass test bottles. To suppress nitrification, 5 drops of nitrification inhibitor were then added to the BOD test bottles, accompanied by the introduction of a clean magnetic stir bar. The dry seal cups were then filled with 4 drops of 45 % potassium hydroxide solution for binding of carbon dioxide and placed in the BOD test bottles. BOD screw sensor caps, see insert of Figure 3-2, were affixed to the BOD test bottles and arranged in the test bottle rack. The entire set was positioned in a thermostat cabinet, Figure 3-2, set to 20ºC for the 5-day BOD testing period. The cabinet was checked every day to ensure continuous power supply.

Figure 3-2: Potassium hydroxide solution and nitrification inhibitor used (left) the test bottle rack placed in the thermostat cabinet (middle) and, 500 mL BOD brown glass test bottles with BOD sensor screw caps (right)

3.5.2. Characterisation of alum sludge

a) Sample collection and preparation

The environmentally dried alum sludge samples (sludge cakes) were collected on 16th May 2023 at midday in polyethylene bags randomly according to drying age from different points of the open dump site at the Katosi plant to attain representative results (Ren *et al.*, 2020c). The samples were then further dried in an oven (MATEST

A005-01 forced ventilation laboratory oven) at 105°C for 24 hours and then left to cool, see Figure 3-3, (Abba *et al.*, 2022; Djekoune *et al.*, 2022; Nguyen *et al.*, 2022a; Nguyen *et al.*, 2023). The cooled sample was then crushed using a DE 500 g Universal Mill Electric Powder Grinder, Figure 3-4, (Wu *et al.*, 2019; Alwan and Rashid, 2021). It was then passed through a 120-mesh sieve (0.125 mm opening size) using a vibratory sieve shaker AS 300 set at an amplitude of 1.0 to 1.5 mm, shown in Figure 3-4, to obtain fine ground powder, which was sealed in an airtight glass container and stored at ambient temperature (Wu *et al.*, 2019).

Figure 3-3: Alum sludge sample placed in an oven (left) and sludge sample left to cool at room temperature (right)

Figure 3-4: Grinding of oven-dried alum sludge sample using a Universal Mill Electric Powder Grinder (left and center) and sieving using a Vibratory Sieve Shaker AS 300 (right)

b) Alum sludge sample characterisation

To determine the pH of the alum sludge, 20 ml of distilled water was added to 0.5 g of powdered alum sludge, and an ODEON portable pH meter was utilized for measurement (Ren *et al.*, 2020b). The moisture content of both the sludge cakes and alum sludge powder was determined using a PMB Adam Scale moisture analyser. Further Characterisation of the powdered Alum sludge before granulation was conducted using two analytical techniques: Fourier Transform Infrared (FTIR) microscopy with the Shimadzu IR Tracer 100 Fourier Transform Infrared Spectrophotometer within a range of 500-4500 cm^{-1} and X-ray fluorescence (XRF) with the Malvern PANalytical Epsilon 3XLE X-Ray Spectrometer. These analyses aimed to determine both the functional groups and chemical compositions present in the alum sludge (Garg *et al.*, 2021; Nguyen *et al.*, 2022a). This analysis was done from the Directorate of Government Analytical Laboratories (DGAL) – Kampala, Uganda.

To obtain magnified images of the alum sludge powder and the alum sludge granule surface, Scanning Electron Microscopy (SEM) was employed (Ul-Hamid, 2018; Wu *et al.*, 2019; Everaert *et al.*, 2021). For SEM imaging, a prepared alum sludge granule (ASG) underwent several steps of preparation. Initially, it was dehydrated using increasing concentrations of ethanol, desiccated, and subsequently stored in an air-tight container. A surgical blade was then used to trim a portion of the dried alum sludge granule to fit onto SEM stubs (Ul-Hamid, 2018). This trimmed piece was affixed to the stub using double-sided carbon tape. The oven-dried alum sludge powder was also mounted on the SEM stubs with the help of double-sided carbon. To ensure conductivity, a 5 nm layer of chromium was applied to the samples using a Q150T ES sputter coater, see Figure 3-5. The prepared samples, in the form of an alum sludge granule and the oven-dried alum sludge powder, were then transferred to the Vapour Pressure Sigma 300 High-Resolution Scanning Electron Microscope for detailed surface characterisation (Wu *et al.*, 2019; Everaert *et al.*, 2021; Thabet *et al.*, 2022), as depicted in Figure 3-5 below.

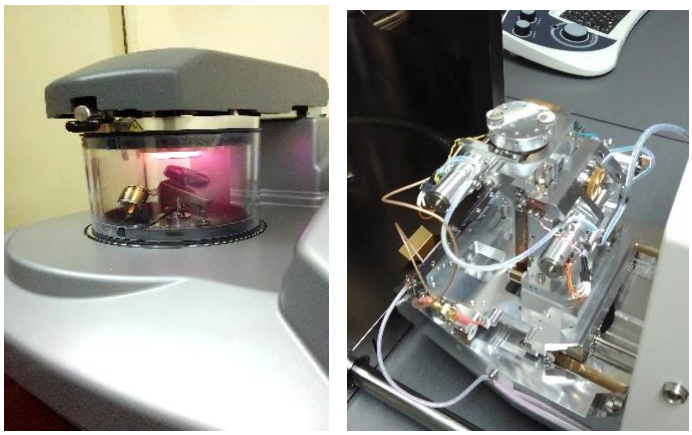


Figure 3-5: Coating ASG and alum sludge powder samples with chromium using a Q150T ES splutter coater (left) and prepared samples transferred to the Vapour Pressure Sigma 300 High-Resolution Scanning Electron Microscope for detailed surface characterisation (right)

3.5.3. Evaluation of phosphorus reduction efficiencies of alum sludge

a) Preparation of alum sludge granules

This involved the incorporation of an organic binder, Carboxymethyl cellulose (CMC), into the powdered alum sludge, which was added at a weight percentage of 3 % during the mixing process (Wu *et al.*, 2019), Figure 3-6-(A). For every 80 grams, 2.4 g of CMC was mixed with 77.6 g of powdered alum sludge thoroughly, and then 80 ml of distilled water was added to form a wet mixture, Figure 3-6-(B). The mixture was then carefully transferred into a spherical silicon mould, Figure 3-6-(C), where it was allowed to undergo a natural air-drying process for approximately 48 hours (Wu *et al.*, 2019). This was carried out within a well-ventilated room, maintained at ambient temperature (Wu *et al.*, 2019; Everaert *et al.*, 2021; Shi *et al.*, 2023), Figure 3-6-(D). Consequently, this method facilitated the gradual formation of the Alum Sludge Granules (ASG), Figure 3-6-(E and F).

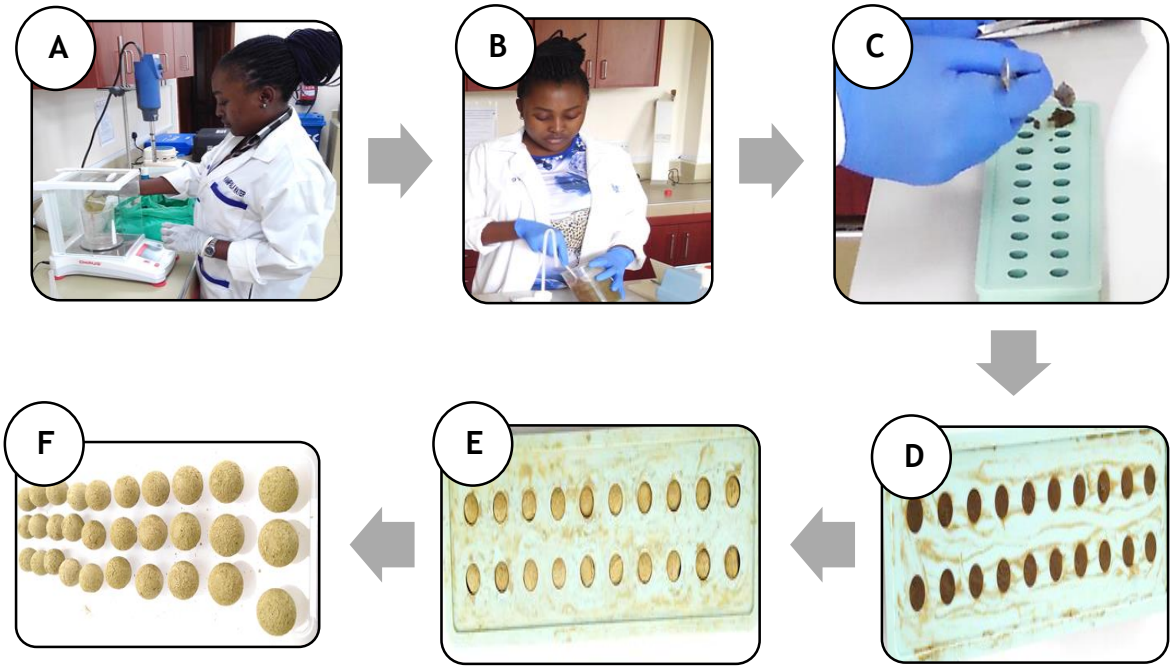


Figure 3-6: Alum sludge granulation process; weighing of alum sludge powder and CMC (A), formation of a wet mixture (B), wet mixture put in a silicon mould (C), mixture left to dry for 48 hours (D), and alum sludge granules formed (E and F)

b) Preparation of phosphorus stock solution for positive control

Effluent spiking, a critical step in the experiment, was used to artificially elevate the concentration of phosphorus (the target compound) in the wastewater effluent sample, for the positive control (Sabri and Gyateng, 2015; Moser, 2019; Hendricks-Sturrup, 2023). By adding a known amount of the target compound to the effluent, a "spiked" sample that reflects a higher concentration than that found in the original wastewater effluent is obtained (Hendricks-Sturrup, 2023). This spiked sample in this study was then used as the positive control. Potassium di-hydrogen Phosphate was used for the preparation of the stock solution for the wastewater effluent sample spiking.

Potassium di-hydrogen Phosphate (KH_2PO_4) was dried at 105°C for 2 hours (Wu *et al.*, 2019). 3.4 g of KH_2PO_4, from Equation 3-1, was transferred to a 500 mL volumetric flask and dissolved in distilled water to the mark to prepare the 50 mg/L of phosphorus stock solution (Wu *et al.*, 2019; Nguyen *et al.*, 2022a).

$$Required\ mass\ of\ salt = molar\ mass\ of\ salt \times desired\ stock\ solution\ concentration \times desired\ volume\ of\ stock\ solution$$

Equation 3-1

The stock solution, 50 mg P/L, was diluted following Equation 3-2, to attain the desired spike volume: 47.6 mL/flask.

$$C_1V_1 = C_2V_2$$

Equation 3-2

Where, C_1 and V_1 are the concentration and volume of the stock solution, and C_2 and V_2 are the concentration and volume of the desired solution.

c) Batch experiments with wastewater effluent

Batch experiments were performed with the effluent samples to evaluate the phosphorus adsorption and the impact of the different quantities of the granulated alum sludge adsorbent at different contact times (Wu *et al.*, 2019). 250 mL of effluent sample was poured into each of the 500 mL BOD brown glass sample flasks (Lovibond® BD 600) and 3 g, 6 g, and 9 g of Alum Sludge Granules (ASG) were added to differently labelled flasks for the experimental group. A magnetic stirrer was then added to each of the flasks to ensure continuous agitation (Wu *et al.*, 2019), sealed off with their respective Lovibond BD 600 BOD measurement system sensor heads, and placed on the inductive stirring unit. A timer was set for the respective sampling times (6 hours, 15 hours, and 24 hours) for each flask (Razali, Zhao and Bruen, 2018; Wu *et al.*, 2019; Everaert *et al.*, 2021; Nguyen *et al.*, 2022a). All the batch experiments were carried out under ambient temperature conditions, and the entire set of experiments was replicated three times (Shi *et al.*, 2023).

Controls were used to measure the impact of the treatment (Sabri and Gyateng, 2015; Moser, 2019). For the negative control, the original wastewater treatment plant effluent (from the exit of the facultative ponds before discharge into the Lubigi Wetland), with no phosphorus spike, was used with no alum sludge granules added and the positive control had 250 ml of spiked effluent (spiked with 9.5 mg/L of phosphorus) with the same granulated alum sludge masses as the experimental group.

All the experiments were carried out in a laboratory at a temperature of 25 °C ± 1. The initial total phosphorus concentration of the effluent sample used for the experiments was; 22.581 mg/L for the experimental group and the negative control whereas the positive control was spiked to 32.107 mg/L. Each of the ASGs made for this study was approximately 1.5 g at the time of the experimental setup.

Aliquot samples were pipetted from each flask at each of the time durations to measure the residual TP concentrations in the liquid phase following the US EPA Method 365.3 (United States Environmental Protection Agency, 1983) using the HACH DR6000 UV VIS spectrophotometer at a wavelength of 880 nm. The ascorbic acid method used to determine the residual TP converts all forms of phosphorus to orthophosphates. It enables conversion of the organic and inorganic phosphorus forms into orthophosphates, providing a total phosphorus reading. This simplifies analysis and allows comparison with regulatory limits.

The percent reduction was determined by Equation 3-3 (He *et al.*, 2022);

$$R = \frac{C_{in} - C_{out}}{C_{in}} \times 100\ \%$$

Equation 3-3

Where; R is the percent reduction and C_{in} and C_{out} are the initial and final total phosphorus concentrations in mg/L respectively.

3.5.4. Assessment of phosphorus adsorption capacity of alum sludge

The results of the adsorption batch experiments were evaluated using adsorption isotherms, whose importance is to describe how adsorbates interact with adsorbents (Muisa *et al.*, 2020; Abin-Bazaine, Trujillo and Olmos-Marquez, 2022), and the percent phosphorus reduction which served as the performance indicator for each contact time duration (Everaert *et al.*, 2021; Zhao *et al.*, 2021; Nguyen *et al.*, 2022a).

The adsorption capacity of the ASG was assessed through the application of adsorption isotherms (Ayawei, Ebelegi and Wankasi, 2017; Al-Ghouti and Da'ana, 2020; Musah *et al.*, 2022). The adsorption capacity at equilibrium was determined using Equation 3-4;

$$q_e = \frac{C_i - C_f}{m} \times V$$

Equation 3-4

Where; q_e is the adsorption capacity of the adsorbate (mg/g), C_i and C_f are the initial and final phosphorus concentrations (mg/L) respectively, m is the mass of the adsorbent (g), and V is the volume of the solution (L).

In this study, the isotherm studies involved the use of Langmuir and Freundlich isotherms (Maqbool, Khan and Asghar, 2016; Everaert *et al.*, 2021; Pająk, 2023).

i. Langmuir isotherm model

This model assumes that the highest level of adsorption aligns with a monolayer of adsorbate molecules covering the adsorbent's surface, the adsorption energy remains consistent, and there is no movement of the adsorbate on the adsorbent's surface (Ayawei, Ebelegi and Wankasi, 2017; Sreeremya, 2017; Al-Ghouti and Da'ana, 2020). The Langmuir model is expressed by the linear Equation 3-5 below.

$$\frac{C_e}{q_e} = \frac{1}{q_m} C_e + \frac{1}{q_m K_L}$$

Equation 3-5

Where; C_e is the concentration of the adsorbate at equilibrium (mg/L), K_L is the Langmuir constant (L/g), q_m is the maximum adsorption capacity (mg/g) and q_e is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg/g). The values of K_L and q_m were determined from the slope and intercept of the line obtained from a graph of $\frac{C_e}{q_e}$ against C_e. The model was also represented by the separation factor, R_L, as expressed in Equation 3-6:

$$R_L = \frac{1}{(1 + K_L C_i)}$$

Equation 3-6

Where; C_i is the initial concentration in mg/L. The values of the separation factor indicate adsorption to be unfavourable when $R_L > 1$, linear when $R_L < 1$, and favourable when $0 < R_L < 1$ (Ayawei, Ebelegi and Wankasi, 2017; Ojha, Sharma and Amatya, 2019; Al-Ghouti and Da'ana, 2020; Musah *et al.*, 2022).

ii. Freundlich isotherm model

This approach considers the adsorbent's surface heterogeneity (Abin-Bazaine, Trujillo and Olmos-Marquez, 2022). The Freundlich model, utilizing an exponential distribution of active sites and energies, effectively explains reversible and non-ideal adsorption (Ayawei, Ebelegi and Wankasi, 2017; Sreeremya, 2017; Musah *et al.*, 2022). Unlike the Langmuir model, Freundlich accommodates multilayer, not just monolayer, adsorption (Nimibofa, Augustus . N and Donbebe, 2017; Mohammad A and Dana A, 2020; Monday *et al.*, 2022). Moreover, the Freundlich isotherm accounts for the uneven distribution of adsorption heat and affinities on diverse surfaces (Mohammad A. and Dana A., 2020). The model is expressed in its linear form as in Equation 3-7;

$$logq_e = \frac{1}{n} logC_e + logK_F$$

Equation 3-7

Where; $\frac{1}{n}$ is the adsorption intensity and K_F is the Freundlich constant (L/g).

A graph of $logq_e$ versus $logC_e$ was plotted and was used to determine the intercept and slope as $logK_F$ and $\frac{1}{n}$ respectively.

Suitability of isotherm models

Statistical methods are utilized to assess how well the values obtained through the selected isotherm equation align with the experimentally determined values (Al-Ghouti and Da'ana, 2020; Musah *et al.*, 2022). The evaluation of discrepancies between the observed experimental values and the values calculated using the isothermal model is quantified through a parameter known as the "goodness of fit" (Nimibofa, Augustus . N and Donbebe, 2017; Mohammad A and Dana A, 2020; Monday *et al.*, 2022).

i. The Chi-square test (χ^2)

To identify the optimal isothermal model, the Chi-square values and linear regression (R^2) were integrated (Abin-Bazaine, Trujillo and Olmos-Marquez, 2022). The Chi-square test statistic, Equation 3-8 captured the summed squared errors between actual experimental data and model-calculated values (Nimibofa, Augustus N and Donbebe, 2017; Mohammad A and Dana A, 2020; Monday *et al.*, 2022).

$$\chi^2 = \sum_{i=1}^{n} \frac{(q_{e,exp} - q_{e,calc})^2}{q_{e,calc}}$$

Equation 3-8

Where; $q_{e,cal}$ is the theoretical concentration of adsorbate on the adsorbent which has been calculated from the isotherm model (mg/g) and $q_{e,exp}$ is the concentration measured from the experiment (mg/g).

ii. The t-tests and F-tests

These served as crucial statistical tools to assess the validity and significance of the isotherm models (Langmuir and Freundlich) in describing the adsorption behaviour of phosphorus onto ASG (Montgomery, 2013; Seltman, 2018).

Note: The most suitable isotherm model was selected following the criteria highlighted by Al-Ghouti and Da'ana, (2020)

3.6. Quality Control

All the glassware and PE bottles used for the study were prepared with an acid wash soaking overnight and rinsed with distilled water before use (Smith, 2016; Kayiwa *et al.*, 2022). The effluent sample was characterised within a 24-hour timeframe from its collection, following the recommended guidelines outlined by Smith, (2016).

The experiments were performed in triplicate to achieve valid and more reliable estimates to enhance precision, resulting in more accurate and dependable findings and reduced experimental error (Seltman, 2018; Herzog, Francis and Clarke, 2019; Natoli and Oimoen, 2019). These replicates were presented as average values.

To ensure that all treatment combinations were catered for, the study involved a two-factor factorial experiment with three levels each (3^2 factorial design). The factorial design enabled systematic investigation of the main effects of each independent variable (contact time and ASG mass), as well as the interactions between them (Montgomery, 2013; Natoli and Oimoen, 2019). The 3^2 notation indicates that there were three levels for each of the two factors, resulting in nine possible combinations, that is; ASG masses (3 g, 6 g, and 9 g) and also contact time (6, 15, 24) hours.

In summary, this chapter details the materials, procedures, and methods employed to characterise wastewater effluent and alum sludge, crucial elements in the assessment of phosphorus adsorption. The characterisation of wastewater effluent from the Lubigi Faecal Sludge and Wastewater Treatment Plant in Namungona – Kampala, involved a systematic approach, from sample collection and preservation to the analysis of various parameters. The characterisation of alum sludge from the Katosi Drinking Water Treatment Plant in Katosi – Mukono, involved the use of advanced techniques such as FTIR microscopy, XRF analysis, and Scanning Electron Microscopy, enhancing the understanding of its properties. Batch experiments with prepared alum sludge granules were used to further explore the potential of alum sludge in reducing phosphorus in wastewater effluent. The results of these experiments, along with their implications, are presented and discussed in the upcoming chapter, shedding light on the potential of alum sludge from the Katosi plant as a phosphorus adsorbent in wastewater effluent in Uganda.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Wastewater treatment plant effluent characteristics

The effluent quality of the grab sample obtained from the Lubigi Faecal Sludge and Wastewater Treatment Plant served as the initial baseline data against which the effectiveness of the adsorption experiments was evaluated. The effluent grab sample quality, in Table 4-1, was compared against the Maximum Permissible Limits for the discharge of effluent into water or land.

Table 4-1: Comparison of effluent quality (grab sample) with Maximum Permissible Limits

Parameters	Units	Effluent sample quality	National standards for effluent discharge (Maximum Permissible Limits)	Compliance
Temperature	°C	25.8 ± 1.29	20 - 35	C
pH	-	8.65 ± 0.26	6.0 – 8.0	NC
Electrical conductivity	µS/cm	2840 ± 8.54	1500	NC
Colour	TCU	2808 ± 29.51	500	NC
Turbidity	NTU	241 ± 3.61	300	C
Total suspended solids	mg/L	379 ± 10.60	100	NC
Total phosphorus	mg/L	22.581 ± 1.18	10	NC
BOD_5	mg/L	153 ± 9.85	50	NC
COD	mg/L	430 ± 9.64	100	NC

The Maximum Permissible Limits in Table 4-1 are as per National Environment Management Authority, (2020); C = Compliant and NC = Non-compliant

The effluent sample quality results showed notable deviations from the Maximum Permissible Limits, particularly in colour, suspended solids, phosphorus, Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD), Table 4-1. The wastewater effluent sample quality parameters provide essential context, outlining the initial conditions and challenges posed by the effluent (Usman *et al.*, 2022). The presence of coexisting constituents in the wastewater effluent competing for the same adsorption sites as the phosphorus ions can collectively affect the adsorption ability of adsorbents (Wu *et al.*, 2019; Muisa *et al.*, 2020; Nguyen *et al.*, 2022a;

Usman *et al.*, 2022). According to Wu *et al.*, (2019), these coexisting constituents create competition for adsorption sites, physically block these sites, interfere with phosphorus adsorption, and lead to quicker saturation of available sites, hence reducing the adsorption capacity of the alum sludge granules.

4.2. Alum sludge characteristics

The environmentally dried alum sludge cakes were relatively dry; therefore, their moisture content was found to be 17.32 %. The cakes were then oven-dried to a final moisture content of 9.23 %. They were then crushed and sieved to a uniform particle size of 0.125 mm. Uniform powder particle size in granule production is crucial for consistent and reproducible adsorption processes, enhancing reliability and efficiency, promoting scalability in practical applications (Diaba-Nuhoho and Amponsah-Offeh, 2021). The pH of the alum sludge was 7.24. While slightly alkaline, this pH falls within the optimal pH range (6.5 – 8.5) as reported by multiple studies; (Ackah *et al.*, 2018; Ghorpade and Ahammed, 2018; Barakwan, Trihadiningrum and Bagastyo, 2019; Abba *et al.*, 2022; Pająk, 2023). The pH of alum sludge is important because it indicates the availability of aluminium ions for phosphorus adsorption (Bacelo *et al.*, 2020; Muisa *et al.*, 2020). Aluminium ions readily bind to phosphorus ions, reducing them from the wastewater effluent (Bacelo *et al.*, 2020). However, their availability is dependent on pH (Tibebe, Kassa and Bhaskarwar, 2019). At a pH of 7.24, a portion of the aluminium ions remains soluble, allowing them to bind to the phosphorus ions in the wastewater effluent.

4.2.1. Chemical composition of alum sludge

The composition of alum sludge is location-specific and depends on the seasonal changes in raw water quality, the use of chemicals as well and the treatment processes (Wu *et al.*, 2019; Nguyen *et al.*, 2022b). The qualitative analysis of the powdered alum sludge using X-ray fluorescence (XRF), Table 4-2, revealed that silicon dioxide (SiO_2) constituted the majority of the sludge followed by aluminium oxide (Al_2O_3) and other oxides were also found in smaller percentages.

Table 4-2: Chemical composition of alum sludge from XRF analysis

Components	Percentage (%)
SiO_2	58.955
Al_2O_3	38.614
Fe_2O_3	2.031
CaO	9.499
K_2O	0.177
P_2O_5	0.403
MnO	8.710
TiO_2	0.443
Cr_2O_3	0.731
Cl	0.051

The XRF results presented in Table 4-2 were consistent with those of prior studies (Ahmad, Ahmad and Alam, 2016; Breesem, Abood and Rahman, 2016; Breesem, Faris and Abdel-Magid, 2016; El-Tokhy *et al.*, 2020; Djekoune *et al.*, 2022; Sharma and Ahammed, 2023). SiO_2, as noted by Nguyen *et al.*, (2022b), is mainly from raw water and accounts for a significant part of alum sludge's composition. Silicon is also likely originated from sand in the drying beds from which the alum sludge sample was obtained. Additionally, the presence of aluminium can be linked to the coagulant used in water treatment at the KDWTP during the time of sampling. The proportion of Al is due to the use of aluminium sulphate as a coagulant in the water treatment process (Abd EL- Razek, Elgendy and Fouad, 2016; Djekoune *et al.*, 2022; Nguyen *et al.*, 2022b). The presence of aluminium is important since it has been established as a substantial contributor to alum sludge's adsorption capabilities, a fact supported by studies conducted by Wu *et al.*, (2019), Muisa *et al.*, (2020), Everaert *et al.*, (2021), Zhao *et al.*, (2021), Djekoune *et al.*, (2022), and Nguyen *et al.*, (2022a). This is primarily attributed to the positively charged aluminium oxide, which electrostatically attracts the negatively charged phosphorus, as documented by (Muisa *et al.*, 2020; Sharma and Ahammed, 2023). The presence of phosphorus in the alum sludge before the adsorption experiments may be attributed to the source raw water quality. When alum is added for water treatment, it reacts with impurities in the raw water which leads to the incorporation of these impurities in the resulting

alum sludge (Ackah *et al.*, 2018; Zhao *et al.*, 2021; Nguyen *et al.*, 2022b). The 2-year raw water quality monitoring report by SOGEA SATOM and SUEZ, (2019) recounted the presence of phosphorus (at an average of 0.73 mg TP /L) in the source water which was evidenced by the enhancing algae growth.

4.2.2. FTIR characterisation

Figure 4-1 presents the FTIR spectrum of the alum sludge at a wavelength between 500-4500 cm^{-1} representing the functional groups present in the alum sludge from FTIR analysis. The FTIR spectrum band revealed the presence of the hydroxyl group and C-O stretching vibrations as well as Si-O-Si and O-Si-O bands in the fingerprint region.

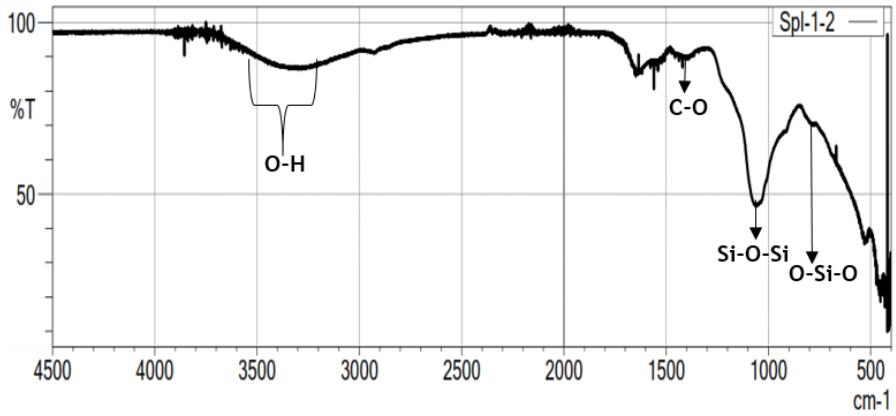


Figure 4-1: FTIR spectrum of the powdered alum sludge sample

The FTIR spectrum (Figure 4-1) showed a distinctive feature at 3200 to 3550 cm^{-1}, indicating hydroxyl (O-H) stretching vibrations, as stated by Khan *et al.*, (2018). These hydroxyl groups enhance alum sludge's adsorption, especially for phosphorus removal, and facilitate strong interactions with phosphorus compounds in water, a key aspect of effective phosphorus removal (Muisa *et al.*, 2020; Abba *et al.*, 2022). The spectrum also revealed C-O stretching vibrations and Si-O-Si and O-Si-O bands in the fingerprint region (Khan *et al.*, 2018; Nandiyanto, Oktiani and Ragadhita, 2019). The presence of Si-O-Si and O-Si-O bands confirms the presence of silicon dioxide. The C-O bands may suggest the presence of organic compounds present in the water from the source as noted by Abba *et al.*, (2022) and Nguye *et al.*, (2022a).

4.2.3. Morphological characterisation

Alum sludge powder, Figure 4-2; the Scanning Electron Microscope (SEM) images of the oven-dried alum sludge reveal a rough surface with particles exhibiting diverse sizes and shapes, indicative of an amorphous structure. This amorphous nature is due to the presence of non-crystalline aluminium hydroxide (Sharma and Ahammed, 2023). This is consistent with results reported by several studies (Ghorpade and Ahammed, 2018; Wu *et al.*, 2019; Muisa *et al.*, 2020; Pająk, 2023; Sharma and Ahammed, 2023). The alum sludge powder shows a loose and dispersed arrangement of particles; this contributes to a more porous structure with a high surface area (Everaert *et al.*, 2021).

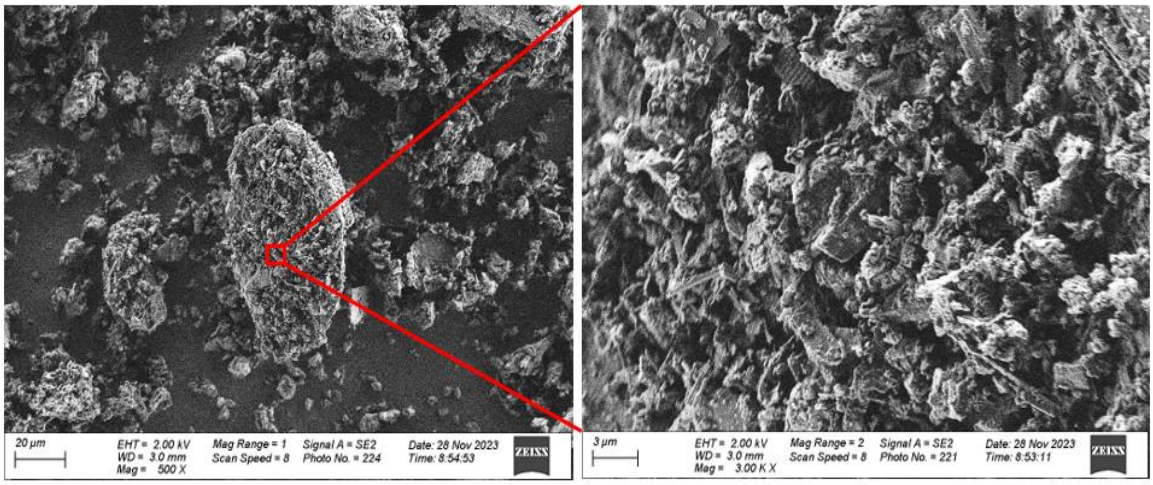


Figure 4-2: SEM micrographs of the oven-dried alum sludge powder at magnifications of 500 and 3000

Alum sludge granules (ASG), Figure 4-3 and Figure 4-4; the SEM images of the analysed alum sludge granule surface are presented in the figures below. Figure 4-3 represents the physical morphology of the alum sludge granule surface at magnifications of 76 (left) and 222 (right) at resolutions of 100 μm and 40 μm respectively.

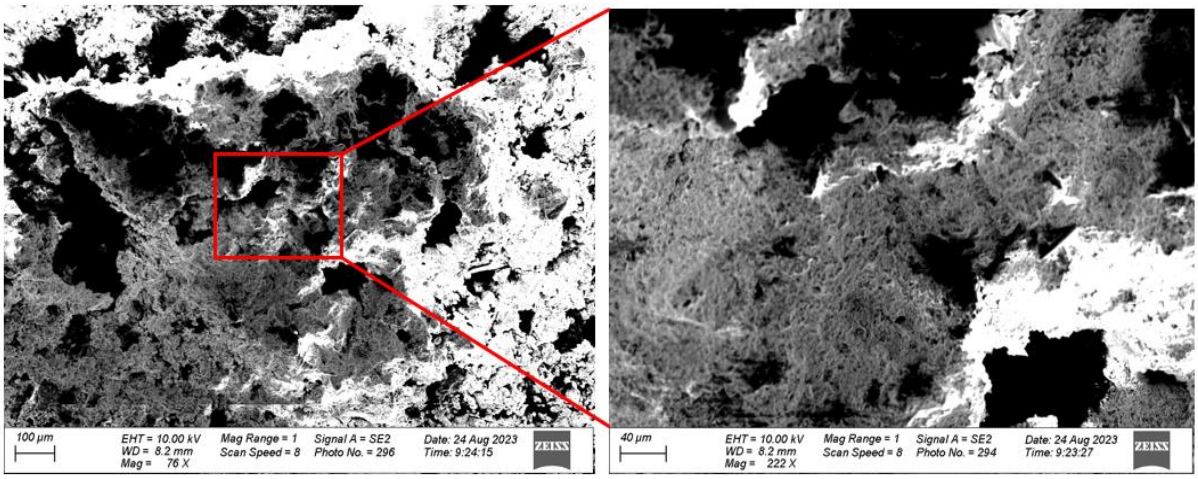


Figure 4-3: SEM micrographs showing the surface of the alum sludge granule at magnifications of 76 and 222

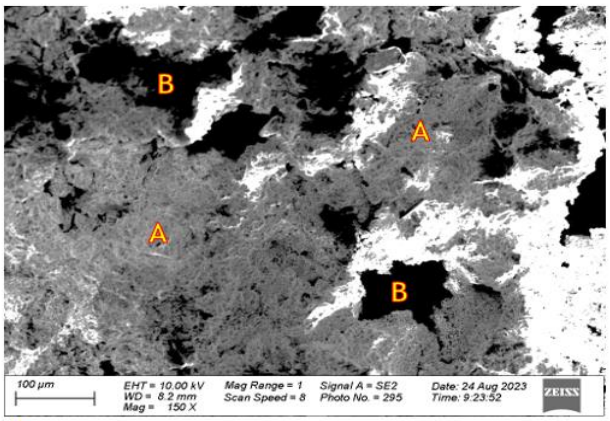


Figure 4-4: SEM micrograph of alum sludge granule showing the compact areas (A) as well as the pores (B)

The ASG SEM micrographs, Figure 4-3 and Figure 4-4, underscored the key structural characteristics of the ASG including;

Porosity: The presence of numerous pores of varying sizes is evident in the SEM images of the ASG. However, Everaert *et al.*, (2021) noted the reduced surface area of alum sludge granules as compared to the alum sludge powder due to the granulation contributing to the overall reduction in the adsorbent's adsorption capacity.

Surface roughness: the alum sludge exhibits a rough surface before and after moulding, Figure 4-2 and Figure 4-3 respectively. However, compared to the powder

the granule exhibits a more localized and controlled roughness due to the granulation process. These results and observation are consistent with those reported by Turner *et al.*, (2019), Wu *et al.*, (2019) and Shi *et al.*, (2023).

Compactness: When compared with the alum sludge powder, the alum sludge granules were more compact and consolidated. The compact parts of the granule, Figure 4-4- B, appear to have tightly packed particles with reduced space between them. Wu *et al.*, (2019) specifically noted the compactness of the granulated alum sludge granules in their study as well. This structural compactness holds significance for P adsorption, as it minimizes mass transfer limitations, reduces channelling, maximizes surface contact, and enhances overall stability (Wu *et al.*, 2019, 2022). Consequently, ASG's compact yet porous nature contributes to its effectiveness as an adsorbent for P reduction.

4.3. Adsorption of TP onto ASG

All the experiments were carried out in a laboratory at a temperature of 25 °C ± 1. The initial total phosphorus concentration of the effluent sample used for the experiments was; 22.581 mg/L for the experimental group and the negative control whereas the positive control was spiked to 32.107 mg/L. Each of the ASG made for this study was approximately 1.5 g at the time of the experimental setup. The effect of the contact time (6,15 and 24) hours and the masses (3, 6, and 9) g of the ASG on the Total phosphorus (TP) concentration are presented in this section.

4.3.1. Effect of the mass of alum sludge granules

The effect of the masses (3, 6, and 9) g of the ASG on the Total phosphorus (TP) concentration for both the experimental group and the postive control is presented in Figure 4-5. The Maximum Permissible Limit (MPL) represents the desired treatment target.

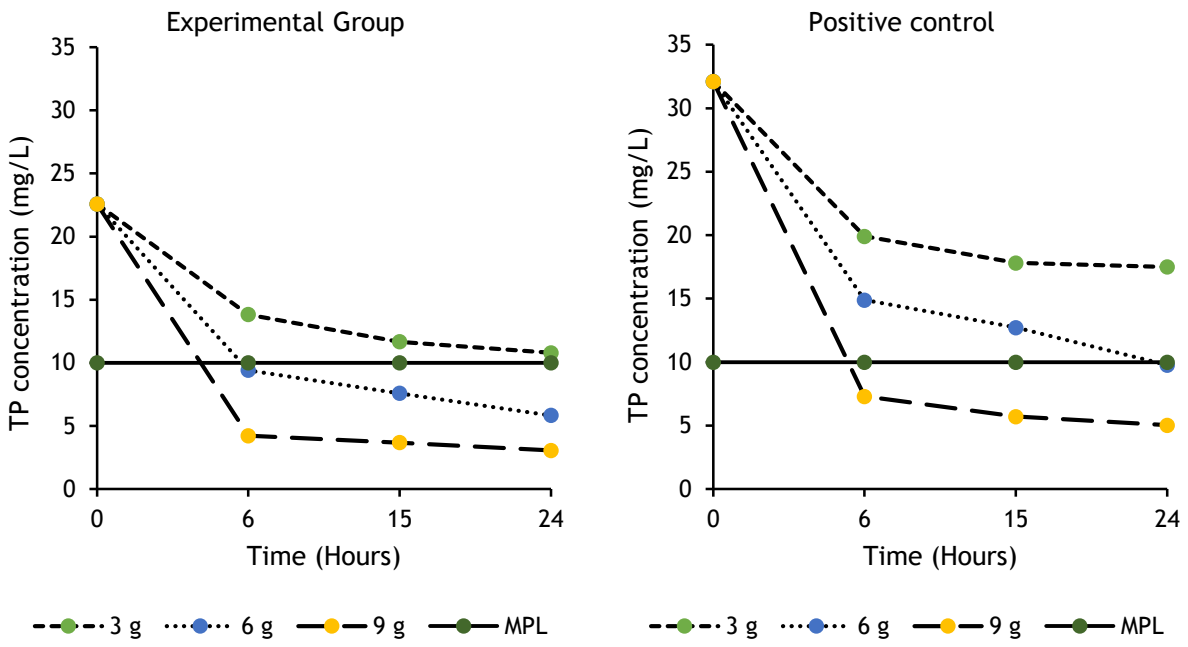


Figure 4-5: Effect of mass of ASG on the Total Phosphorus concentration for the experimental group with an initial TP concentration of 22.581 mg/L and the positive control with an initial concentration of 32.107 mg/L compared against the MPL of 10 mg/L

The relation between the mass of the alum sludge granules (ASG) and the total phosphorus concentration is shown in Figure 4-5. As the ASG mass increased (3 g, 6 g, and 9 g), the TP concentration decreased for both the experimental and positive control groups. The MPL for both the experimental group and the positive control was attained by the 6 g and 9 g ASG masses. This is because the amount of phosphorus reduced by adsorption is directly proportional to the mass of the adsorbent (Muisa *et al.*, 2020; Usman *et al.*, 2022). Increasing the adsorbent mass enhances P-reduction as it increases the number of active sites and total surface area for adsorption (Wu *et al.*, 2019; Muisa *et al.*, 2020; Zhang *et al.*, 2020; Alwan and Rashid, 2021; Abba *et al.*, 2022). However, the Maximum Permissible Limit was not attained in both groups by the 3 g ASG mass. This suggests that 3 g of ASG is not sufficient to reduce the total phosphorus to the desired MPL. This may be due to the presence of limited adsorption sites for phosphorus adsorption as reported by Maqbool, Khan and Asghar, (2016), Hou *et al.*, (2018) and Muisa *et al.*, (2020) hence highlighting the limitations of low ASG masses for achieving desired TP reductions.

Initially, there was a rapid decline in the TP concentration for all ASG masses in both the experimental group and the positive control followed by gradual declines. This

is because phosphorus is swiftly adsorbed onto easily accessible sites, including macro pores and surface functional groups, primarily through a ligand exchange mechanism (Hou *et al.*, 2018; Zhao *et al.*, 2021). Muisa *et al.*, (2020) noted that the exchange mechanism involving the hydroxyl functional groups accounts for a substantial portion of phosphorus adsorption onto the alum sludge's surface during the rapid phase. As the surface sites become saturated with phosphorus ions, the adsorption process shifts to slower mechanisms, including intra-particle diffusion into meso- and micropores (Muisa *et al.*, 2020; Zhao *et al.*, 2021).

However, for both the experimental group and the positive control, the reduction in TP concentration by the 9 g ASG mass, after the initial rapid decline, was slower as compared to those by the 3 g and 6 g ASG masses. This is due to the excessive amount of adsorbent introduced which causes particle aggregation hence reducing the active surface area and sites available for phosphorus adsorption (Muisa *et al.*, 2020; Trinh *et al.*, 2020). This is in line with conclusions made from studies by Wu *et al.*, (2019), Muisa *et al.*, (2020), Trinh *et al.*, (2020), and Alwan and Rashid, (2021).

The experimental group with an initial TP concentration of 22.581 mg TP /L, attained the lowest final TP concentration of 3.056 mg/L by an ASG mass of 9 g. The positive control group, which started with a higher initial TP concentration (32.107 mg/L), required more ASG to achieve comparable reductions. This is because phosphorus removal has an inverse relationship with the initial phosphorus concentration, at lower concentrations, nearly all phosphorus ions engage with the accessible binding sites (Trinh *et al.*, 2020; Alwan and Rashid, 2021). However, when the initial phosphorus concentration is high, these binding sites become saturated, resulting in a reduction in the phosphorus adsorbed (Trinh *et al.*, 2020).

For the experimental group, there was a significant, $p<0.05$ (p-value = 0.002), decrease in TP concentration with an increase of the ASG mass. These results illustrate the dose-dependent relationship between ASG and TP reduction as concluded by (Alwan and Rashid, 2021). Higher doses of ASG are associated with more significant reductions in TP concentrations. This, therefore, is indicative of the alum sludge’s ability to reduce TP from the wastewater effluent.

4.3.2. Effect of contact time

The effect of the contact time on the Total Phosphorus (TP) concentration, Figure 4-6, and percent reduction, Figure 4-7, is illustrated by the graphs, below.

a) Effect of time on the TP concentration for 3 g, 6 g, and 9 g of ASG

The effect of contact time on the TP concentration, Figure 4-6, shows an inverse relationship for the experimental group and the positive control. For all the graphs, the negative control did not receive treatment, that is, no alum sludge granules were added to the negative control group. This was done to provide a baseline for assessing the effect of the alum sludge granules on the TP concentrations of both the experimental group and positive control (Sabri and Gyateng, 2015; Moser, 2019; Hendricks-Sturrup, 2023). The positive control (initial TP concentration of 32.107 mg/L) and experimental group (initial TP concentration of 22.581 mg/L) both received the same amount of alum sludge granules. The Maximum Permissible Limit (MPL) represents the desired treatment target.

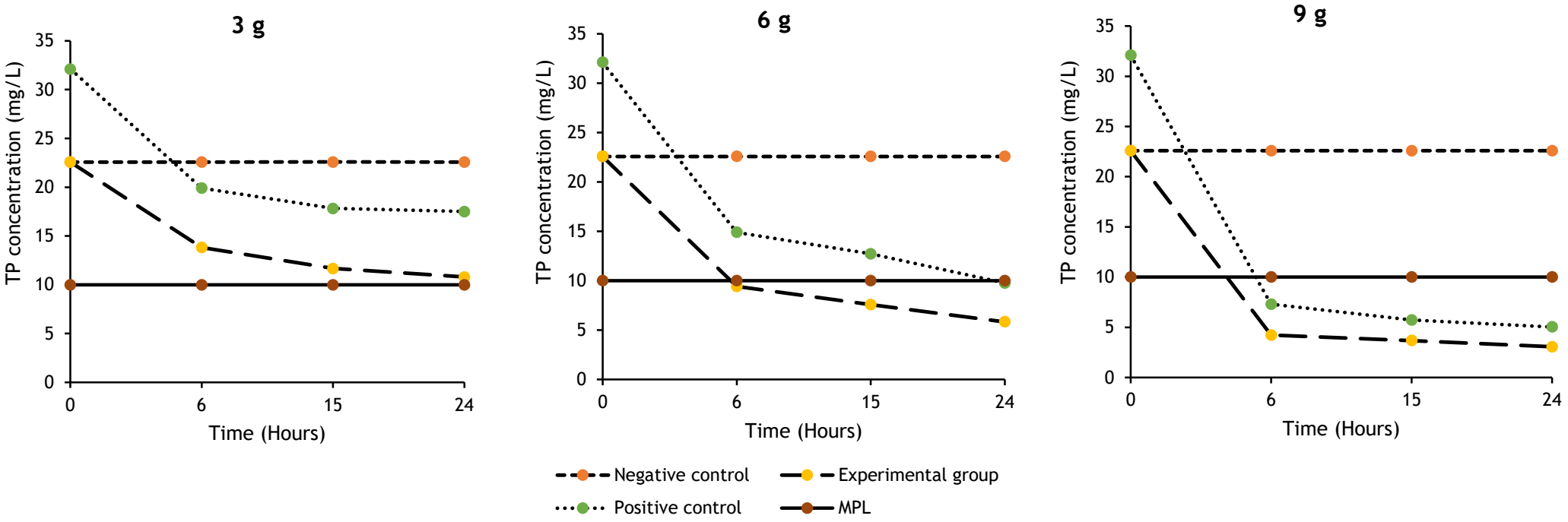


Figure 4-6: Effect of contact time on the TP concentration for 3 g, 6 g, and 9 g of ASG

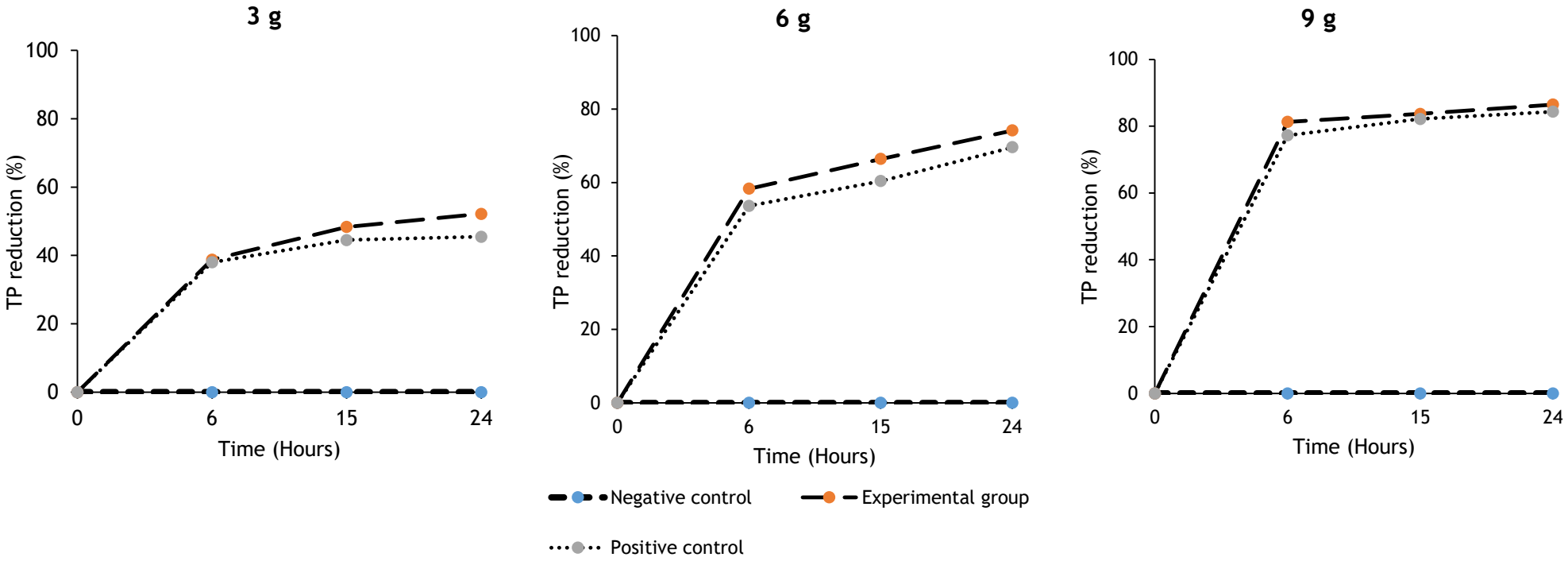


Figure 4-7: Effect of contact time on the TP reduction for 3 g, 6 g, and 9 g of ASG

For all three graphs - 3 g, 6 g, and 9 g of ASG- the TP concentration, for both the experimental group and the positive control, decreases with an increase in contact time. This is because, for a given mass, longer contact times lead to better binding of phosphorus to the adsorbent, as more phosphorus ions bind to active sites on the adsorbent's surface (Muisa *et al.*, 2020; Alwan and Rashid, 2021). Shorter contact times result in incomplete phosphorus reduction because the process doesn't have enough time to reach its full potential (Muisa *et al.*, 2020; Trinh *et al.*, 2020; Alwan and Rashid, 2021; Usman *et al.*, 2022). For the negative control where no treatment was added, the TP concentration remained relatively the same throughout the 24 hours for all three graphs. This is because the negative control group is typically used to establish a baseline condition where no effects are expected (Hendricks-Sturrup, 2023).

The maximum permissible limit (MPL)- 10 mg/L, in the 6 g and 9 g ASG masses, was attained by the experimental group and positive control albeit at different contact times. For the 6 g ASG mass, the experimental group achieved the MPL with a TP concentration of 9.415 mg/L at 6 hours while the positive control barely achieved the MPL with a TP concentration of 9.769 mg/L at 24 hours. For the 9 g ASG mass, both the experimental group (4.226 mg/L) and the positive control (7.3 mg/L) attained the MPL after 6 hours of contact. However, the MPL was not attained in both the experimental group and the positive control for the entire 24-hour duration for 3 g ASG mass. This is because of the following;

ASG mass: Increasing ASG mass increases the available surface area and active sites for adsorption leading to faster TP reduction within shorter contact times required to reach the Maximum Permissible Limit (Wu *et al.*, 2019; Muisa *et al.*, 2020; Usman *et al.*, 2022). This explains why the experimental group and the positive control reached the MPL with 9 g masses within 24 hours while failing to do so with 3 g ASG.

Initial TP concentration: The positive control group started with a higher initial TP concentration (32.107 mg/L) compared to the experimental group (22.581 mg/L). This higher initial concentration requires more contact time to achieve the MPL, as more time is needed for the available adsorption sites to bind with the greater number of TP ions (Muisa *et al.*, 2020; Alwan and Rashid, 2021). This is why the

positive control required longer contact times than the experimental group to reach MPL.

b) Effect of time on the TP reduction for 3 g, 6 g, and 9 g of ASG

The influence of contact time on the percent TP reduction for all three graphs, Figure 4-8, shows that the percent removal of all the masses increased with time. The graphs exhibited a uniform pattern: an elongated contact duration led to an increase in the percent TP reduction for both the experimental group and positive control. However, the 6g and 9g doses manifested more pronounced increases in percent TP reductions, while, the 3g dose had a comparatively gradual and less extensive reduction. The percent TP reduction for the negative control remained relatively constant throughout.

During the initial phases (0 to 6 hours), there were rapid increases in percent TP reductions, this is indicative of the quick adsorption of TP ions to available sites (Hou *et al.*, 2018; Muisa *et al.*, 2020; Zhao *et al.*, 2021). Subsequently, from 6 to 24 hours, the rate of increase in percent removal became more gradual. This suggests that while TP removal was still occurring, it did so at a slower pace as the available adsorption sites became progressively occupied (Muisa *et al.*, 2020). The percent TP reduction of the 9 g ASG mass started to plateau at 15 hours, suggesting that the ASG reached saturation at some point (Trinh *et al.*, 2020).

In summary, the trends indicate that time plays a crucial role in TP reduction using ASG. Longer contact times resulted in lower TP concentrations and higher percent TP reductions, showcasing the significance of extended exposure for effective TP adsorption onto ASG surfaces. The rapid initial increase in percent TP reduction followed by a more gradual increase suggested the progressive saturation of adsorption sites over time.

However, (Muisa *et al.*, 2020; Usman *et al.*, 2022) noted that contact time alone may not hold singular importance; rather, it serves as a contributing factor when combined with other conditions. The effectiveness of the interaction between the adsorbent and the adsorbate is reliant on both the quantity of adsorbent used and the duration of contact.

4.3.3. The combined effect of the mass of ASG and contact time

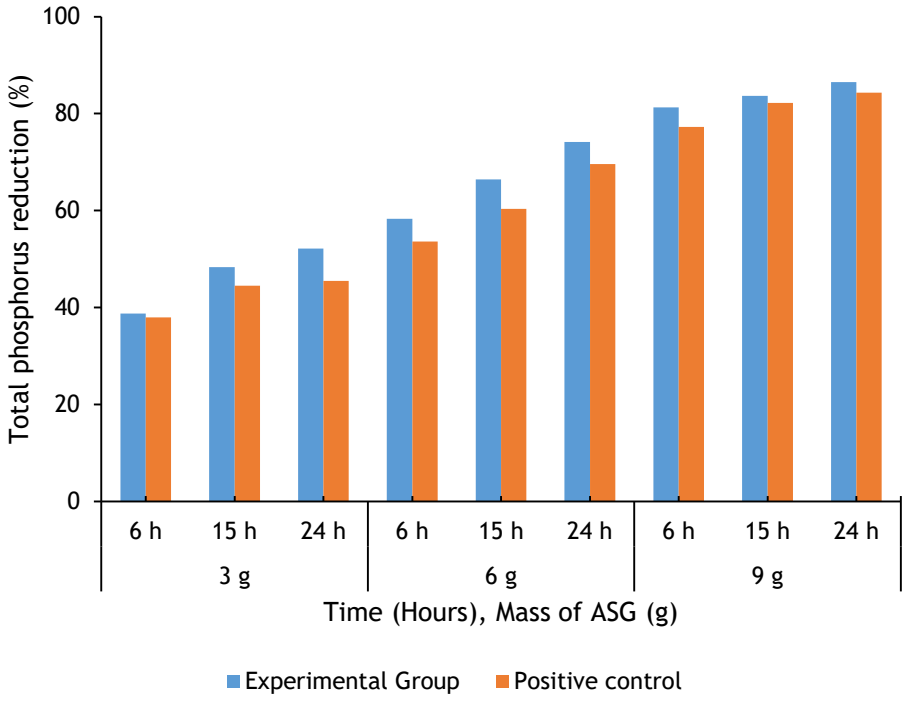


Figure 4-8: Total phosphorus percent reduction for respective ASG masses and contact times

From the graph, Figure 4-8, the TP percent reduction for both the experimental and positive control groups increases over time, but this increase varies among the different ASG masses.

While the 3 g ASG mass showed a moderate response to contact time, with TP percent reduction increasing gradually, the 6g and 9g ASG masses exhibited more pronounced improvements with longer contact times. The 6 g ASG mass achieved a maximum TP reduction of 74.142 % and 69.575 % at 24 hours for the experimental group and positive control respectively. Whereas, the 3 g ASG mass achieved a maximum TP reduction of 52.184 % and 45.490 % at 24 hours for the experimental group and positive control respectively. The 9 g ASG mass achieved the highest TP percent reduction, 86.468 % and 84.331 % for the experimental group and positive control respectively, compared to the other ASG masses. This is attributed to the fact that longer contact times allow for increased interaction between the alum sludge granules and the phosphorus in the wastewater effluent (Muisa *et al.*, 2020).

The combined effect of ASG mass and contact time on TP reduction is synergistic. This means that the effect of increasing ASG mass is greater at longer contact times, and vice versa, this aligns with findings from various studies (Ghorpade and Ahammed, 2018; Muisa *et al.*, 2020; Alwan and Rashid, 2021; Abba *et al.*, 2022). This is because the increased surface area provided by the granules is more effective at reducing phosphorus when the contact time is longer (Muisa *et al.*, 2020; Usman *et al.*, 2022). This synergistic interaction maximizes the phosphorus adsorption opportunities, sustains the adsorption process, and maintains a favourable concentration gradient, all contributing to the reduction in the TP concentration (Muisa *et al.*, 2020; Alwan and Rashid, 2021; Zhao *et al.*, 2021). This, therefore, as concluded by Muisa *et al.*, (2020) and Usman *et al.*, (2022), indicates that while contact time is a critical factor for phosphorus adsorption, the mass of the adsorbent significantly influences the adsorbent's effectiveness in reducing phosphorus.

This finding underscores the importance of optimizing both contact time and adsorbent mass in practical applications to achieve efficient TP reduction using Alum Sludge Granules (ASG).

4.4. Suitable Isotherm Model

To study the adsorption behaviour of the Alum Sludge Granules for phosphorus reduction, the linearized forms of the Langmuir, Equation 3-5 and Freundlich, Equation 3-7, isotherm models were used. The maximum adsorption capacity of the ASG was determined using the linearized equation of the Langmuir isotherm model, Equation 3-5, and was determined as 0.3 mg/g.

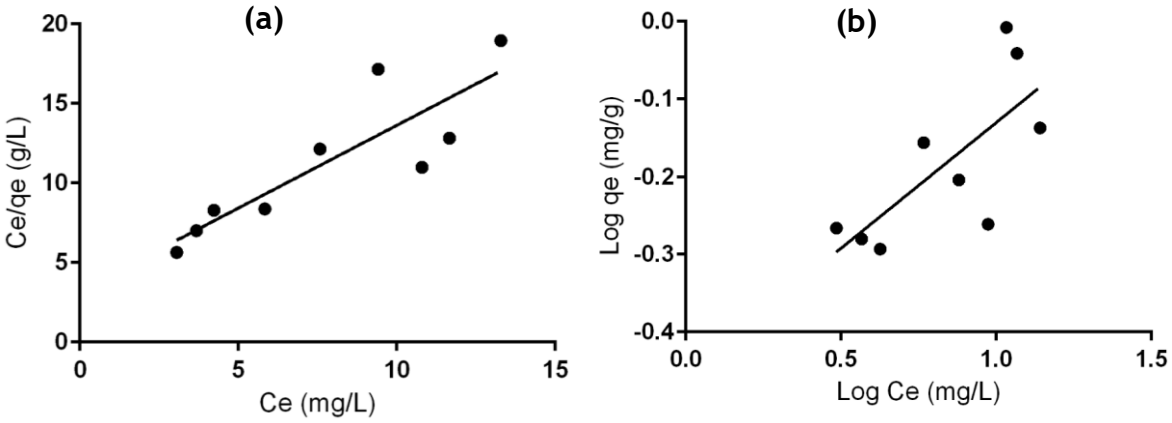


Figure 4-9: Langmuir (a) and Freundlich (b) models fitting TP adsorption for the experimental group

Table 4-3: Summary of parameters of the adsorption isotherms on adsorption of TP by ASG for the experimental group

Isotherm model	Constants	R^2	r	χ^2	p-value	F-value
Langmuir **(a)**	R_L = 0.033 K_L = 3.202	0.7431	0.862	5.097	0.0028	20.25
Freundlich **(b)**	n = 3.088 K_F = 0.635	0.5345	0.7311	0.375	0.0252	8.038

Significance level, $\propto = 5\ \%$, and from statistical tables, the critical values are;

$X^2 = 14.067$ and $F_{critical} = 5.59$.

In the evaluation of the ASG's adsorption capacity, the Langmuir isotherm model revealed a maximum adsorption capacity of 0.3 mg/g. This capacity was comparatively lower than that reported in studies by Ojha, Sharma and Amatya, (2019), and Nguyen *et al.*, (2022a, 2023) that used powdered alum sludge for their phosphorus adsorption experiments with synthetic phosphorus solutions. The granulation of alum sludge made a fraction of the adsorption sites less accessible, a phenomenon also noted by Everaert *et al.*, (2020) and Muisa *et al.*, (2020).

Furthermore, the utilization of real effluent containing various contaminants (Table 4-1) created competition for adsorption sites, physically blocked the sites, interfered with phosphorus adsorption, and led to quicker saturation of available sites, hence reducing the adsorption capacity of the granules as corroborated by Wu *et al.*, (2019). However, the adsorption capacity of 0.3 mg/g exceeded that reported by Wu *et al.*, (2019), who achieved 0.23 mg/g when using actual wastewater effluent, although they observed a higher capacity of 0.9 mg/g when utilising simulated phosphorus-containing wastewater with alum sludge granules in their comparative study.

The determination of the most suitable isotherm model involved the use of the Chi-square test in conjunction with the coefficient of determination (Abin-Bazaine, Trujillo and Olmos-Marquez, 2022). As summarized in Table 4-3, the Langmuir isotherm emerged as the best fit for the experimental data, affirming monolayer adsorption of TP onto the ASG. It yielded a separation factor (R_L) of 0.033, indicating highly favourable TP adsorption onto the Alum Sludge Granules (ASG). The Langmuir

constant (K_L) further emphasized the strong affinity between TP and the adsorbent, with a K_L of 3.202. Moreover, the Langmuir model exhibited a commendable coefficient of determination (R^2) of 0.7431, indicating a robust fit between the experimental and predicted data. The correlation coefficient (r) highlighted the model's capacity to accurately represent the adsorption phenomenon. Additionally, the low chi-square value (χ^2) of 5.097 and $p<0.05$ (0.0028) underscored the statistical significance and reliability of the Langmuir model. This significance was further corroborated by a substantial F-value of 20.25. These results were in line with the conclusion of the review by (Muisa *et al.*, 2020), who stated that the majority of studies on phosphorus adsorption by alum sludge found the Langmuir isotherm model to provide the best fit.

In contrast, the Freundlich isotherm, while indicating strong adsorption (n = 3.088), exhibited a relatively weaker fit to the experimental data with a lower R^2 value (0.5345), and less compelling statistical parameters.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study investigated the physicochemical properties of discarded alum sludge from the Katosi Drinking Water Treatment Plant, assessed its potential for reuse in phosphorus reduction. The research findings provided valuable insights into the suitability of alum sludge from the Katosi Drinking Water Treatment Plant as a phosphorus adsorbent.

1. Effluent Characteristics

The characterisation of effluent from the Lubigi Faecal Sludge and Wastewater Treatment Plant revealed that the effluent sample quality deviated significantly from the Maximum Permissible Limits set by the National Environment Management Authority, particularly in colour, suspended solids, phosphorus, Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD). These findings indicated a high level of contaminants in the effluent, which could reduce the adsorption capacity of the alum sludge granules for phosphorus due to competition for adsorption sites and interference with the adsorption process. The observed deviations from the environmental standards in the Lubigi Faecal Sludge and Wastewater Treatment Plant effluent highlight the urgency of addressing residual contaminants after wastewater treatment.

2. Physicochemical Properties of Alum Sludge

The analysis of alum sludge from the Katosi Drinking Water Treatment Plant revealed important characteristics. The sludge exhibited a moisture content of 17.32 %, with a pH of 7.24. The chemical composition analysis showed a predominant presence of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3). The presence of aluminium is important since it is a vital contributor to alum sludge's adsorption capabilities. This finding supports the suitability of the studied alum sludge for further exploration and development in phosphorus reduction applications from wastewater effluent. Understanding the characteristics of alum sludge informs decisions on its potential reuse for phosphorus reduction in wastewater treatment plant effluents.

3. Adsorption of TP onto ASG

The adsorption experiments demonstrated the potential of the alum sludge granules (ASG) for phosphorus reduction in wastewater effluent. The dose-dependent effect

of ASG revealed that increasing the ASG masses led to reduced final TP concentrations. Longer contact times consistently improved percent TP reduction. The maximum permissible limit (10 mg/L) was attained by both the experimental and positive control groups with ASG masses of 6 g and 9 g but not 3 g, indicating that low ASG masses may not achieve the desired TP reductions. The combined effect of the ASG mass and contact time on TP reduction was synergistic underscoring the importance of optimizing both contact time and adsorbent mass in practical applications to achieve efficient TP reduction using the alum sludge granules. Notably, the highest percent reduction (86 %) was achieved at an ASG mass of 9 g at 24 hours, further underscoring the significance of optimizing both the mass of the adsorbent and contact time for practical applications.

4. Adsorption capacity of ASG

The Langmuir isotherm model provided the best fit for the experimental data, indicating monolayer adsorption of TP onto the ASG. It exhibited a maximum adsorption capacity of 0.3 mg/g, which was lower than that of studies that used powdered alum sludge but comparable with others using granules and real wastewater effluent. The Langmuir model's strong fit to the data, an R_L value of 0.033, a K_L value of 3.202, a coefficient of determination (R^2) of 0.7431, a low chi-square value (χ^2) of 5.097, and a small P-value of 0.0028 emphasized the favourable TP adsorption capacity of the ASG. This implies that granulation as well as the presence of contaminants in wastewater effluent reduces the accessible adsorption sites and contributes to lower adsorption capacity of the alum sludge. There is need for further research to enhance the adsorption capacity of granulated alum sludge including exploring alternative granulation techniques, modifying sludge properties, or investigating pre-treatment methods to mitigate competition from other contaminants.

Overall Implications

In conclusion, this study demonstrates that alum sludge from the Katosi Drinking Water Treatment Plant possesses the potential for reuse for phosphorus reduction in wastewater effluent in Uganda. The research underscores the importance of optimizing the mass of the alum sludge granules and the contact time for efficient TP reduction. The findings also emphasize the need for careful consideration of the

constituents in wastewater effluent when implementing alum sludge-based treatment methods. Further research and pilot studies are warranted to explore the scalability and long-term sustainability of alum sludge-based treatment processes in real-world wastewater treatment facilities.

5.2. Limitations to the study

The experiments were carried out with a bulk spiked grab sample if effluent not with real-time effluent discharges.

The different species of phosphorus were not tested for.

The alum sludge used for the study was attained only from one drinking water treatment plant.

The density of the alum sludge from the Katosi Drinking Water Treatment Plant was not known and neither was it recorded at the plant.

5.3. Recommendations

Understanding the specific constituents of wastewater effluent is crucial before implementing alum sludge-based treatment methods. Further research should focus on evaluating the effect of diverse effluent compositions on alum sludge's adsorption capacity, addressing the potential challenges associated with contaminants that may interfere with the adsorption process.

Due to the variations in alum sludge composition among drinking water treatment plants, individualised characterisations by drinking water treatment plants should be encouraged. This approach could go a long way in ensuring accurate insights into potential reuse applications of alum sludge in diverse environmental contexts.

Different granulation techniques should also continue to be investigated to enhance the adsorption capabilities of alum sludge and also validate its practical use.

Conduct mass balance studies to quantify the distribution of phosphorus throughout the treatment process, including adsorption onto ASG and potential losses to other phases. This will provide a comprehensive understanding of the percent reduction of phosphorus and also identify areas of improvement.

In order to maximize resource recovery and minimise waste generation, desorption of phosphorus from the spent alum sludge granules should be investigated. This

allows for designing of efficient regeneration processes for recovering the adsorbed phosphorus and hence contributing to a circular economy.

Establish standardised monitoring and reporting practices for alum sludge-based treatment methods, ensuring consistent data collection for performance evaluation across treatment plants.

REFERENCES

Abba, A.B., Saggai, S., Touil, Y., Al-ansari, N., Kouadri, S., Nouasria, F.Z., Najm, H.M., Mashaan, N.S., Eldirderi, M.M.A. and Khedher, K.M. (2022) 'Copper and Zinc Removal from Wastewater Using Alum Sludge Recovered from Water Treatment Plant', *Sustainability 2022*, 14(16), p. 9806.

Abd EL- Razek, T.M., Elgendy, A.S. and Fouad, M.M. (2016) 'Utilization of Drinking Water Treatment Sludge to produce Aluminium Sulphate', *Journal of Environmental Science*, 33(1), pp. 87–104. Available at: https://doi.org/10.21608/jes.2016.25107.

Abin-Bazaine, A., Trujillo, A.C. and Olmos-Marquez, M. (2022) 'Adsorption Isotherms: Enlightenment of the Phenomenon of Adsorption', in *Wastewater Treatment*. Available at: https://doi.org/10.5772/intechopen.104260.

Ackah, L.A., Guru, R., Peiravi, M., Mohanty, M., Ma, X., Kumar, S. and Liu, J. (2018) 'Characterization of Southern Illinois water treatment residues for sustainable applications', *Sustainability (Switzerland)*, 10(5), p. 1374. Available at: https://doi.org/10.3390/su10051374.

Ahmad, T., Ahmad, K. and Alam, M. (2016) 'Characterization of Water Treatment Plant's Sludge and its Safe Disposal Options', *Procedia Environmental Sciences*, 35, pp. 950–955. Available at: https://doi.org/10.1016/j.proenv.2016.07.088.

Akinnawo, S.O. (2023) 'Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies', *Environmental Challenges*, 12, p. 100733. Available at: https://doi.org/10.1016/j.envc.2023.100733.

Al-Ghouti, M.A. and Da'ana, D.A. (2020) 'Guidelines for the use and interpretation of adsorption isotherm models : A review', *Journal of Hazardous Materials*, 393, p. 122383. Available at: https://doi.org/10.1016/j.jhazmat.2020.122383.

Ali, A. (2015) 'Phosphate Removal from Water and Wastewater by Membrane Operations', *Encyclopedia of Membranes* [Preprint]. Edited by E. Drioli and

L. Giorno. Berlin, Heidelberg: Springer Berlin Heidelberg. Available at: https://doi.org/10.1007/978-3-642-40872-4_2182-1.

Aljamali, N.M., Khdur, R.A. and Alfatlawi, I.O. (2021) *Thermodynamics and Chemical Kinetics Review IJTCK Physical and Chemical Adsorption and its Applications*, *International Journal of Thermodynamics and Chemical Kinetics*. Available at: https://doi.org/10.37628/IJTCK.

Alwan, A.M. and Rashid, M.A. (2021) 'Phosphorus Removal From Iraqi Treated Wastewater Using Alum Sludge', *Journal of Engineering and Sustainable Development*, 25(Special), pp. 3-203-3–212. Available at: https://doi.org/10.31272/jeasd.conf.2.3.20.

APHA (1999) *Standard Methods for the Examination of Water and Wastewater*, *American Public Health Association*.

Ayawei, N., Ebelegi, A.N. and Wankasi, D. (2017) 'Modelling and Interpretation of Adsorption Isotherms', *Journal of Chemistry*, 2017. Available at: https://doi.org/10.1155/2017/3039817.

Bacelo, H., Pintor, A.M., Santos, S.C., Boaventura, R.A. and Botelho, C.M. (2020) 'Performance and prospects of different adsorbents for phosphorus uptake and recovery from water', *Chemical Engineering Journal*, 381, p. 122566. Available at: https://doi.org/https://doi.org/10.1016/j.cej.2019.122566.

Barakwan, R.A., Trihadiningrum, Y. and Bagastyo, A.Y. (2019) 'Characterization of Alum Sludge from Surabaya Water Treatment, Indonesia', *Journal of Ecological Engineering*, 20(5), pp. 7–13. Available at: https://doi.org/10.12911/22998993/104619.

Basri, M.H., Don, N.M., Kasmuri, N., Hamzah, N., Alias, S. and Azizan, F.A. (2019) 'Aluminium recovery from water treatment sludge under different dosage of sulphuric acid', in *Journal of Physics: Conference Series*. IOP Publushing, p. 012005. Available at: https://doi.org/10.1088/1742-6596/1349/1/012005.

Breesem, K.M., Abood, M.M. and Rahman, N.A. (2016) 'Influence of Magnesium Sulfate on Self-Compacting Alum Sludge Concrete Incorporating with Pozzolanic Materials', *Modern Applied Science*, 10(8), p. 187. Available at:

https://doi.org/10.5539/mas.v10n8p187.

Breesem, K.M., Faris, F.G. and Abdel-Magid, I.M. (2016) 'Reuse of alum sludge in construction materials and concrete works: a general overview', *IUKL Research Journal*, 2(1), pp. 20–30.

Bunce, J.T., Ndam, E., Ofiteru, I.D., Moore, A. and Graham, D.W. (2018) 'A Review of Phosphorus Removal Technologies and Their Applicability to Small-Scale Domestic Wastewater Treatment Systems', *Frontier in Environmental Science*, 6(8). Available at: https://doi.org/10.3389/fenvs.2018.00008.

Chapagain, Y. (2016) 'Methods and Possibility for Recycling of Phosphorus from Sludge', p. 46. Available at: https://urn.fi/URN:NBN:fi:amk-201604154434.

Chardon, W.J., Groenenberg, J.E., Vink, J.P.M., Voegelin, A. and Koopmans, G.F. (2022) 'Use of iron-coated sand for removing soluble phosphorus from drainage water', *Science of The Total Environment*, 815, p. 152738. Available at: https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.152738.

Chen, Z., Wu, Y., Huang, Y., Song, L., Chen, H., Zhu, S. and Tang, C. (2022) 'Enhanced adsorption of phosphate on orange peel-based biochar activated by Ca/Zn composite: Adsorption efficiency and mechanisms', *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 651, p. 129728. Available at: https://doi.org/https://doi.org/10.1016/j.colsurfa.2022.129728.

Dan, E.U., Inam, E., Fatunla, K., Essien, J., Odon, A., Kang, S. and Semple, K. (2018) 'Chemical Characterisation of Sludge Generated from Water Treatment Plants (WTPs) in Nigeria', *Journal of Chemical Society of Nigeria*, 43(4), pp. 643–655.

Dassanayake, K.B., Jayasinghe, G.Y., Surapaneni, A. and Hetherington, C. (2018) 'A review on alum sludge reuse with special reference to agricultural applications and future challenges', *Waste Management*, 38, pp. 321–335. Available at: https://doi.org/10.1016/j.wasman.2018.11.025.

Deirmendjian, L., Descy, J.-P., Morana, C., Okello, W., Borges, M.P.S.-G.,

Bouillon, S. and Borges, A. V. (2021) ‘Limnological changes in Lake Victoria since the mid-20th century’, *Freshwater Biology*, 66(8), pp. 1630–1647. Available at: https://doi.org/10.1111/fwb.13780.

Diaba-Nuhoho, P. and Amponsah-Offeh, M. (2021) ‘Reproducibility and research integrity: the role of scientists and institutions’, *BMC Research Notes*, 14(1), p. 451. Available at: https://doi.org/10.1186/s13104-021-05875-3.

Dias, R., Sousa, D., Bernardo, M., Matos, I., Fonseca, I., Cardoso, V.V., Carneiro, R.N., Silva, S., Fontes, P., Daam, M.A. and Maurício, R. (2021) ‘Study of the Potential of Water Treatment Sludges in the Removal of Emerging Pollutants’, *Molecules*, 26(4), p. 1010.

Djekoune, L., Salem, Z., Maaliou, A. and Boucetta, S. (2022) ‘Reuse of sludge from drinking water production in dye wastewater treatment of textile industry Reuse of sludge from drinking water production in dye wastewater treatment of textile industry’, *Desalination and Water Treatment*, 277(June 2023), pp. 72–84. Available at: https://doi.org/10.5004/dwt.2022.28962.

Du, M., Zhang, Y., Wang, Z., Lv, M., Tang, A., Yu, Y., Qu, X., Chen, Z., Wen, Q. and Li, A. (2022) ‘Insight into the synthesis and adsorption mechanism of adsorbents for efficient phosphate removal: Exploration from synthesis to modification’, *Chemical Engineering Journal*, 442, p. 136147. Available at: https://doi.org/https://doi.org/10.1016/j.cej.2022.136147.

El-Tokhy, T.T., Ahmed, M.A., ElGammal, M.I. and Ibrahim, M.S. (2020) ‘Improvement and characterization of alum sludge by nano-iron oxide and rice husk for removal of methylene blue dye from aqueous solution’, *Journal of Environmental Studies*, 21(1), pp. 25–59.

Elgarhy, A.H., Mahran, B.N.A., Liu, G., Salem, T.A., ElSayed, E.E. and Ibrahim, L.A. (2022) ‘Comparative study for removal of phosphorus from aqueous solution by natural and activated bentonite’, *Scientific reports*, 12(1), p. 19433. Available at: https://doi.org/10.1038/s41598-022-23178-w.

European Investment Bank (2022) ‘Wastewater as a resource’, *The EIB Projects Directorate*, p. 40. Available at: https://doi.org/10.2867/31206.

Everaert, M., Bergmans, J., Broos, K., Hermans, B. and Michielsen, B. (2021) 'Granulation and calcination of alum sludge for the development of a phosphorus adsorbent : From lab scale to pilot scale', *Journal of Environmental Management*, 279, p. 111525. Available at: https://doi.org/10.1016/j.jenvman.2020.111525.

Garg, V.K., Srivastav, A.L., Tiwari, M.K., Sharma, A. and Kanwar, V.S. (2021) 'Synchrotron based X-ray fluorescence for trace elemental analysis of industrial sludge', *Journal of Environmental Treatment Techniques*, 9(1), pp. 192–195.

Geissdoerfer, M., Savage, P., Bocken, N. and Hultink, E. (2017) 'The Circular Economy – A new sustainability paradigm?', *Journal of Cleaner Production*, 143, pp. 757–768. Available at: https://doi.org/10.1016/j.jclepro.2016.12.048.

Ghorpade, A. and Ahammed, M.M. (2018) 'Water treatment sludge for removal of heavy metals from electroplating wastewater', *Environmental Engineering Research*, 23(1), pp. 92–98.

Guida, S., Rubertelli, G., Jefferson, B. and Soares, A. (2021) 'Demonstration of ion exchange technology for phosphorus removal and recovery from municipal wastewater', *Chemical Engineering Journal*, 420, p. 129913. Available at: https://doi.org/https://doi.org/10.1016/j.cej.2021.129913.

He, X., Zhao, X., Zhang, W., Ren, B. and Zhao, Y. (2022) 'Developing a Novel Alum Sludge-Based Floating Treatment Wetland for Natural Water Restoration', *Water*, 14(15), p. 2433. Available at: https://doi.org/10.3390/w14152433.

Hendricks-Sturrup, R. (2023) 'Understanding the Use of Negative Controls to Assess the Validity of Non-Interventional Studies of Treatment Using Real-World Evidence', p. 206.

Herzog, M.H., Francis, G. and Clarke, A. (2019) *Understanding Statistics and Experimental Design*. Springer Nature Switzerland AG. Available at: https://link.springer.com/book/10.1007/978-3-030-03499-3.

Hien, L.P.T., Khoa, L.N.D., Thanh, D. Van, Hieu, N.T., Thi, T., Oanh, P., Thuy,

V.T.T. and Huy, N.N. (2021) ‘Utilization of Alum Sludge from Water Treatment Plant as an Adsorbent for Hydrogen Sulphide removal’, *SN RU Journal of Science and Technology*, 13(3), pp. 117–125.

Ho, L. and Goethals, P.L.M. (2020) ‘Municipal wastewater treatment with pond technology: Historical review and future outlook’, *Ecological Engineering*, 148, p. 105791. Available at: https://doi.org/https://doi.org/10.1016/j.ecoleng.2020.105791.

Hou, Q., Meng, P., Pei, H., Hu, W. and Chen, Y. (2018) ‘Phosphorus adsorption characteristics of alum sludge: Adsorption capacity and the forms of phosphorus retained in alum sludge’, *Materials Letters*, 229, pp. 31–35. Available at: https://doi.org/https://doi.org/10.1016/j.matlet.2018.06.102.

Hu, Q., He, L., Lan, R., Feng, C. and Pei, X. (2023) ‘Recent advances in phosphate removal from municipal wastewater by electrocoagulation process: A review’, *Separation and Purification Technology*, 308, p. 122944. Available at: https://doi.org/https://doi.org/10.1016/j.seppur.2022.122944.

Hussein, A.M., Mahmoud, R.K., Sillanpää, M. and Wahed, M.S.A. (2021) ‘Impacts alum DWTPs sludge discharge and changes in flow regime of the Nile River on the quality of surface water and cultivated soils in Fayoum watershed, Egypt’, *Science of The Total Environment*, 766, p. 144333. Available at: https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.144333.

Kabenge, I., Ouma, G., Aboagye, D. and Banadda, N. (2018) ‘Performance of a constructed wetland as an upstream intervention for stormwater runoff quality management’, *Environmental Science and Pollution Research*, 25, pp. 36765–36774. Available at: https://doi.org/10.1007/s11356-018-3580-z.

Kabenge, M., Wang, H. and Li, F. (2016) ‘Urban eutrophication and its spurring conditions in the Murchison Bay of Lake Victoria’, *Environmental Science and Pollution Research*, 23, pp. 234–241. Available at: https://doi.org/10.1007/s11356-015-5675-0.

Kayiwa, R., Kasedde, H., Lubwama, M., Kirabira, J.B. and Timothy, K. (2022) ‘Occurrence and toxicological assessment of selected active pharmaceutical

ingredients in effluents of pharmaceutical manufacturing plants and wastewater treatment plants in Kampala , Uganda', 17(4). Available at: https://doi.org/10.2166/wpt.2022.024.

Khan, S.A., Khan, S.B., Khan, L.U., Farooq, A., Akhtar, K. and Asiri, A.M. (2018) 'Chapter 9 Fourier Transform Infrared Spectroscopy: Fundamentals and Application in Functional Groups and Nanomaterials Characterization', in *Handbook of Materials Characterization*, pp. 317–344. Available at: https://doi.org/10.1007/978-3-319-92955-2.

Kim, Y.-S., Kim, D.-H., Yang, J.-S. and Baek, K. (2012) 'Adsorption Characteristics of As(III) and As(V) on Alum Sludge from Water Purification Facilities', *Separation Science and Technology*, 47(14–15), pp. 2211–2217. Available at: https://doi.org/10.1080/01496395.2012.700676.

Koul, B., Yadav, D., Singh, S., Kumar, M. and Song, M. (2022) 'Insights into the Domestic Wastewater Treatment (DWWT) Regimes : A Review', *Water*, 14(21), p. 3542. Available at: https://doi.org/10.3390/ w14213542.

Krupinska, I. (2020) 'Aluminium Drinking Water Treatment Residuals and Their Toxic Impact on Human Health', *Molecules*, 25(3), p. 641. Available at: https://doi.org/10.3390/molecules25030641.

Kuldeyev, E., Ospanov, K., Andraka, D. and Merkýreva, S. (2023) 'Experimental Study on the Application of Sludge from Water Treatment Plant as a Reagent for Phosphate Removal from Wastewater', *Water*, 15(15). Available at: https://doi.org/10.3390/w15152691.

Kyayesimira, J., Ssemaganda, A., Muhwezi, G. and Andama, M. (2019) 'Assessment of Cadmium and Lead in Dried Sewage Sludge from Lubigi Feacal Sludge and Wastewater Treatment Plant in Uganda', *Journal of Water Resource and Protection*, 11(6), pp. 690–699. Available at: https://doi.org/10.4236/jwarp.2019.116040.

Lovibond® Water Testing Tintometer® Group (2015) 'BOD-System BD 600 Instruction Manual', p. 36. Available at: https://www.manualslib.com/download/1404702/Lovibond-Bd-600.html.

Manasa, R.L. and Mehta, A. (2020) 'Wastewater: Sources of Pollutants and Its Remediation', in *Environmental Biotechnology Vol. 2*, pp. 197–219. Available at: https://doi.org/10.1007/978-3-030-38196-7_9.

Maqbool, N., Khan, Z. and Asghar, A. (2016) 'Reuse of alum sludge for phosphorus removal from municipal wastewater', *Desalination and Water Treatment*, 57(28), pp. 13246–13254. Available at: https://doi.org/10.1080/19443994.2015.1055806.

Mecham, J. (2018) 'Dissolved Air Flotation (DAF)', p. 11.

Ministry of Water and Environment Water (2019) 'Water and Environment Sector Performance Report', *Government of Uganda Ministry of Water and Environment*, 11, p. 305. Available at: https://www.mwe.go.ug/library/sector-performance-report-2019.

Ministry of Water and Environment Water (2020) 'Water and Environment Sector Performance Report 2020', *Government of Uganda Ministry of Water and Environment*, 12, p. 343.

Montgomery, D.C. (2013) *Design and Analysis of Experiments*. EIGTH EDIT. Edited by R. Linda, M. Anna, and T. Christopher. Arizona: John Wiley & Sons, Inc. Available at: https://doi.org/2012000877.

Moser, P. (2019) 'Out of Control? Managing Baseline Variability in Experimental Studies with Control Groups', in *Handbook of Experimental Pharmacology*, pp. 101–117. Available at: https://doi.org/10.1007/164_2019_280.

Mugidde, R., Hecky, R.E. and Ndawula, L. (2005) 'Eutrophication of Lake Victoria, Uganda', *Water Quality and Quantity Synthesis Final Report, Lake Victoria Environmental Project*, (December), pp. 131–148. Available at: https://www.mwe.go.ug/sites/default/files/library/Chapter 8 Eutrophication.pdf.

Muisa, N., Nhapi, I., Ruziwa, W. and Manyuchi, M.M. (2020) 'Utilization of alum sludge as adsorbent for phosphorus removal in municipal wastewater: A review', *Journal of Water Process Engineering*, 35, p. 101187. Available at: https://doi.org/https://doi.org/10.1016/j.jwpe.2020.101187.

Musah, M., Azeh, Y., Mathew, J.T., Umar, M.T., Abdulhamid, Z. and Muhammad, A.I. (2022) 'Adsorption kinetics and isotherm models: a review', *Caliphate Journal of Science and Technology*, 4(1), pp. 20–26. Available at: https://doi.org/10.4314/cajost.v4i1.3.

Nandiyanto, A.B.D., Oktiani, R. and Ragadhita, R. (2019) 'How to Read and Interpret FTIR Spectroscope of Organic Material', *Indonesian Journal of Science & Technology*, 4(1), pp. 97–118.

National Environment Management Authority (2020) *The National Environment (Standards for Discharge of Effluent Into Water or on Land) Regulations*. Uganda. Available at: https://nema.go.ug/sites/all/themes/nema/docs/National Environment (Standards for Discharge of Effluent into Water or Land) Regulations 2020.pdf.

National Planning Authority (2012) 'Uganda Vision 2040', *Annual meeting of the Midwest Political Science …*, pp. 114–117. Available at: https://www.greengrowthknowledge.org/sites/default/files/downloads/policy-database/UGANDA%29 Vision 2040.pdf.

National Water and Sewerage Corporation (2020) 'Integrated Annual Report 2020/2021.', *NWSC Annual Report 2020-2021*, p. 176. Available at: https://www.nwsc.co.ug/wp-content/uploads/2022/05/NWSC-Annual-Report-202021-Final-May-2022.pdf.

Natoli, C. and Oimoen, S. (2019) 'Classical Designs: Full Factorial Designs', *STAT Center of Excellence: Dayton, OH, USA.*, p. 25.

Nguyen, M.D., Adhikari, S., Mallya, D.S., Thomas, M., Surapaneni, A., Moon, E.M. and Milne, N.A. (2022a) 'Reuse of aluminium-based water treatment sludge for phosphorus adsorption: Evaluating the factors affecting and correlation between adsorption and sludge properties', *Environmental Technology and Innovation*, 27, p. 102717. Available at: https://doi.org/10.1016/j.eti.2022.102717.

Nguyen, M.D., Donaldson, D., Adhikari, S., Amini, N., Mallya, D.S., Thomas, M., Moon, E.M. and Milne, N.A. (2023) 'Phosphorus adsorption and organic

release from dried and thermally treated water treatment sludge', *Environmental Research*, 234 (March), p. 116524. Available at: https://doi.org/10.1016/j.envres.2023.116524.

Nguyen, M.D., Thomas, M., Surapaneni, A., Moon, E.M. and Milne, N.A. (2022b) 'Beneficial reuse of water treatment sludge in the context of circular economy', *Environmental Technology & Innovation*, 28, p. 102651. Available at: https://doi.org/https://doi.org/10.1016/j.eti.2022.102651.

Niwagaba, C.B., Ayii, A.E., Kibuuka, A.O. and Pomi, R. (2019) 'Possibilities for the use of sludge from a Drinking Water Treatment Plant at Ggaba III in Kampala, Uganda', *Multidisciplinary Journal for Waste Resources and Residues*, 6, pp. 59–67. Available at: https://doi.org/10.31025/2611-4135/2019.13824.

Njagi, D.M., Routh, J., Odhiambo, M., Luo, C., Basapuram, L.G., Olago, D., Klump, V. and Stager, C. (2022) 'A century of human-induced environmental changes and the combined roles of nutrients and land use in Lake Victoria catchment on eutrophication', *Science of the Total Environment*, 835, p. 155425.

Nyakairu, G.W., Usman, M.O. and Ntale, M. (2023) 'Adsorption of Phosphate by Synthesized Silver/Calcium Oxide-Activated Carbon Nanocomposite', *Advances in Environmental and Engineering Research*, 4(2), pp. 1–20. Available at: https://doi.org/10.21926/aeer.2302033.

O'Dell, J.W. (1993) 'Method 410.4 The Determination of Chemical Oxygen Demand By Semi-Automated Colorimetry', *Environmental Monitoring Systems Laboratory Office of Research and Development; Revision*, 2, pp. 2015–08. Available at: www.epa.gov.

O'Dell, J.W. (1999) 'TOTAL SUSPENDED SOLIDS (TSS) EPA Method 160.2 (Gravimetric, Dried at 103-105 E C)', *Environmental Monitoring Systems Laboratory Office of Research and Development; Revision*, 2, pp. 1–3. Available at: https://19january2017snapshot.epa.gov/sites/production/files/2015-06/documents/160_2.pdf.

Obuya, J.A., Onyango, H.O., Olokotum, M., Zepernick, B., Natwora, K., Otieno, D., Owoko, W., Achieng, D., Otuo, P.W. and Keyombe, J.L. (2023) 'Socioeconomic consequences of cyanobacterial harmful algal blooms in small-scale fishing communities of Winam Gulf, Lake Victoria', *Journal of Great Lakes Research*, p. 102236. Available at: https://doi.org/https://doi.org/10.1016/j.jglr.2023.09.007.

Odimegwu, T.C., Zakaria, I., Abood, M.M., Nketsiah, C.B.K. and Ahmad, M. (2018) 'Review on Different Beneficial Ways of Applying Alum Sludge in a Sustainable Disposal Manner', *Civil Engineering Journal*, 4(9), p. 2230. Available at: https://doi.org/10.28991/cej-03091153.

Ojha, B., Sharma, R.K. and Amatya, I.M. (2019) 'Application of Alum Sludge in Phosphate Phosphorus Removal from Contaminated Water', *Journal of the Institute of Engineering*, 15(2), pp. 141–146.

Olokotum, M., Mitroi, V., Troussellier, M., Semyalo, R., Bernard, C., Montuelle, B., Okello, W., Quiblier, C. and Humbert, J.-F. (2020) 'A review of the socioecological causes and consequences of cyanobacterial blooms in Lake Victoria', *Harmful Algae*, 96, p. 101829. Available at: https://doi.org/https://doi.org/10.1016/j.hal.2020.101829.

Olokotum, M., Troussellier, M., Escalas, A., Hamlaoui, S., Okello, W., Semyalo, R., Humbert, J.-F. and Bernard, C. (2021) 'High nutrient loading and climatic parameters influence the dominance and dissimilarity of toxigenic cyanobacteria in northern bays of Lake Victoria', *Journal of Great Lakes Research*, 47(4), pp. 985–996. Available at: https://doi.org/https://doi.org/10.1016/j.jglr.2021.04.021.

Opoku, A., Ahmed, V. and Akotia, J. (2016) 'Choosing an appropriate research methodology and method', in *Research methodology in the built environment: A selection of case studies*. Routledge London, pp. 30–43.

Pająk, M. (2023) 'Alum sludge as an adsorbent for inorganic and organic pollutants removal from aqueous solutions: a review', *International Journal of Environmental Science and Technology* [Preprint]. Available at: https://doi.org/10.1007/s13762-023-04854-4.

Pourhakkak, P., Taghizadeh, A., Taghizadeh, M., Ghaedi, M. and Haghdoust, S. (2021) ‘Chapter 1 - Fundamentals of adsorption technology’, in M.B.T.-I.S. and T. Ghaedi (ed.) *Adsorption: Fundamental Processes and Applications*. Elsevier, pp. 1–70. Available at: https://doi.org/https://doi.org/10.1016/B978-0-12-818805-7.00001-1.

Pratap, B., Kumar, S., Nand, S., Azad, I., Bharagava, R.N., Romanholo Ferreira, L.F. and Dutta, V. (2023) ‘Wastewater generation and treatment by various eco-friendly technologies: Possible health hazards and further reuse for environmental safety’, *Chemosphere*, 313, p. 137547. Available at: https://doi.org/https://doi.org/10.1016/j.chemosphere.2022.137547.

Razali, M., Zhao, Y.Q. and Bruen, M. (2018) ‘Effectiveness of a drinking-water treatment sludge in removing different phosphorus species from aqueous solution’, *Separation and Purification Technology*, 55(3), pp. 300–306. Available at: https://doi.org/10.1016/j.seppur.2006.12.004.

Ren, B., Lyczko, N., Zhao, Y. and Nzihou, A. (2020a) ‘Alum sludge as an efficient sorbent for hydrogen sulfide removal : Experimental , mechanisms and modeling studies’, *Chemosphere*, 248, p. 126010. Available at: https://doi.org/10.1016/j.chemosphere.2020.126010.

Ren, B., Zhao, Y., Ji, B., Wei, T. and Shen, C. (2020b) ‘Granulation of Drinking Water Treatment Residues: Recent Advances and Prospects’, *Water*, 12(5). Available at: https://doi.org/10.3390/w12051400.

Ren, Y., Chen, J., Tang, X., Sun, Q. and Wang, Z. (2020c) ‘Characterization of sludge from a drinking water treatment plant in a large-scale city and its potential application as a soil conditioner’, *Environmental Science and Pollution Research*, 8(27), pp. 8349–8361. Available at: https://doi.org/10.1007/s11356-019-07476-w.

Robalds, A., Dreijalte, L., Bikovens, O. and Klavins, M. (2016) ‘A novel peat-based biosorbent for the removal of phosphate from synthetic and real wastewater and possible utilization of spent sorbent in land application’, *Desalination and Water Treatment*, 57(28), pp. 13285–13294. Available at: https://doi.org/10.1080/19443994.2015.1061450.

Rudi, N.N., Muhamad, M.S., Te Chuan, L., Alipal, J., Omar, S., Hamidon, N., Abdul Hamid, N.H., Mohamed Sunar, N., Ali, R. and Harun, H. (2020) 'Evolution of adsorption process for manganese removal in water via agricultural waste adsorbents', *Heliyon*, 6(9). Available at: https://doi.org/10.1016/j.heliyon.2020.e05049.

Sabri, F. and Gyateng, T. (2015) 'Understanding Statistical Significance : A Short Guide', *NPC* [Preprint]. London: New Philanthropy Capital.

Seltman, H.J. (2018) *Experimental Design and Analysis*. Available at: http://www.stat.cmu.edu/~hseltman/309/Book/Book.pdf.

Shafii, M.A., Ling, E.C.M. and Shaffie, E. (2019) 'The use of sewage sludge and its ash in construction and agriculture industry: a review', *Jurnal Teknologi*, 81(5), pp. 81–90. Available at: https://doi.org/10.11113/jt.v81.13486.

Sharma, S. and Ahammed, M.M. (2023) 'Application of modified water treatment residuals in water and wastewater treatment : A review', *Heliyon*, 9(5), p. e15796. Available at: https://doi.org/10.1016/j.heliyon.2023.e15796.

Shi, L., Zhao, X., Cao, Y., Ma, H. and Sun, X. (2023) 'Physicochemical Properties and Phosphorus Adsorption Capacity of Ceramsite Made from Alum Sludge'.

Singh, M.K. and Singh, A. (2022) 'Chapter 17 - Scanning electron microscope', in M.K. Singh and A.B.T.-C. of P. and F. Singh (eds) *Characterization of Polymers and Fibres*. Woodhead Publishing, pp. 387–419. Available at: https://doi.org/https://doi.org/10.1016/B978-0-12-823986-5.00008-7.

Smith, D.S. (2016) *Phosphorus Analysis in Wastewater: Best Practices, The Water Research Foundation*. IWA Publishing. Available at: https://doi.org/10.2166/9781780407807.

SOGEA SATOM and SUEZ (2019) *Katosi Drinking Water Treatment Plant & Nsumba Pumping Main & Reservoir Design Report*.

Sreeremya, S. (2017) 'Adsorption-Review', *International Journal of Advanced Research and Development*, 2, pp. 15–18.

Thabet, Rr.H., Fouad, M.K., Sherbiny, S.A. El and Tony, M.A. (2022) 'Multivariate-

Parameters Effect of Dewatered Aluminium-Based Sludge in Catalytic Oxidation into Wastewater Treatment with A Special Strategy for Solar Energy Application', *Journal of Physics: Conference Series*, 2305(1), p. 012036. Available at: https://doi.org/10.1088/1742-6596/2305/1/012036.

Tibebe, D., Kassa, Y. and Bhaskarwar, A.N. (2019) 'Treatment and characterization of phosphorus from synthetic wastewater using aluminum plate electrodes in the electrocoagulation process', *BMC Chemistry*, 13(1), pp. 1–14. Available at: https://doi.org/10.1186/s13065-019-0628-1.

Tolofari, A., Adesanya, T., Zvomuya, F. and Yuan, Q. (2022) 'Aluminum phosphate sludge as a phosphorus source for maize production under low soil phosphorus availability.', *PeerJ*, 10, p. e13885. Available at: https://doi.org/10.7717/peerj.13885.

Tony, M.A. (2022) 'Valorization of undervalued aluminum - based waterworks sludge waste for the science of " The 5 Rs ' criteria "', *Applied Water Science*, 12(2), p. 20. Available at: https://doi.org/10.1007/s13201-021-01554-7.

Trinh, V.T., Nguyen, T.M.P., Van, H.T., Hoang, L.P., Nguyen, T.V., Ha, L.T., Vu, X.H., Pham, T.T., Nguyen, T.N., Quang, N. V and Nguyen, X.C. (2020) 'Phosphate Adsorption by Silver Nanoparticles-Loaded Activated Carbon derived from Tea Residue', *Scientific reports*, 10(1), p. 3634. Available at: https://doi.org/10.1038/s41598-020-60542-0.

Turner, T., Wheeler, R., Stone, A. and Oliver, I. (2019) 'Potential Alternative Reuse Pathways for Water Treatment Residuals: Remaining Barriers and Questions—a Review', *Water, Air, and Soil Pollution*, 230(9), p. 227. Available at: https://doi.org/10.1007/s11270-019-4272-0.

Ugwu, C.I., Ekere, J.N. and Onoh, C. (2021) 'RESEARCH PARADIGMS AND METHODOLOGICAL CHOICES IN THE RESEARCH PROCESS', *Journal of applied Information Science and Technology*, 14(2), pp. 116–124.

Ul-Hamid, A. (2018) 'Sample Preparation', in A. Ul-Hamid (ed.) *A Beginners' Guide to Scanning Electron Microscopy*. Cham: Springer International Publishing, pp. 309–359. Available at: https://doi.org/10.1007/978-3-319-98482-7_8.

United States Environmental Protection Agency (1983) ‘Phosphorous, all Forms (colorimetric, ascorbic acid, two reagent)’, *Method 365.3*, National P, pp. 3–7.

Ural, N. (2021) ‘The significance of scanning electron microscopy (SEM) analysis on the microstructure of improved clay : An overview’, *Open Geosciences*, 13(1), pp. 197–218. Available at: https://doi.org/10.1515/geo-2020-0145.

Usman, M.O., Aturagaba, G., Ntale, M. and Nyakairu, G.W. (2022) ‘A review of adsorption techniques for removal of phosphates from wastewater’, *Water Science and Technology*, 86(12), pp. 3113–3132. Available at: https://doi.org/10.2166/wst.2022.382.

Valavanidis, A. (2018) ‘Concept and Practice of the Circular Economy: Turning goods at the end of their service life into resources, closing loops in industrial ecosystems and minimizing waste’, *SCIENTIFIC REVIEWS* [Preprint]. Available at: http://chem-tox-ecotox.org/wp-content/uploads/2018/07/CIRCULAR-ECONOMY-REVIEW-JULY2018.pdf.

Velenturf, A.P.M. and Purnell, P. (2021) ‘Principles for a sustainable circular economy’, *Sustainable Production and Consumption*, 27, pp. 1437–1457. Available at: https://doi.org/10.1016/j.spc.2021.02.018.

Vu, M.T., Nguyen, L.N., Hasan Johir, M.A., Ngo, H.H., Skidmore, C., Fontana, A., Galway, B., Bustamante, H. and Nghiem, L.D. (2021) ‘Phosphorus removal from aqueous solution by steel making slag – Mechanisms and performance optimisation’, *Journal of Cleaner Production*, 284, p. 124753. Available at: https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124753.

Wang, Z., Li, W., Zhu, J., Wang, D., Meng, H., Wang, H. and Li, J. (2021) ‘Simultaneous adsorption of phosphate and zinc by lanthanum modified zeolite’, *Environmental Technology & Innovation*, 24, p. 101906. Available at: https://doi.org/https://doi.org/10.1016/j.eti.2021.101906.

Wong, J.M. and Hess, R.J. (2019) ‘Operation and Performance of the AquaDAF ® Process System for Water Purification’, *Evolutionary Progress in STEAM Series*, 1(7), pp. 13–16.

Wu, H.F., Wang, J.P., Duan, E.G., Feng, Y.F., Wan, Z.Y., Wu, Y.X. and Lu, Y.Q. (2019) 'Study on the preparation of granular alum sludge adsorbent for phosphorus removal', *Water Science and Technology*, 79(12), pp. 2378–2386. Available at: https://doi.org/10.2166/wst.2019.241.

Wu, J., Zhu, X., Yang, F., Wang, R. and Ge, T. (2022) 'Shaping techniques of adsorbents and their applications in gas separation: a review', *Journal of Materials Chemistry A*, 10(43), pp. 22853–22895. Available at: https://doi.org/10.1039/D2TA04352A.

Xu, J., Luu, L. and Tang, Y. (2017) 'Phosphate removal using aluminum-doped magnetic nanoparticles', *Desalination and Water Treatment*, 58, pp. 239–248. Available at: https://doi.org/10.5004/dwt.2017.0356.

Zhang, L., Dan, H., Bukasa, O.T., Song, L., Liu, Y., Wang, L. and Li, J. (2020) 'Low-Cost Efficient Magnetic Adsorbent for Phosphorus Removal from Water', *ACS Omega*, 5(39), pp. 25326–25333. Available at: https://doi.org/10.1021/acsomega.0c03657.

Zhao, W., Xie, H., Li, J., Zhang, L. and Zhao, Y. (2021) 'Application of Alum Sludge in Wastewater Treatment Processes : " Science " of Reuse and Reclamation Pathways', *Processes*, 9(4), pp. 1–612. Available at: https://doi.org/10.3390/pr9040612.

APPENDICES

Appendix 1: Results from the alum sludge XRF analysis

08-Jun-2023 16:59:05

Page 1

Sample results

Sample ident
TOX Sludge 8-6-2023

Application	<Omnian>
Sequence	1 of 1
Position	5
Measurement time	08-Jun-2023 16:33:14

	Normalisation factor	0.000
	Minimum He Flow (l/min)	0.43

Compound	MgO	Al2O3	SiO2	P2O5	SO3	Cl	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	CuO	ZnO	Ga2O3	As2O3
Conc	0.0	38.614	58.955	40.3	0.0	5.1	0.177	949.9	44.3	0.0	73.1	871.0	2.031	0.0	0.0	0.0	0.0
Unit	ppm	%	%	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm

Compound	Br	Rb2O	SrO	Y2O3	ZrO2	Nb2O5	PdO	CdO	SnO2	BaO	Eu2O3	IrO2	PbO	Re
Conc	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	252.0	0.0	0.0	0.0
Unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm

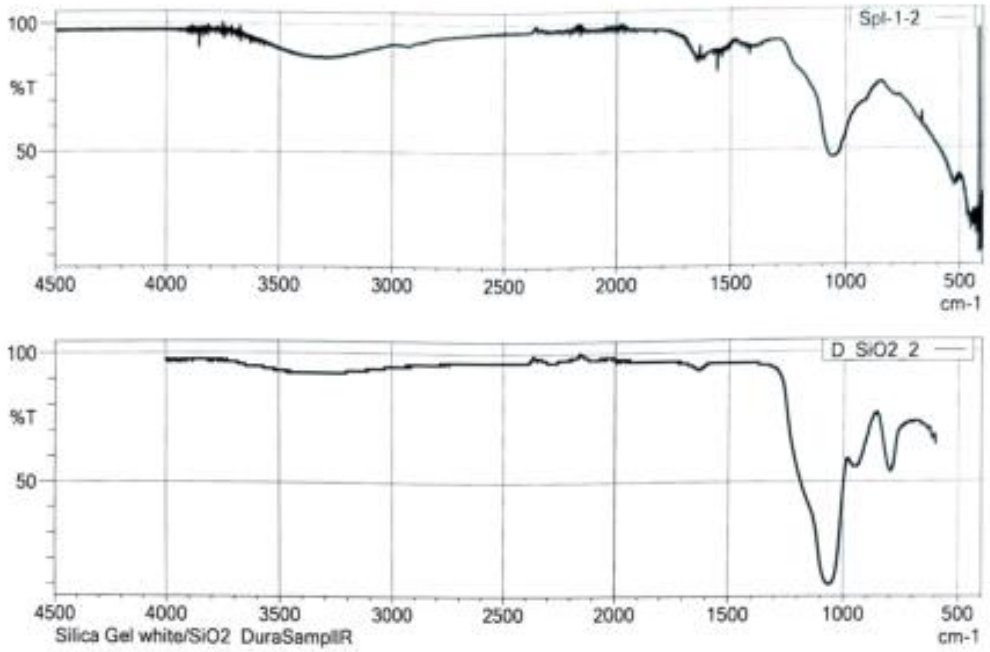
DIRECTORATE OF GOVERNMENT ANALYTICAL LABORATORY

09 AUG 2023

SIGN

Appendix 2: Results from the alum sludge FTIR analysis

SHIMADZU



D:¥FRED¥DFD¥Resty¥Spl-1-2.ispd

	Score	Library	Name	Comment
1	793	1 - ATR-Inorganic2	D_SiO2_2	Silica Gel white/SiO2 DuraSamplIR
2	785	24 - ATR-Inorganic2	D_ZnSO4	ZincSulfate/ZnSO4 7H2O DuraSamplIR
3	785	22 - ATR-Inorganic2	D_MgSO4	MagnesiumSulfate/MgSO4 7H2O DuraSamplIR
4	784	23 - ATR-Inorganic2	D_CuSO4	CupricSulfate/CuSO4 5H2O DuraSamplIR
5	770	111 - ATR-Polymer2	D_Methyl_Cellulose	Methyl Cellulose(Methoxyl content 30%) DuraSamplIR-II
6	764	184 - ATR-Polymer2	D_Methylcellulose	Methylcellulose DuraSamplIR
7	764	108 - ATR-Polymer2	D_Hydroxybutyl_Methyl_Cellulose	Hydroxybutyl Methyl Cellulose(8% Hydroxybutyl, 20%Methoxyl) DuraSamplIR-II
8	762	110 - ATR-Polymer2	D_Hydroxypropyl_Methyl_Cellulose	Hydroxypropyl Methyl Cellulose(10% Hydroxypropyl, 30% Methoxyl) DuraSamplIR-II
9	756	2 - ATR-Inorganic2	D_SiO2_1	Diatomaceous Earth,Granular/SiO2 DuraSamplIR

Appendix 3: Effluent characterisation and adsorption experiment results

NATIONAL WATER AND SEWERAGE CORPORATION
CENTRAL LABORATORY - BUGOLOBI
P.O BOX 7053 KAMPALA Email: waterquality@nwsc.co.ug

Student: Sharon Anneys Naayo (RM22M45/008)

Address: Uganda Christian University

P.O. Box 4, Mukono

Date Sample Received: 10/08/2023

EFFLUENT CHARACTERIZATION

Table 1: Effluent quality

Parameters	Units	Test Results
BOD_5	mg/L	153
COD	mg/L	430
Colour	PtCo	3240
Electrical conductivity	µS/cm	2840
pH	-------	8.65
Temperature	^0C	25.8
Total phosphorus	mg/L	22.581
Total suspended solids	mg/L	379
Turbidity	NTU	241

Table 2: Final Total phosphorus (TP) concentrations for the Negative control

Negative control; Initial concentration = 22.581 mg/L				
Time (hours)	Replicate 1 (mg/L)	Replicate 2 (mg/L)	Replicate 3 (mg/L)	Averaged Final Concentration (mg/L)
6	22.580	22.583	22.578	22.580
15	22.582	22.579	22.584	22.582
24	22.579	22.581	22.582	22.581

NATIONAL WATER AND SEWERAGE CORPORATION
10 AUG 2023
THE CENTRAL LABORATORY

EXPERIMENT RESULTS

Table 3: Experimental Group - Replicated Values

Dosage (g)	Time (hours)	Replicate 1 (mg/L)	Replicate 2 (mg/L)	Replicate 3 (mg/L)
3	6	14.612	13.760	13.116
3	15	11.474	12.040	11.474
3	24	10.997	10.741	10.654
6	6	9.644	9.564	9.037
6	15	8.706	7.759	6.293
6	24	6.264	6.070	5.183
9	6	4.444	4.303	3.930
9	15	3.870	3.643	3.533
9	24	3.167	3.000	3.000

Positive Control (Spiked Sample) - Replicated Values and Averaged Values

Table 4: Positive Control (Spiked Sample) - Replicated Values

Positive control; Initial concentration = 32.107 mg/L				
Dosage (g)	Time (hours)	Replicate 1 (mg/L)	Replicate 2 (mg/L)	Replicate 3 (mg/L)
3	6	19.940	19.882	19.891
3	15	17.808	17.870	17.789
3	24	17.505	17.528	17.472
6	6	14.916	14.894	14.872
6	15	12.707	12.748	12.711
6	24	9.764	9.788	9.754
9	6	7.426	7.123	7.352
9	15	6.388	5.379	5.390
9	24	5.694	4.688	4.711

Tested by: Sharon. A. Naayo &

Innocent Twinomujuni

NATIONAL WATER AND SEWERAGE CORPORATION
10 AUG 2023
THE CENTRAL LABORATORY