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FACULTY OF ENGINEERING AND TECHNOLOGY.

DEPARTMENT OF AGRICULTURAL MECHANIZATION AND IRRIGATION ENGINEERING

FINAL YEAR PROJECT REPORT

# COMPARATIVE ASSESSMENT OF EMITTER CLOGGING UNDER FISHPOND AND SWAMP WATER SOURCES FOR SMALL HOLDER DRIP IRRIGATION SYSTEMS.

A CASE STUDY: LIMOTO WETLAND RESTORATION SITE, PALLISA DISTRICT, UGANDA

BY

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**This final year project report is to be submitted to the Department of Agricultural Mechanization & Irrigation Engineering as a partial fulfilment for the requirement of the Award of Bachelor Degree in Agricultural Mechanization & Irrigation Engineering**

**JUNE, 2026**

**ABSTRACT**.

Emitter clogging is the leading operational constraint of drip irrigation systems when low-quality surface water is used. At the Limoto Wetland Restoration Site, Pallisa District, Uganda, fishpond water (FW) and swamp water (SW) are alternately supplied through a solar-powered drip system serving smallholder vegetable farmers. This study comparatively assessed emitter clogging under both sources over a 90-day field experiment, addressing water quality characterization, emitter discharge performance, deposit characterization, and source-specific engineering mitigation. FW posed Severe clogging risk across all parameter categories: total suspended solids (185 mg/L), turbidity (126 NTU), iron (1.66 mg/L), calcium (82 mg/L), phosphate (6 mg/L), total coliforms ($1.6 \times 10^6$ CFU/100 mL), and algal biomass (85 µg/L), all substantially exceeding SW values and FAO risk thresholds. Field monitoring revealed a clear divergence: FW emitter discharge declined from 1.599 L/h to 1.025 L/h, yielding a clogging rate of 35.90% surpassing the ISO failure threshold of 25%. SW emitters recorded only 20.64% clogging, remaining within acceptable operational limits throughout. Welch's t-test confirmed highly significant differences at every monitoring interval ($t = 29.07$, $df = 12$, $p = 1.71 \times 10^{-12}$). Deposit characterization via SEM, loss on ignition, and UV-Vis spectrophotometry revealed contrasting clogging regimes. FW deposits were dominated by a biological fraction (48%), driven by a synergistic EPS-iron hydroxide ochre biofilm. SW deposits were predominantly physical (54%), comprising porous granular silt despite greater deposit mass a phenomenon termed the "Clogging Paradox." The standard 130-µm disc filter was found inadequate for both sources. Recommended mitigation includes sand media filtration with periodic shock chlorination (10-20 mg/L) and acid injection for FW, and sedimentation basins with bi-weekly lateral flushing for SW. These findings provide actionable, context-specific engineering guidance for improving smallholder drip irrigation sustainability at Limoto Wetland Restoration Site.

**DECLARATION**

I, Etum Samuel, declare that this report entitled Comparative Assessment of Emitter Clogging under Fishpond and Swamp Water Sources for Smallholder Drip Irrigation Systems, A Case Study of Limoto Wetland Restoration Site, Pallisa District, Uganda is my original work and has not been presented for any other academic award.

Signature.......................................Date 12/06/2026.....

**APPROVAL**

This report has been submitted for examination with the approval of my supervisor.

Name: Mr. Igga Huzairu

Signature.................................................Date....18|06|2026..........

**ACKNOWLEDGEMENT.**

All glory and gratitude are first owed to the Almighty God for His guidance, strength, and providence throughout this work.

I express my sincere appreciation to my supervisor, Mr. Igga Huzairu, for his unwavering academic guidance, constructive feedback, and dedication to the success of this project.

Special gratitude is extended to the Ministry of Water and Environment (Water for Production Department) and the smallholder farmer groups at the Limoto Wetland Restoration Site, Pallisa District, for their cooperation and invaluable assistance during both the preliminary field visits and the full project implementation phase.

I am deeply grateful to Mr. Obia George for his fatherly encouragement and generous financial support, which proved instrumental in sustaining field operations throughout the study period. I also wish to acknowledge Mr. Olwa Ronald, Water Analyst at the Ministry of Water and Environment, for his close technical engagement and support in ensuring the successful execution of all water quality analyses. Further appreciation is extended to the Department of Chemistry, Nagongera Campus, for their support in facilitating the laboratory analyses required for the third study objective.

Finally, I extend heartfelt thanks to all my friends and colleagues whose moral support and encouragement contributed to the successful completion of this project.

**TABLE OF CONTENTS**

**LISTS OF TABLES**

**LISTS OF FIGURES.**

**LIST OF ACRONYMS**

APHA-American Public Health Association

$CaCO_3$-Calcium Carbonate

CFU-Colony Forming Units

CI-Clogging Intensity Index

CU-Christiansen's Uniformity Coefficient

CV-Coefficient of Variation

DF-Dilution Factor

DO-Dissolved Oxygen

EBT-Eriochrome Black T

EC-Electrical Conductivity

EDTA-Ethylenediaminetetraacetic Acid

EPS-Extracellular Polymeric Substances

EU-Emission Uniformity

FAO-Food and Agriculture Organization

$Fe(OH)_3$-Iron Hydroxides

FW-Fishpond Water

$H_2S$-Hydrogen Sulphide

$HCO_3^-$-Bicarbonate

HCl-Hydrochloric Acid

ISO-International Organization for Standardization

L/h-Liters per Hour

LOI-Loss on Ignition

$MgCO_3$-Magnesium Carbonate

$NH_4^+$-Ammonium

$NO_3^-$-Nitrate

NTU-Nephelometric Turbidity Units

$PO_4^{3-}$-Phosphate

PPE-Personal Protective Equipment

Pt-Co-Platinum-Cobalt (color units)

PVC-Polyvinyl Chloride

Qvar-Emitter Flow Variation

Rq-Relative Emitter Flow Rate

$R^2$-Coefficient of Determination

SD-Standard Deviation

SEM-Scanning Electron Microscopy

SU-Statistical Uniformity

SW-Swamp Water

TDS-Total Dissolved Solids

TNTC-Too Numerous To Count

TSS-Total Suspended Solids

UNCST-Uganda National Council for Science and Technology

UNDP-United Nations Development Programme

Us-Statistical Uniformity Coefficient

UV-Vis-Ultraviolet-Visible Spectrophotometry

# CHAPTER 1 INTRODUCTION

## 1.1 Background to the Study

Globally, the escalating demand for food production coupled with increasing water scarcity has amplified the significance of efficient irrigation technologies. Drip irrigation, a micro irrigation system, stands as a cornerstone in sustainable agriculture due to its remarkable water-use efficiency and ability to deliver water and nutrients directly to the plant root zone, thereby maximizing crop yields under limited water conditions(Dr. Arvind, 2025). However, the widespread adoption and long-term efficacy of drip irrigation systems, particularly among smallholder farmers, are frequently hampered by a critical operational challenge: emitter clogging.

Emitter clogging is unequivocally recognized as the leading cause of system inefficiency and performance degradation in drip irrigation(El Bouhali et al., 2023). The study reveals that the efficiency of drip irrigation systems is largely influenced by emitter clogging, which results from poor water quality and inadequate maintenance. It further indicates that emitter clogging significantly impacts drip irrigation efficiency, with no emitters completely clogged. However, average flow rates decreased by 89% at times, reflecting performance issues(El Bouhali et al., 2023). The consequence of clogging is a spatially heterogeneous water distribution, leading to uneven crop growth, reduced yields, and increased operational costs due to maintenance and replacement of affected components (Capra & Scicolone, 2007). Recent innovations, such as the novel inlet designs proposed by (Huynh et al., 2024), aim to improve clog resistance and maintain higher flow rates even when exposed to grit, highlighting the persistent and critical nature of this issue in drip system design and management.

In sub-Saharan Africa, where rain-fed agriculture is highly vulnerable to erratic rainfall patterns and prolonged droughts, governments and international donors have increasingly supported smallholder irrigation initiatives as a crucial strategy for climate change adaptation and food security (Okolie et al., 2023). Despite these efforts, a significant proportion of smallholder farmers rely on readily accessible yet often unfiltered water sources such as open ponds, swamps, and rivers. Studies conducted across various African contexts, including Kenya, Ethiopia, and South Africa, consistently demonstrate that irrigation water characterized by high concentrations of suspended sediments, organic matter, and dissolved solids significantly exacerbates emitter clogging, diminishing the anticipated benefits of drip irrigation (Shen et al., 2022). This reliance on low-quality water sources without adequate filtration mechanisms often negates the efficiency gains of drip irrigation, leading to farmer disillusionment and abandonment of these otherwise beneficial technologies.

Uganda, like many developing nations, has prioritized agricultural productivity enhancement through various interventions, including the Ministry of Water and Environment's Water for Production program. Under this initiative, solar-powered drip irrigation schemes have been established in several regions to bolster agricultural output and improve rural livelihoods. A notable example is the scheme located at the Limoto Wetland Restoration Site in Pallisa District, Eastern Uganda. This site presents a unique case study, as farmers utilize two distinct water sources for their irrigation needs: swamp water, typically sourced from a valley tank and used routinely, and fishpond water, applied occasionally for its perceived nutrient enrichment benefits. Despite the introduction of modern irrigation technology, farmers at Limoto consistently report issues of uneven emitter flow and frequent clogging, necessitating a detailed technical assessment. This study aims to comparatively evaluate the susceptibility of drip emitters to clogging under these two prevalent water sources fishpond and swamp water at the Limoto Wetland Restoration Site, thereby informing sustainable irrigation practices for smallholder farmers in similar agro-ecological zones.

The Limoto wetland, situated within the expansive Kyoga plains of Eastern Uganda, serves as the geographical context for this investigation. Located between latitudes 1°10’0” N and longitudes 33°57’0” E, the wetland exhibits an average elevation ranging from 1040m above sea level around Lake Lemwa to 1060 m above sea level within its floodplains. It constitutes a significant arm of the larger Mpologoma wetland system, dominant in these plains, and encompasses a total area of 136 sq. km, with approximately 70% lying within Pallisa District and the remaining 30% in Kibuku District (UNDP, 2016). The region is characterized by small-scale subsistence agriculture, primarily involving annual crops, limited pastoralism, and a discernible high level of food insecurity (Undp et al., n.d.). With a moderate human population density of 260 persons per $km^2$, the annual rainfall varies between 900-1500 mm, and the predominant vegetation comprises savanna species (Bunyangha et al., 2022). This environmental profile, encompassing specific hydrological features, agricultural practices, and socio-economic conditions, underscores the practical relevance of understanding emitter clogging dynamics from locally available water sources in Limoto.

### 1.2 Problem Statement.

In Uganda, smallholder farmers increasingly adopt drip irrigation to cope with erratic rainfall and improve crop productivity. However, the long-term efficiency of these systems is often undermined by emitter clogging, which restricts water flow, causes uneven irrigation, and reduces yields. This challenge is particularly severe when farmers use untreated open water sources such as swamps and fishponds, which typically contain suspended sediments, organic matter, dissolved minerals, and microorganisms that promote both physical and biological clogging. (Huynh et al., 2024). At the Limoto Wetland Restoration Site in Pallisa District, a solar-powered drip irrigation system established under the Ministry of Water and Environment's Water for Production Program supports smallholder vegetable production. Farmers there rely mainly on swamp water for daily irrigation and occasionally apply fishpond water for its nutrient benefits. These differing water qualities expose emitters to varying clogging risks, resulting in non-uniform discharge, increased maintenance, and reduced system lifespan. Despite recurring clogging complaints from farmers, there is limited empirical evidence comparing the extent and causes of emitter clogging between these two water sources under local field conditions. This knowledge gap prevents effective decision making on water source selection, filtration, and maintenance strategies. Therefore, a comparative assessment of emitter clogging under fishpond and swamp water is essential to determine which source poses higher clogging risks and to propose practical solutions for sustaining efficient smallholder drip irrigation at Limoto and similar sites across Uganda.

### 1.3 Research Hypothesis

$H_0$ (Null Hypothesis): There is no significant difference in emitter clogging between fishpond and swamp water sources in smallholder drip irrigation systems at the Limoto Wetland Restoration Site, Pallisa District, Uganda.

$H_1$ (Alternative Hypothesis): There is a significant difference in emitter clogging between fishpond and swamp water sources in smallholder drip irrigation systems at the Limoto Wetland Restoration Site, Pallisa District, Uganda.

### 1.4 Objectives of the Study

#### 1.4.1 Main objective

To comparatively assess emitter clogging under fishpond and swamp water sources at the Limoto Restoration Site, Pallisa District, Uganda.

#### 1.4.2 Specific Objectives

1. To characterize the physical, chemical, and biological quality of fishpond and swamp water and assess their clogging potential for smallholder drip irrigation systems.
2. To establish the extent to which fishpond and swamp water sources differ in their rate and severity of emitter clogging under equivalent field operating conditions.
3. To characterize the composition and nature of clogging deposits formed under fishpond and swamp water conditions, and to establish evidence-based mitigation strategies for each source.

### 1.5 Research Questions

1. What are the physical, chemical, and biological characteristics of fishpond and swamp water used for smallholder drip irrigation at the Limoto Wetland Restoration Site?
2. To what extent do fishpond and swamp water sources differ in the rate and severity of emitter clogging when operated under equivalent field conditions at the Limoto Wetland Restoration Site?
3. What is the composition and nature of clogging deposits formed within emitters under fishpond and swamp water conditions, and what evidence-based engineering mitigation strategies can be established for each source?

### 1.6 Justification of the Study

From an engineering and economic standpoint, the absence of empirical, source-specific clogging data for sites like Limoto represents a critical design and management failure. Irrigation engineers and programme managers under Uganda's Water for Production Programme currently lack the technical evidence needed to specify appropriate filtration systems, recommend pre-treatment protocols, or justify capital expenditure on filtration upgrades for fishpond versus swamp water sources. This is not merely an academic gap; it translates directly into suboptimal engineering decisions: systems are installed with uniform 130-micron disc filters regardless of water source, when in reality the bio-chemical clogging profile of fishpond water demands an entirely different filtration architecture than the physical sedimentation profile of swamp water. The consequent system failures incur measurable economic costs including premature emitter replacement, reduced crop yields due to non-uniform irrigation, increased maintenance labor, and in some cases complete system abandonment representing a poor return on government and donor investment in smallholder irrigation infrastructure (FAO, 2021; Kanda et al., 2018).

Currently, there is a critical knowledge gap regarding the comparative clogging potential of fishpond and swamp water under real smallholder operating conditions. Farmers at Limoto, and likely in other similar regions, often make decisions about water use without evidence based guidance, leading to inefficient irrigation, reduced yields, higher labor demands for maintenance (cleaning or replacing clogged emitters), and potential economic losses. Moreover, limited understanding of the dominant clogging mechanisms physical, chemical, or biological hinders the design of targeted, cost-effective mitigation strategies.

This study is justified because it will generate context-specific, actionable evidence that benefits farmers, extension agents, engineers, and policymakers. Specifically, the research will:

Provide actionable guidance: Offer clear, evidence-based insights on the comparative risks of using fishpond versus swamp water, enabling farmers to make informed water source choices.

Facilitate targeted solutions: Identify and classify the dominant clogging mechanisms for each water type, supporting the development of appropriate filtration and maintenance strategies tailored to local conditions.

Enhance system sustainability: Recommend low-cost mitigation measures such as filtration, sedimentation, and optimized flushing schedules, thereby extending the lifespan and reliability of smallholder drip irrigation systems.

Support food security and livelihoods: By improving the efficiency and durability of irrigation, the study will contribute to higher agricultural productivity, reduced water waste, and increased economic resilience for smallholder communities in Limoto and other comparable agro-ecological zones.

Furthermore, the study aligns with Uganda's Vision 2040 and the National Irrigation Policy, which emphasize sustainable irrigation development, smallholder empowerment, and climate-resilient agriculture. By filling the existing empirical evidence gap, this research will provide both practical solutions for immediate application and a scientific basis for future smallholder irrigation planning and management in Uganda.

### 1.7 Scope of the Study

Geographical Scope: Limoto Wetland Restoration Site, Pallisa District, Eastern Uganda.

Content Scope: Physical, chemical, and biological causes of emitter clogging under fishpond and swamp water.

Time Scope: The overall study was conducted over six months (December 2025-May 2026), encompassing preparatory field assessments, water quality characterization, and laboratory analyses. The core emitter clogging experiment was conducted over a 90-day (three-month) continuous monitoring period, representing one complete smallholder vegetable cropping cycle.

Conceptual Scope: Focus on emitter clogging mechanisms, not crop yield or economics.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Introduction

Drip irrigation has become a cornerstone of sustainable agriculture due to its high water use efficiency, precise nutrient delivery, and ability to maintain crop yields under water limited conditions (Dr. Arvind, 2025). However, the operational success of these systems, especially among smallholder farmers in sub Saharan Africa, is heavily constrained by emitter clogging a persistent issue that limits uniform water distribution and reduces productivity (Nam et al., 2012). Understanding the complex interactions between water quality and clogging mechanisms is essential for designing sustainable drip irrigation strategies.

This chapter synthesizes existing literature on drip irrigation, emitter clogging mechanisms, water quality parameters, comparative assessment of fishpond and swamp water, and mitigation strategies.

Emphasis is placed on recent studies to ensure relevance and to highlight gaps in empirical data concerning smallholder irrigation systems, particularly in Eastern Uganda at sites like Limoto Wetland Restoration.

## 2.2 Overview of Drip Irrigation Systems and Their Importance

Drip irrigation, also called trickle or micro irrigation, applies water and nutrients directly to the root zone in small, controlled amounts, reducing evaporation, runoff, and deep percolation losses (Bwire et al., 2024). Recent meta-analyses confirm that drip irrigation increases crop yields while minimizing water consumption compared to conventional methods (Cui et al., 2024). Beyond water savings, drip irrigation allows for precise fertigation, reduces weed growth, lowers energy use, and improves nutrient use efficiency (Kapoor et al., 2022).

The adoption of drip irrigation is expanding in sub Saharan Africa due to climate variability, population growth, and increasing food demand (Ringler et al., 2020). In Uganda, smallholder farmers, including those at Limoto Wetland Restoration, increasingly rely on solar-powered drip systems to improve livelihoods. However, the operational efficiency and long-term sustainability of these systems depend heavily on the quality of water used and the ability to manage emitter clogging (Bawa et al., 2023)

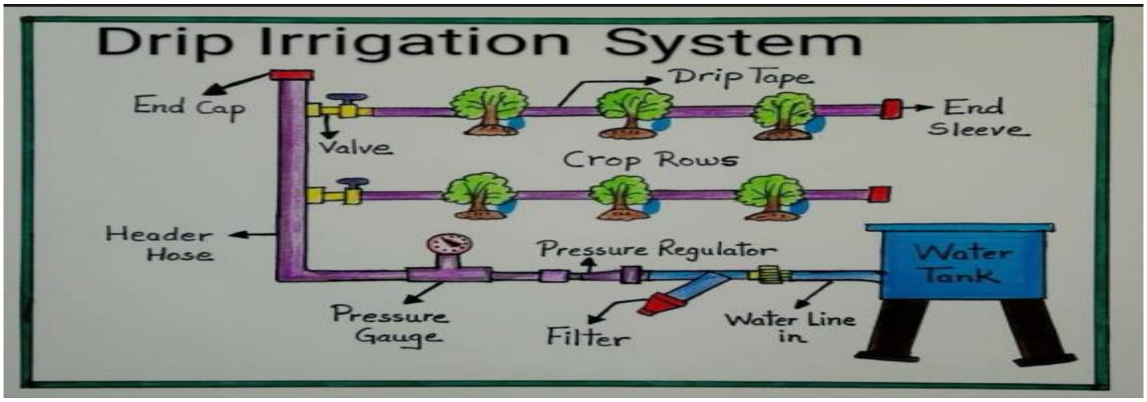


Figure 2-1 Typical layout and components of a drip irrigation system.

### 2.3 Emitter Clogging: A Major Constraint in Drip Irrigation

Emitter clogging is the most significant operational challenge for drip irrigation systems and can result in uneven water distribution, crop stress, and reduced yields(H. Li et al., 2020). The problem is intensified for smallholder farmers who often lack filtration systems, technical expertise, or resources to mitigate clogging(Kim et al., 2021).

Emitter clogging is generally categorized into three mechanisms: physical, biological, and chemical. These mechanisms often occur simultaneously and interact with one another, resulting in combined or compounded effects that accelerate the decline in emitter performance over time (Ramachandrula & Kasa, 2022) and the study continued and categorized the mechanisms into percentages, of which physical (31%), biological (37%), and chemical (22%) types, while other minor forms account for approximately 10%. The increasing adoption of fertigation practices where fertilizers are delivered through irrigation water has been shown to elevate the risk of chemical clogging, as nutrient-rich solutions promote both precipitation reactions and microbial growth within emitters (Ramachandrula & Kasa, 2022). These findings emphasize the need for a comprehensive understanding of clogging behavior, especially under varying water sources such as swamp and fishpond water, which contain different combinations of suspended solids, dissolved minerals, and organic matter that can trigger multiple clogging mechanisms simultaneously.

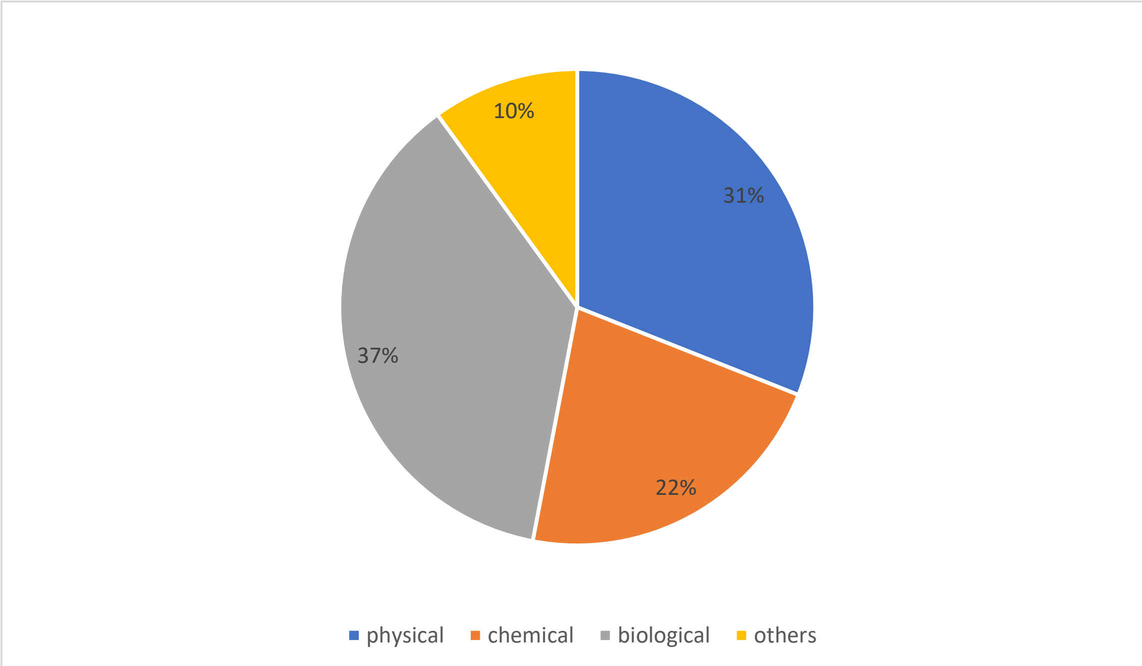


Figure 2-2 Pie chart showing clogging mechanisms in percentages.

### 2.3.1 Physical Clogging

Physical clogging arises from suspended solids such as sand, silt, clay, and organic debris ( Capra & Scicolone, 2007). High turbidity and particulate concentrations, especially in surface water sources like swamps, directly contribute to blockage in emitter channels. Particle size, density, and shape influence clogging severity, with even fine particles capable of causing significant obstruction over time (Niu et al., 2013). More recently, Shen et al. (2022) confirmed that high-sediment surface water sources induce progressive physical clogging detectable within 30–60 days of continuous drip system operation, while Ramachandrula and Kasa (2022) found physical clogging to account for approximately 31% of all emitter blockage events globally, underscoring its persistent relevance across diverse water quality contexts.

### 2.3.2 Biological Clogging

Biological clogging is caused by microorganisms forming biofilms within emitters. Bacteria, algae, fungi, and iron bacteria colonize pipes and emitters, producing extracellular polymeric substances that trap additional particles and exacerbate clogging (Dehghanisanij et al., 2004). Water sources rich in nutrients, such as fishponds, accelerate biofilm formation due to high organic and nitrogen/phosphorus content (Paul et al., 2020). Light-exposed swamp water can also promote algal growth, contributing to clogging, particularly in warm climates.

### 2.3.3 Chemical Clogging

Chemical clogging results from the precipitation of minerals like calcium carbonate, iron hydroxides, and magnesium compounds (Larroque & Franceschi, 2011). Factors such as high pH, elevated calcium or iron concentrations, and temperature fluctuations influence precipitate formation. Chemical clogging is exacerbated when fertilizers or mixed water sources introduce ions that react to form insoluble compounds (Wang et al., 2024). Typical chemical agents responsible for clogging which included iron ($Fe^{2+}$), manganese ($Mn^{2+}$), calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), bicarbonates ($HCO_3^-$), phosphates ($HPO_4^{2-}$ / $PO_4^{3-}$), and hydrogen sulfide ($H_2S$) each contributing differently to emitter blockage.

Iron ($Fe^{2+}$) is one of the most common chemical clogging agents. When its concentration exceeds 1.5 mg $L^{-1}$, oxidation occurs upon exposure to air, forming insoluble iron hydroxides ($Fe(OH)_3$) with this equation $Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3$ that accumulate as reddish brown deposits inside emitter (Obreza et al., 2009). Similarly, manganese ($Mn^{2+}$) oxidizes to manganese oxide ($MnO_2$) when concentrations rise above 0.1 mg $L^{-1}$, producing dark, stubborn scales that obstruct emitter flow, particularly under fluctuating oxygen conditions common in ponds and wetlands(Robbins & Corley, 2005).

Water hardness, represented by calcium and magnesium ions, is another key factor. When the combined hardness ($Ca^{2+} + Mg^{2+}$) exceeds 300 mg $L^{-1}$, or when pH > 7.5 and bicarbonate > 5 mmol $L^{-1}$, precipitation of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) readily occurs, forming white, crust-like deposits (Wang et al., 2024) and these scale formations are intensified under fertigation practices, where phosphate fertilizers interact with calcium to form calcium phosphate, a poorly soluble compound.

Additionally, hydrogen sulfide ($H_2S$) generated under anaerobic conditions reacts with dissolved metals such as iron and manganese to form insoluble sulfides (e.g., FeS and MnS). These black deposits are commonly found in irrigation systems drawing water from swamps or fishponds rich in decomposing organic matter (Gammons & Frandsen, 2001). The interaction of these chemical processes can be particularly problematic in swamp and fishpond waters used by smallholder farmers. Fishpond water often exhibits fluctuating oxygen and pH levels due to algal photosynthesis and organic decomposition, promoting both oxidation and precipitation of metal ions. Swamp water, on the other hand, tends to be rich in bicarbonates and sulfides due to prolonged water-soil interaction and anaerobic microbial activity. Together, these conditions create an environment conducive to multi-mechanistic chemical clogging, exacerbating performance decline in drip emitters over time.

### 2.4 Water Quality Parameters and Clogging Potential

The quality of irrigation water fundamentally determines drip system performance (Bawa et al., 2023).Water sources vary in physical, chemical, and biological characteristics, each influencing specific clogging mechanisms.

Physical parameters: High turbidity, suspended solids, and organic debris increase the risk of physical clogging (Capra & Scicolone, 2007).

Chemical parameters: pH, EC, bicarbonate, calcium, magnesium, iron, and manganese affect chemical precipitation. High nutrient content in fishpond water promotes biological growth and indirectly enhances clogging (Paul et al., 2020).

Biological parameters: Microbial counts, algal concentration, and presence of iron bacteria indicate the potential for biofilm formation and biological clogging (Dehghanisanij et al., 2004).

### 2.5 Comparative Assessment of Fishpond and Swamp Water Sources

#### 2.5.1 Fishpond Water Characteristics and Clogging Potential

Fishpond water is a highly dynamic and biologically active water source. It contains a complex mixture of dissolved nutrients, particulate organic matter, and a diverse microbial community. Nutrients primarily originate from fish feed residues, excreta, and decomposed organic matter. Nitrogen (ammonium, nitrate) and phosphorus (phosphate) levels are typically elevated compared to natural surface waters, which can accelerate microbial growth and biofilm formation inside emitters.

Suspended solids in fishpond water include uneaten feed, fish feces, and planktonic organisms such as algae and protozoa. These fine and coarse particles pose a high risk for physical clogging, particularly in micro emitters with small flow paths (Paul et al., 2020). The continuous input of organic material makes the water prone to rapid biological fouling. Microorganisms, including heterotrophic bacteria and algae, can adhere to emitter surfaces, producing extracellular polymeric substances (EPS) that trap additional particulates, accelerating clogging (Dehghanisanij et al., 2004).

Fishpond water is also characterized by fluctuating dissolved oxygen levels. Surface agitation, aeration, and photosynthetic activity during the day increase oxygen concentrations, while decomposition of organic matter at night reduces oxygen, creating anaerobic micro zones. These fluctuations can promote iron and manganese precipitation when water is pumped through the irrigation system, potentially causing chemical clogging in addition to biological and physical obstruction (Guang et al., 2003).

In summary, fishpond water exhibits; high nutrient content leading to strong biological clogging potential, moderate to high suspended solids, contributing to physical clogging.

Variable oxygen levels and chemical composition, occasionally leading to chemical precipitation. A highly active microbial ecosystem capable of rapid biofilm formation.

Overall, fishpond water represents a high-risk source for emitter clogging, particularly where pre-filtration or disinfection is inadequate. Smallholder farmers relying on untreated pond water are especially vulnerable to rapid performance decline in drip systems.

## 2.6 Swamp (Wetland) Water Characteristics and Clogging Potential

Swamp water, in contrast, is derived from natural wetland ecosystems and exhibits distinct physical, chemical, and biological properties that influence emitter clogging. Swamps typically receive water from surface runoff, rainfall, and groundwater seepage, often carrying high loads of suspended solids such as silt, clay, and decomposing plant debris. These fine particulates significantly increase turbidity, making swamp water highly prone to physical clogging if filtration is inadequate (Boyd, 2000).

The organic matter content in swamp water is also high, consisting of decayed leaves, plant stems, and microbial detritus. While these organic materials contribute to physical obstruction, they simultaneously provide a substrate for microbial colonization, enhancing biological clogging potential. The microbial community in swamp water is extremely diverse, including heterotrophic bacteria, fungi, algae, protozoa, and iron-oxidizing bacteria. The presence of algae is particularly significant because sunlight penetration in shallow swamp areas promotes rapid photosynthetic growth, which can obstruct emitters and increase biofilm formation (Anderson & Davis, 2013) and (Murray & Hodson, 1984).

Chemically, swamp water can exhibit fluctuating pH and low dissolved oxygen levels, especially in deeper stagnant zones. Low oxygen promotes the solubilization of iron and manganese in anaerobic conditions. When this water is pumped and aerated through drip systems, precipitation occurs, leading to chemical clogging (Scholz, 2006). Moreover, the combination of organic matter, suspended solids, and microbial activity creates a complex environment where physical, biological, and chemical clogging mechanisms interact.

Key characteristics of swamp water includes; very high levels of suspended solids and organic debris, increasing the risk of physical clogging, rich microbial diversity and high algal density, enhancing biological clogging potential, anaerobic zones and dissolved metal ions prone to chemical precipitation, continuous variability due to seasonal runoff, rainfall, and decomposition processes.

Overall, swamp water presents a chronic risk for emitter clogging, particularly physical clogging due to high turbidity, compounded by biological fouling and occasional chemical precipitation. Its variability in quality also challenges smallholder farmers, who may not have access to consistent filtration or pre-treatment solutions.

### 2.7 Knowledge Gaps

Few studies provide direct comparisons of emitter clogging under fishpond versus swamp water conditions, especially in smallholder contexts like Uganda. Most existing research focuses on generalized surface water or treated wastewater, leaving a critical gap in context-specific, operational guidance for farmers. Understanding the dominant clogging mechanisms for each water source is essential to design effective, low-cost mitigation strategies tailored to local conditions.

**Table 2.1 Summary of water quality parameters and their influence on emitter clogging**

| Parameter | Type | Effect on Clogging | Source type (most affected |
|---|---|---|---|
| Suspended solids | Physical | Block flow paths | Swamp water |
| PH | Chemical | Promotes $CaCO_3$ precipitations | Fishpond water |
| Algal Biomass, total coliform, p.aeruginosa. | Biological | Biofilm | Fishpond water |

### 2.8 Relevant Formulas for Evaluating Emitter Clogging and Drip Irrigation Performance.

Evaluating the performance of drip irrigation systems under different water qualities requires several analytical formulas that quantify flow uniformity, clogging rate, and system efficiency. These formulas are widely applied in similar studies comparing emitter clogging under various water sources(J. Li et al., 2009).

### 2.8.1 Christiansen's Uniformity Coefficient (CU)

$$CU = 100 \times \left(1 - \frac{\sum_{i=1}^{n} |q_i - \bar{q}|}{n \times \bar{q}}\right)$$ ……………………….. Equation 1

Where:

$q_i$ = discharge from the $i^{th}$ emitter (L/h)

$q_{i}$=discharge from the ith emitter $\left(\frac{L}{h}\right)$, $\bar{q}$=average discharge$\left(\frac{L}{h}\right)$, n=number of emitters

The CU expresses the overall uniformity of emitter discharge. Values above 90% indicate excellent performance, while values below 80% reflect significant non-uniformity (Osei & A., 2022).

### 2.8.2 Statistical Uniformity (Us)

$$Us = 100 \times \left(1 - \frac{S_d}{\bar{q}}\right)$$ ……………………………………………. Equation 2

Where; $S_d$ = standard deviation of emitter discharge (L/h).

$\bar{q} = mean\ discharge \left(\frac{L}{h}\right)$.

This formula evaluates the statistical spread of emitter flows. A low standard deviation indicates consistent flow among emitters, implying minimal clogging (Nam et al., 2012).

CU and Us provide a direct measure of how evenly water is distributed through emitters across the irrigation system. In the context of Limoto, where water sources differ significantly in sediment and biological content, these parameters will be critical in identifying whether clogging is random or progressive.

A decline in CU or Us over time would indicate increasing non-uniformity often a symptom of partial clogging caused by physical particles (such as silt and suspended solids in swamp water) or biological accumulation (such as algae and microbial films in fishpond water). Studies by (Osei & A., 2022) and (Nam et al., 2012) confirmed that a drop in CU below 85% reflects noticeable clogging effects in systems using unfiltered surface water.

### 2.8.3 Coefficient of variation (CV).

$CV = \frac{S_d}{\bar{q}}$ ………………………………………… Equation 3

The coefficient of variation is used to assess emitter manufacturing or operational variation.

CV and Qvar are statistical tools used to describe the variability in emitter discharge. High CV values typically occur when clogging materials are distributed unevenly, leading to fluctuating emitter flows.

At Limoto, these metrics will help distinguish between localized clogging (caused by heavier sediment loads in swamp water) and systemic clogging (often biological, associated with fishpond water). According to (J. Li et al., 2008) , a CV exceeding 0.10 indicates poor uniformity and is directly correlated with the presence of suspended organic matter and microbial biofilms and also that CV<0.05 denotes excellent uniformity, 0.05<$CV$<0.10 is acceptable, while CV>0.10 indicates poor uniformity.

## 2.9 Emitter Flow Rate, pressure relationship.

$\boldsymbol{q = K \times H^x}$ ………………………………………… Equation 4

Where; q=emitter discharge (L/h), K=emitter discharge coefficient, H= pressure head (m), x= emitter flow exponent.

This relationship expresses the emitter hydraulic characteristics. A high flow exponent indicates pressure sensitivity, while a lower exponent (close to zero) represents pressure-compensating emitters (Dehghanisanij et al., 2004). This formula will assist in determining the hydraulic sensitivity of the emitters under test. Since different emitter types respond differently to clogging, comparing the flow exponent (x) between those operated with swamp water and those with fishpond water will indicate whether clogging alters emitter pressure sensitivity. For instance, emitters operating with fishpond water may show higher deviation from the designed pressure flow curve due to biological slime formation on internal flow paths (Dehghanisanij et al., 2004).

### 2.10 Relative Emitter Flow Rate (clogging rate)

$$\mathbf{R_q} = \frac{q_t}{q_o} \times \mathbf{100} \quad \text{................................................ Equation 5}$$

Where; $q_t$ = emitter discharge after t, $q_o$ = initial discharge.

The clogging percentage can also be expressed as;

Clogging Rate (%) $= \frac{q_o - q_t}{qo} \times 100$

This formula quantifies how emitter discharge reduces over time due to clogging from suspended solids, biofilms, or precipitates (El Bouhali et al., 2023).

These formulas will be used to quantify the degree of clogging over time. The reduction in discharge ($q_0 - q_t$) reflects the combined effects of suspended solids, precipitates, and bio fouling.

For Limoto's conditions, it is expected that swamp water may lead to faster initial clogging due to inorganic sediment accumulation, while fishpond water may exhibit gradual clogging dominated by biological processes. The clogging rate will therefore help determine which source causes more frequent and severe discharge reduction.

### 2.11 Emitter Flow Variation (Qvar).

Qvar= $\frac{q_{max} - q_{min}}{q_{max}} \times \mathbf{100}$ ................................................ Equation 6

Where; $q_{max}$ = maximum emitter flow rate, $q_{min}$ = minimum emitter flow rate,

This measures the extent of emitter discharge fluctuation and is particularly useful for identifying localized clogging effects within laterals (Pinto et al., 2017).

### 2.12 Emission Uniformity (EU)

$$EU = 100 \times \frac{q_{25}}{\bar{q}} \times \left(1 - \frac{CV}{\sqrt{n}}\right)$$ …………………………………………… Equation 7

Where; $q_{25}$ = average discharge of the lowest 25% of emitters, CV = coefficient of variation, n = number of emitters per plant and $\bar{q} = overall\ discharge.$

Emission uniformity reflects how efficiently the system distributes water to all plants. It is considered very well when above 90%, and poor when below 70%. (Pourkhiz, 2012).

The emission uniformity equation links discharge variability with emitter performance, making it an effective indicator of field efficiency.

At the Limoto site, EU will help assess whether clogging patterns affect only a few emitters or a broader section of the system. Previous studies demonstrated that when EU drops below 70%, crop water distribution becomes significantly uneven, leading to water stress in parts of the field.

### 2.13 Clogging intensity index

$$\boldsymbol{CI = \frac{1}{n}\sum_{i=1}^{n} \frac{q_{oi} - q_{ti}}{q_{oi}} \times 100}$$ …………………………………………… Equation 8

Where; $q_{oi}$ and $q_{ti}$ are the initial and final discharge rates of the $i^{th}$ emitter.

This index helps identify the severity of clogging within an emitter population (Zhou et al., 2019). CI provides a single numerical representation of emitter performance degradation. It integrates the effects of both partial and complete clogging, making it especially useful in long-term observation.

For this study, CI will be instrumental in ranking the clogging severity between fishpond and swamp water treatments, identifying which emitter type is more resilient under different water quality conditions.

The application of the above formulas is essential in quantitatively assessing the extent, nature, and effects of emitter clogging when using different water sources specifically, swamp water and fishpond water under smallholder drip irrigation conditions such as those at the Limoto Wetland Restoration Site in Pallisa District.

### 2.14 Mitigation Strategies for Emitter Clogging

Emitter clogging can be managed through preventive and corrective measures, adapted to water quality and smallholder capabilities (Tripathi, 2016).

Filtration: Screen, disc, and sand media filters remove suspended solids and organic matter. Correct selection and maintenance are critical (Duran-Ros et al., 2009).

Sedimentation: Settling tanks or ponds reduce the load of heavy particles before filtration, particularly effective for swamp water (Owuor et al., 2020).

Chemical Treatment: Chlorination controls biological growth, while acids dissolve chemical precipitates. Careful application is required to avoid crop damage and excessive cost (Su et al., 2023; De Kreij & Van der Staay, 2000).

Flushing: Regularly flushing laterals removes accumulated sediments and biofilms, extending system lifespan. Frequency depends on water quality and emitter type (Nakayama & Bucks, 1986; Ma et al., 2020).

### 2.15 Conclusion of Literature Review

Emitter clogging remains the primary constraint on drip irrigation performance, influenced by water quality and source characteristics. Fishpond water predominantly induces biological clogging due to high nutrients and microbial load, while swamp water mainly causes physical clogging due to suspended solids, with potential chemical clogging from iron and manganese precipitation. Current literature lacks direct comparative studies in smallholder African contexts, especially for sites like Limoto Wetland. Understanding the specific clogging dynamics for each water source is essential to implement effective, affordable mitigation strategies and improve smallholder irrigation efficiency. This study addresses this gap by empirically evaluating emitter clogging under fishpond and swamp water, with the aim of providing context-specific guidance for sustainable drip irrigation management.

# CHAPTER 3 METHODOLOGY

## 3.1 Introduction:

This chapter presents the methodological framework that guided the study titled "Comparative Assessment of Emitter Clogging under Fishpond and Swamp Water Sources for Smallholder Drip Irrigation Systems at the Limoto Wetland Restoration Site, Pallisa District, Uganda." The methodology outlines the procedures that were followed to achieve the study objectives and provide reliable, evidence-based insights into the nature, rate, and mechanisms of emitter clogging under different irrigation water sources.

A mixed-methods approach was employed, integrating quantitative field-based assessments with qualitative analytical methods. This approach was appropriate because it allowed for both numerical comparison of clogging rates and in-depth examination of the physical, chemical, and biological materials responsible for clogging.

The research methodology was organized around three main objectives:

Characterization of the physical, chemical, and biological properties of fishpond and swamp water sources.

Establishing the extent to which fishpond and swamp water sources differ in their rate and severity of emitter clogging under equivalent field operating conditions.

Characterizing the composition and nature of clogging deposits formed under each water source, and establishing evidence-based mitigation strategies through UV-Vis spectrophotometry (Fe and Mg), EDTA titration (Ca), and loss on ignition analysis.

This chapter also describes the study area, research design, sampling procedures, data collection techniques, equipment used, and data analysis methods, while addressing ethical considerations, data management protocols, and study limitations. This comprehensive approach ensured that the study's findings are methodologically sound, reproducible, and applicable to similar irrigation contexts in Uganda and beyond

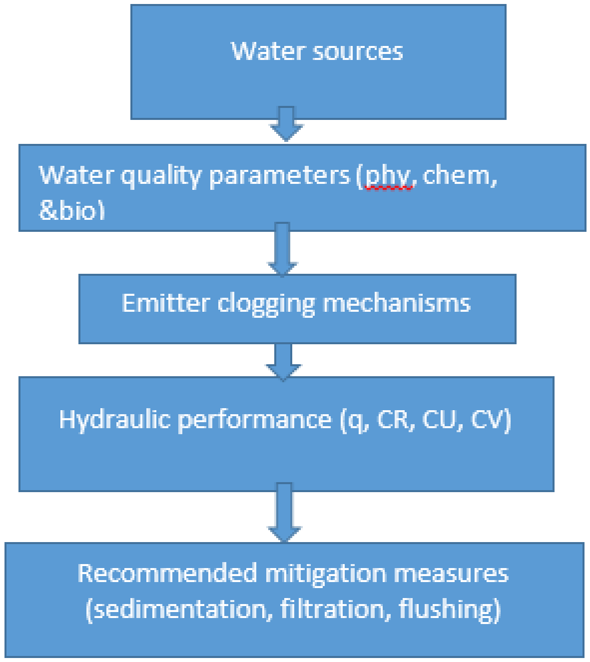


Figure 3-1 shows Conceptual framework.

### 3.2 Research Design

The study adopted an experimental case study design focused on the Limoto Wetland Restoration Site as the case location. This design was suitable for controlled comparison between fishpond and swamp water sources, allowing detailed examination of clogging under field conditions.

The research employed a comparative experimental framework with two treatments fishpond water and swamp water evaluated under replicated setups.

Quantitative component: Field trials were conducted to measure emitter discharge rates, clogging severity, and water quality parameters.

Qualitative component: Scanning Electron Microscopy (SEM) analysis and visual identification of clogging materials were carried out to characterize the biological, chemical, and physical deposits recovered from emitters.

Integration: Quantitative results were triangulated with qualitative findings to provide a holistic understanding of clogging behavior under both water sources at the Limoto Wetland Restoration Site.

Statistical tests were used to verify the hypothesis at a 5% significance level ($\alpha = 0.05$). A randomized block design was applied in the field layout to minimize spatial bias.

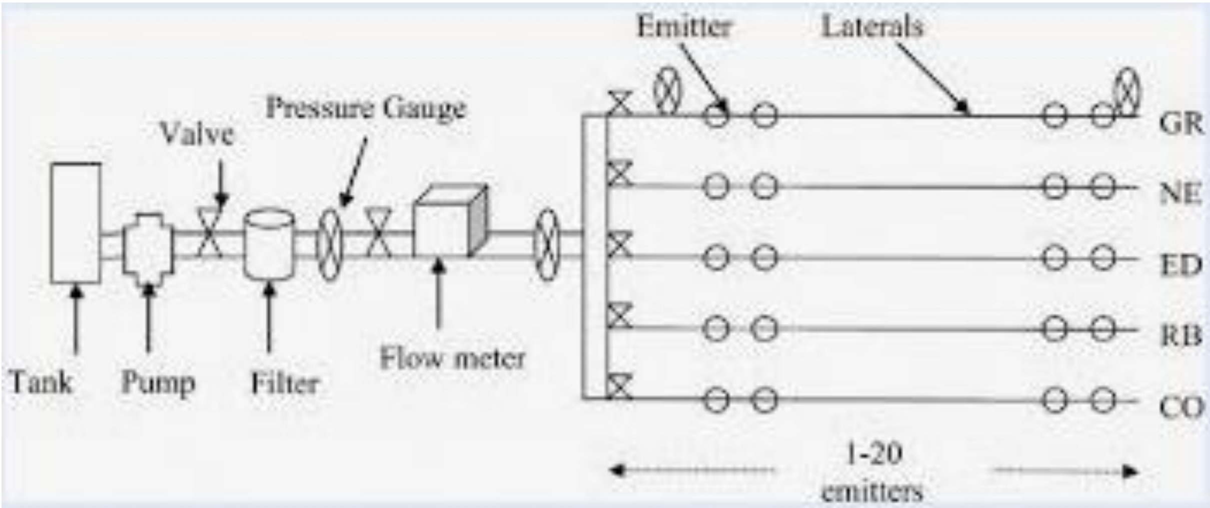


Figure 3-2 Experimental setup for emitter discharge and clogging evaluation.

### 3.3 Study Area

The study was conducted at the Limoto Wetland Restoration Site, located in Pallisa District, Eastern Uganda (Latitude 1°10′ N, Longitude 33°57′ E). The site forms part of the Mpologoma wetland system and lies at an elevation between 1,040 m and 1,060 m above sea level. The region experiences a bimodal rainfall pattern (900–1,500 mm per annum), with rainy seasons occurring from March to May and September to November. Soils at the site are primarily ferralsols and luvisols, with high organic matter content in the wetland zones.

The Limoto solar-powered drip irrigation scheme, established in 2018 under the Ministry of Water and Environment's Water for Production Programme, serves approximately 50 farmer groups (approximately 200 households). The system utilizes 16 mm PVC laterals fitted with inline emitters rated at 1.6 L/h and spaced at 0.3 m intervals.

### 3.4 Water sources to be assessed.

Two water sources were assessed in this study:

Swamp Water: Drawn from a valley tank within the restored wetland. The water was open, sediment-laden, and frequently used by farmers for routine irrigation.

Fishpond Water: Obtained from adjacent aquaculture ponds. The water was nutrient-rich and occasionally applied by farmers for fertigation purposes.

The Limoto Wetland Restoration Site was selected as the study location on account of its active simultaneous use of both water sources, the documented history of emitter clogging complaints from farmers, and its accessibility for regular and systematic sampling throughout the study period.

### 3.5 Population and Sampling

#### 3.5.1 Target Population

The study population comprised three elements: emitters installed within the Limoto drip irrigation system, water samples drawn from the two irrigation sources (swamp and fishpond), and farmers actively managing the system. Emitters served as the primary unit of analysis for clogging evaluation, while water samples provided the physicochemical and biological context for interpreting clogging behavior. Farmers were consulted primarily for contextual understanding of operational practices and observed clogging occurrences.

#### 3.5.2 Sampling Techniques

**Water sampling.**

The two water sources swamp and fishpond were purposively selected based on their established use within the Limoto irrigation scheme. From each source, 12 composite samples were collected over a three-month period to capture temporal variation in water quality. Each sample (5 L) was collected using a Van Dorn sampler at mid-depth and stored at 4°C during transport to the laboratory. All sampling and preservation procedures were carried out in strict accordance with APHA (2017) standard methods.

**Emitter Sampling**

Emitters were randomly selected from both the laboratory experimental setup and the field system. A total of twenty (20) emitters were selected for destructive sampling: ten (10) from the Fishpond Water (FW) laterals and ten (10) from the Swamp Water (SW) laterals. To ensure representativeness, a randomized systematic sampling approach was used, where emitters were selected from the proximal, middle, and distal sections of the lateral lines to account for potential variations in sediment settling and pressure along the line.

**Farmer Sampling**

Thirty-five farmers with a minimum of two years of experience operating the Limoto drip irrigation system were purposively selected. These farmers provided qualitative information on the frequency of clogging occurrence, maintenance practices, and observed differences in system performance under the two water sources.

## 3.6 Data Collection Methods

Data were collected over a period of six months, structured around the specific objectives of the study. Each objective was matched with corresponding field and laboratory procedures and an appropriate analytical approach, as detailed in the subsections below.

### 3.6.1 Objective One.

To determine the physical, chemical, and biological quality characteristics of fishpond and swamp water sources, Water quality analysis was conducted using standard laboratory methods at the National Water Quality Laboratory. Parameters were grouped into three categories physical, chemical, and biological as described below.

**Physical Parameters.**

The physical parameters measured were Turbidity, Total Suspended Solids (TSS), and Total Dissolved Solids (TDS). Turbidity was measured using a calibrated turbidimeter and expressed in Nephelometric Turbidity Units (NTU). TSS was determined gravimetrically by filtering a known volume of water through a pre-weighed 0.45 µm membrane filter, drying the residue at 105°C, and computing the mass difference. TDS was determined using a calibrated conductivity meter.

**Chemical Parameters**

Chemical parameters included pH, Electrical Conductivity (EC), all measured in the field using a calibrated multipara meter probe. Major ions including calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), nitrate ($NO_3^-$), and phosphate ($PO_4^{3-}$) were determined in the laboratory using a spectrophotometer following standard colorimetric methods.

**Biological Parameters**

Biological parameters assessed included Total Coliform Count, Pseudomonas aeruginosa counts, and Algal Biomass. Total coliforms and P. aeruginosa were enumerated using membrane filtration and selective culture techniques. The algal biomass was estimated using UV-Vis Spectrophotometry as a proxy for total pigment concentration. Water samples were analyzed at a wavelength of 665 nm (standard for chlorophyll-a absorbance) and applied Jeffrey & Humphrey of 1975 equation. This spectrophotometric approach was selected to provide a rapid and objective index of the biological load, allowing for the quantification of organic biomass without the subjectivity of manual microscopic counting. All biological analyses were conducted at the National Water Quality Laboratory following APHA (2017) protocols

**3.7 Objective 2:**

To establish the extent to which fishpond and swamp water sources differ in their rate and severity of emitter clogging under equivalent field operating conditions.

**Field Experiments:** Field Emitter Clogging Assessment

To establish the extent to which fishpond and swamp water sources differ in their rate and severity of emitter clogging under equivalent field operating conditions, parallel field systems using the two water sources were operated under normal field conditions. Emitters were monitored bi-weekly for discharge and uniformity over the six-month study period.

Discharge uniformity was assessed using Christiansen's Uniformity Coefficient (CU) and Emission Uniformity. Field measurements included volumetric discharge readings collected at proximal, medial, and distal positions along laterals to capture the full range of clogging behavior across the system. Emitter flow variation (Qvar), emission uniformity (EU), and clogging intensity index (CI) were computed at each monitoring interval.

### 3.8 Objective 3:

The third objective involved the morphological and compositional analysis of the deposits recovered from the clogged emitters. To ensure high analytical precision, the recovered deposits were dried at 105°C for 24 hours, pulverized, and divided into three representative portions for specialized testing.

### 3.9 Qualitative Morphological Assessment (Portion A).

The first portion of the dry deposit was utilized for Scanning Electron Microscopy (SEM). This was conducted to provide a qualitative visual assessment of the clog's structural architecture. The samples were mounted on stubs and gold-sputtered to enhance conductivity and SEM was employed to identify the presence of the sticky Extracellular Polymeric Substance (EPS) matrix, mineral crystal formations, and the texture of inorganic silt/clay particles. This provided the "visual eyes" required to justify the subsequent quantitative findings.

### 3.10 Quantitative Bulk Composition via LOI and Acid Digestion (Portion B)

A second portion of the deposit was used to determine the general percentage contribution of the three primary clogging mechanisms (Biological, Chemical, and Physical) through a sequential extraction process:

Biological Fraction: Loss on Ignition (LOI) was performed by heating a measured mass in a muffle furnace at 450°C for 6 hours. The resulting weight loss was recorded as the biological/organic fraction.

Chemical and Physical Separation: The residual ash from the LOI was subjected to Acid Digestion using 6M HCl. The minerals that dissolved represented the chemical fraction, while the acid-insoluble residue (the remaining grit) was filtered, dried, and weighed to quantify the physical silt/clay fraction.

#### 3.10.1 Determination of Exact Mineral Concentrations (Portion C)

To obtain the high-precision concentrations of specific minerals, a separate portion of the deposit was analyzed using advanced spectrophotometric and complexometric methods:

Iron (Fe) and Magnesium (Mg) Analysis: These were determined via UV-Vis Spectrophotometry.

Iron: Quantified at 510 nm (1,10-phenanthroline method) using a Dilution Factor of 25 to ensure the samples fell within the 1-10 mg/L linear calibration range.

Magnesium: Quantified using the Calmagite colorimetric method.

Calcium (Ca) Analysis: The concentration of Calcium was determined through EDTA Complexometric Titration.

Procedure: The sample was buffered to a specific pH typically pH 10 using Borax buffer (sodium tetra borate), and titrated against 0.01M EDTA solution.

Indicator: Eriochrome Black T (EBT) was utilized as the indicator, with the endpoint identified by the distinct color change from wine-red to a clear blue.

Data Integration and Mechanism Classification

Finally, the results from the different portions were integrated. The exact mineral concentrations (mg/g) from Portion C were correlated with the bulk percentages found in Portion B and the morphological structures seen in Portion A. This allowed for a definitive classification of the deposits into Bio-Chemical (dominant in Fishpond Water) or Physical (dominant in Swamp Water) clogging categories.

### 3.11 Data Analysis.

Data analysis was conducted using Microsoft Excel with the Data Analysis Toolpak and specialized analytical procedures for each objective. All statistical tests were performed at a 95% confidence level ($\alpha=0.05$)

Objective One: Water Quality Assessment, Descriptive statistics (mean, standard deviation) were used to summarize the physical, chemical, and biological characteristics of the Fishpond Water (FW) and Swamp Water (SW). The water quality parameters were evaluated against international standards for emitter clogging risk, specifically the FAO Irrigation and Drainage Paper 29 and the Nakayama & Bucks (1991) clogging risk thresholds.

Objective Two: Hydraulic Performance and Clogging Rate Emitter discharge data (L/h) collected at monthly intervals were analyzed to compute performance indicators including Relative Flow Rate (Rq), Clogging Rate (%), and Christiansen's Uniformity Coefficient (CU).

Inferential Statistics: To compare the impact of water source (FW vs. SW) on emitter performance, Independent Samples t-tests (Welch's t-test for unequal variances) were conducted for each 30-day monitoring period. This allowed for the determination of statistical significance (p-values) and the rejection of the null hypothesis regarding treatment differences.

Objective Three: Deposit Characterization and Classification, the classification of clogging mechanisms involved both quantitative and qualitative analysis:

Quantitative Mineral Analysis: Linear Regression Analysis was used to develop calibration curves for Iron (Fe) and Magnesium (Mg) using UV-Vis Spectrophotometry. The strength of these relationships was verified using the Coefficient of Determination ($R^2$).

Gravimetric Analysis: A sequential mass-balance approach was used for the classification of deposits. Loss on Ignition (LOI) data and acid-insoluble residue weights were processed to determine the percentage contribution of biological, chemical, and physical mechanisms.

Qualitative Support: Scanning Electron Microscopy (SEM) images were utilized for morphological characterization to provide visual verification of the quantitative findings.

## 3.12 Validity and Reliability

### 3.12.1 Validity

To ensure the internal and external validity of the study, several measures were implemented which included Standardization of Operating Conditions where the drip irrigation system was operated at a constant pressure of 1 bar, and the 90-day monitoring duration was deliberately selected based on three converging scientific justifications: (1) it corresponds to a complete vegetable cropping cycle (approximately 60–90 days) at the Limoto site, thereby reflecting a realistic operational scenario for smallholder farmers; (2) prior clogging studies (Nakayama & Bucks, 1991; Dehghanisanij et al., 2004; Shen et al., 2022) demonstrate that biofilm maturation and mineral scaling within emitters follow a non-linear trajectory that becomes statistically detectable only after 60–90 days of continuous operation; and (3) ISO standards for emitter performance evaluation recommend monitoring intervals of sufficient duration to capture the full development of both physical and biological clogging phases, typically defined as the period required to reach or approach the 25% flow reduction failure threshold,

Experimental Controls, the use of a 130-micron manual disc filter ensured that the study focused on the bio-chemical and fine-particle clogging mechanisms rather than random large-debris blockages.

Triangulation of Methods: The classification of clogging mechanisms (Objective Three) was validated by cross-referencing results from three independent portions: SEM (visual), LOI/Acid Digestion (bulk mass), and UV-Vis/EDTA (specific mineral concentration).

### 3.12.2 Reliability

Reliability was maintained through rigorous calibration and replication:

Instrument Calibration: The UV-Vis Spectrophotometer was calibrated using standard iron and magnesium solutions, achieving a coefficient of determination ($R^2 > 0.99$) for both curves.

Replication: Emitter discharge was measured from 10 independent emitters per treatment to minimize the impact of individual manufacturing variations.

Standard Protocols: Water quality and deposit analyses were conducted in strict adherence to the APHA (American Public Health Association) Standard Methods for the Examination of Water and Wastewater.

## 3.13 Ethical Considerations and Environmental Safety

The research was conducted in compliance with the guidelines of the Uganda National Council for Science and Technology (UNCST).

Permission and Consent: Formal permission was sought and obtained from the managers of the fishpond and swamp sites. For the field experiment, the site was managed in a way that did not interfere with the natural ecosystem of the swamp or the commercial productivity of the fishpond.

Laboratory Safety: All laboratory procedures involving the muffle furnace ($450^0$) and acid digestion (6M HCl) were conducted under strict safety protocols, including the use of appropriate Personal Protective Equipment (PPE).

Waste Management: Chemical wastes from the titration and spectrophotometry processes (EDTA, HCl, and color reagents) were neutralized and disposed of following standard environmental protection guidelines to prevent local water contamination.

### 3.14 Conclusion of Chapter Three.

This chapter has provided a detailed and integrated methodology for evaluating emitter clogging under fishpond and swamp water conditions. By combining long-term field-based discharge monitoring with advanced laboratory characterization techniques including Scanning Electron Microscopy, Loss on Ignition, and UV-Vis Spectrophotometry this design ensures that the results are both practically relevant and scientifically robust. This systematic approach allows for a definitive understanding of how bio-chemical biofilms and physical sediments interact within an irrigation system, ultimately informing better maintenance and water management strategies for smallholder farmers.

# CHAPTER 4 RESULTS AND DISCUSSIONS.

## 4.1 Introduction.

This chapter presents and discusses the results obtained from the comparative assessment of emitter clogging under Fishpond Water (FW) and Swamp Water (SW) sources for the smallholder drip irrigation system at the Limoto Wetland Restoration Site, Pallisa District, Uganda. The results are organized in alignment with the three specific study objectives: (1) characterization of water quality parameters and clogging potential, (2) evaluation of emitter discharge performance and clogging rates over time, and (3) identification, classification, and deposit characterization of dominant clogging mechanisms, together with source-specific engineering mitigation recommendations.

The data collected over the 90-day field trial, supplemented by laboratory analyses, are presented through descriptive statistics, graphical trends, and inferential tests. A central finding that runs through each objective is the existence of a fundamentally different clogging regime between the two water sources: Fishpond Water induced a predominantly bio-chemical clogging pathway, while Swamp Water caused primarily physical sedimentation-based clogging. Together, these findings provide a robust, evidence-based foundation for recommendations to improve irrigation performance and system longevity for smallholder farmers in Uganda.

## 4.2 Results for Objective One: Water Quality Characterization

Note on Baseline Water Quality: Water quality characterization was conducted at Day 0, prior to the commencement of the emitter clogging experiment, to establish the baseline physicochemical and biological profile of each source water. These baseline measurements served as the reference point for interpreting emitter deposit composition and clogging mechanisms identified in subsequent objectives. It is acknowledged that source water quality may exhibit seasonal variation beyond the study period; however, the 12 composite samples collected from each source over the 90-day monitoring window provided a statistically representative characterization of the water quality conditions encountered during the experiment.

**Physical Water Quality Parameters**

Physical water quality parameters directly influence the capacity of particulate matter to enter and accumulate within emitter labyrinths, constituting the primary driver of physical clogging. Table 2 below presents a summary of the physical parameters measured for both water sources, benchmarked against internationally recognized clogging risk thresholds (FAO Irrigation, ISO, and Drainage Paper No. 29; Nakayama & Bucks, 1991).

Table 4.1 shows results for physical water quality parameters and their corresponding risks

| Parameter | Unit | Fishpond Water (FW) | Swamp Water (SW) | Risk (FW) | Risk (SW) | Interpretation |
|---|---|---|---|---|---|---|
| Total Suspended Solids (TSS) | mg/L | 185 | 120 | Severe | Moderate | High particle load blocks emitters |
| Turbidity | NTU | 126 | 39.9 | Severe | Moderate | Suspended particles cause clogging |
| Total Dissolved Solids (TDS) | mg/L | 381 | 332 | Moderate | Low | Dissolved solids contribute to deposits |
| Color | Pt-Co | 770 | 600 | High | Moderate | Indicates high organic matter |

The results reveal that Fishpond Water (FW) consistently exhibited higher values across all physical parameters compared to Swamp Water (SW). Total Suspended Solids (TSS) for FW reached 185 mg/L, more than double the 120 mg/L recorded for SW, placing FW in the "Severe" risk category. This is consistent with the high nutrient enrichment in the fishpond, which stimulates algal growth and particulate organic matter accumulation. Swamp water, while also containing colloidal organic material from wetland decomposition, is subjected to natural sedimentation that reduces its TSS load.

Turbidity followed a similar trend, with FW recording 126 NTU versus 39.9 NTU for SW. At 126 NTU, the FW turbidity far exceeds the FAO threshold of 50 NTU for a "Severe" physical clogging risk. The color parameter, measured in Platinum-Cobalt (Pt-Co) units, was notably high for both sources (770 for FW, 600 for SW), both indicating heavy organic loading. Total Dissolved Solids (TDS) were moderate for both sources, suggesting that while dissolved mineral content contributes to clogging, it is not the dominant physical pathway.

**Chemical Water Quality Parameters.**

Chemical clogging arises from precipitation of dissolved minerals within emitter orifices, particularly iron, calcium carbonate, and other divalent cations. Table 4.2, presents the chemical parameters analyzed for both water sources.

Table 4.2 shows results for chemical water quality parameters and their corresponding risks

| Parameter | Unit | Fishpond Water (FW) | Swamp Water (SW) | Risk (FW) | Risk (SW) | Interpretation |
|---|---|---|---|---|---|---|
| Iron (Fe) | mg/L | 1.66 | 1.26 | Severe | Moderate | Iron precipitation causes clogging |
| Calcium ($Ca^{2+}$) | mg/L | 82 | 14 | High | Low | $CaCO_3$ scaling in emitters |
| Magnesium ($Mg^{2+}$) | mg/L | 55 | 37 | Moderate | Low | Contributes to scaling |
| Total Hardness | mg/L | 80 | 55 | Moderate | Low | Scaling potential |
| PH | - | 7.45 | 6.70 | Moderate | Low | Alkalinity promotes precipitation |
| Electrical Conductivity (EC) | µS/cm | 571 | 487 | Moderate | Low | Indicates dissolved salts |
| Phosphates ($PO_4^{3-}$) | mg/L | 6 | 2 | High | Moderate | Promotes biological clogging through microbial & algal growth. |

Iron (Fe) concentration in FW was 1.66 mg/L, exceeding the FAO "Severe" risk threshold of 1.5 mg/L, while SW registered 1.26 mg/L (Moderate risk). Of all the chemical parameters, dissolved iron is arguably the most critical in this study, as its interaction with the biological load in the fishpond creates the bio-chemical "ochre" biofilm described in Section 4.3. Laboratory calibration curves for UV-Vis spectrophotometry ($R^2 > 0.99$ for both Fe at 510 nm and Mg at 520 nm) were used to quantify mineral concentrations in emitter deposits; these confirmed that FW-sourced deposits contained significantly higher iron (22.7 mg/g) compared to SW deposits.

Calcium ($Ca^{2+}$) concentrations showed the largest disparity between the two sources: 82 mg/L in FW versus only 14 mg/L in SW. EDTA titration of recovered emitter deposits confirmed this disparity, yielding 38.5 mg/g of calcium (as $CaCO_3$) in FW deposits compared to 12.6 mg/g in SW deposits a ratio of approximately 3:1. The higher pH of FW (7.45 versus 6.70 for SW) further promotes $CaCO_3$ and $Fe(OH)_3$ precipitation, as these reactions are thermodynamically favored in near-neutral to slightly alkaline conditions. The relatively elevated phosphate concentration in FW (6 mg/L versus 2 mg/L) also plays a dual role: while classified primarily as a biological risk factor, phosphate is a key nutrient substrate for microbial biofilm formation.

**Biological Water Quality Parameters**

Biological water quality parameters determine the potential for microbial biofilm development within emitter flow pathways, which is the most complex and hydraulically damaging form of clogging. Table 4.3, summarizes the biological parameters for both sources.

Table 4.3 shows results for biological water quality parameters and their corresponding risks

| Parameter | Unit | Fishpond Water (FW) | Swamp Water (SW) | Risk (FW) | Risk (SW) | Interpretation |
|---|---|---|---|---|---|---|
| Total Coliforms | CFU/100 Ml | $1.6 \times 10^6$ | $2.4 \times 10^4$ | High | Minor | Indicates microbial contamination |
| Pseudomonas aeruginosa | CFU/Ml | $4.8 \times 10^5$ | $1.2 \times 10^3$ | Severe | Minor | Strong biofilm formation |
| Algal biomass | µg/L | 85 | 36 | High | Moderate | Biofilm and emitter blockage |
| Temperature | °C | 29 | 27 | High | Moderate | Enhances microbial growth |

The biological quality of FW was dramatically worse than SW across all indicators. Total coliform counts in FW were $1.6 \times 10^6$ CFU/100 mL approximately 67 times higher than the $2.4 \times 10^4$ CFU/100 mL recorded for SW. While total coliforms are primarily used as a general indicator of faecal and organic contamination, the presence of Pseudomonas aeruginosa at $4.8 \times 10^5$ CFU/mL in FW ("Severe" risk) is of direct technical relevance. P. aeruginosa is a known strong biofilm former that secretes Extracellular Polymeric Substances (EPS), a sticky matrix of polysaccharides and proteins that adheres to pipe walls and emitter surfaces. In SW, P. aeruginosa counts were minimal ($1.2 \times 10^3$ CFU/mL, "Minor" risk).

The algal biomass, measured as absorbance at 665 nm and 775nm, was significantly higher in the Fishpond Water (85 µg/L) compared to the Swamp Water (36 µg/L). This higher biomass reading in the FW treatment indicates a greater concentration of organic photosynthetic matter. This finding is critical as it explains the 35.90% discharge reduction; the higher biological load identified by the UV-Vis provided the organic substrate necessary for the development of the non-porous, restrictive biofilms observed in the FW emitters. Algal biomass serve a dual clogging role, they directly block emitter orifices and simultaneously provide a carbon-rich scaffold upon which heterotrophic bacteria colonise and secrete biofilm. The slightly higher water temperature in FW (29°C versus 27°C) further amplifies biological activity, as this temperature range is within the optimal growth zone for the identified microorganisms.


Figure 4.1 membrane filtration results showing TNTC total coliform growth for fishpond and swamp water samples

Consolidated Water Quality Discussion

In synthesis, the water quality characterization confirmed the study hypothesis that the two sources differ significantly in their clogging potential and clogging mechanisms. The consolidated risk profile is discussed in the sections below.

### 4.3 Results for Objective Two: Emitter Discharge Performance and Clogging Rate Analysis

#### 4.3.1 Progressive Discharge Decline Over 90 Days

Emitter discharge performance was monitored at 30-day intervals over the 90-day experimental period. Both treatments started at a baseline discharge of 1.599 L/h (the manufacturer-rated flow rate at 1 bar operating pressure). The results, summarized in Table 4.5, show a diverging pattern of deterioration between the two water sources.

**Table 4.5: Summary of Emitter Discharge and Clogging Rates Over 90 Days**

| Time (Days) | FW Discharge (L/h) | SW Discharge (L/h) | FW Clogging Rate (%) | SW Clogging Rate (%) | Interpretation |
|---|---|---|---|---|---|
| 0 | 1.599 | 1.599 | 0.00% | 0.00% | Baseline both sources at rated performance |
| 30 | 1.435 | 1.499 | 10.26% | 6.25% | Initial divergence; FW clogging rate is higher than SW |
| 60 | 1.215 | 1.379 | 24.02% | 13.76% | FW approaches ISO failure threshold (25%); biofilm maturation phase |
| 90 | 1.025 | 1.269 | 35.90% | 20.64% | FW exceeds ISO failure threshold; SW remains within acceptable limits |

The data clearly demonstrate that Fishpond Water emitters underwent significantly more aggressive clogging throughout the trial. By Day 90, FW emitters had experienced a mean discharge reduction from 1.599 L/h to 1.025 L/h, representing a clogging rate of 35.90%. This exceeds the internationally recognized ISO-defined failure threshold of 25% flow reduction, meaning the FW-treated system had, by the end of the trial, reached a state of functional failure. In contrast, SW emitters maintained a discharge of 1.269 L/h with a clogging rate of 20.64%, remaining within acceptable operational limits for the duration of the experiment.

A notable observation is the inflection point at Day 60, where the FW clogging rate reached 24.02% just below the failure threshold. This point corresponds to the maturation phase of the biofilm identified through SEM analysis (Section 4-4), suggesting that once the EPS matrix becomes structurally consolidated, and the rate of hydraulic resistance increases nonlinearly. The SW system, by contrast, showed a more linear, gradual clogging trajectory consistent with purely physical sedimentation processes.

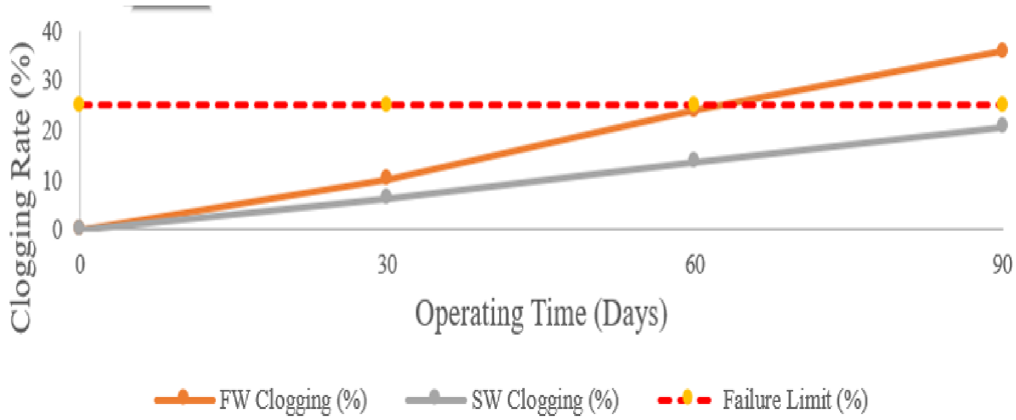


Figure 4.2 Progressive Clogging Rates relative to the ISO 25% failure threshold

**Analysis of the Failure Threshold:**

Figure 4.2 presents the clogging rate as a percentage of the initial flow, compared against the international ISO failure threshold of 25% (represented by the red dashed line). This graph is critical for determining the operational lifespan of the drip system under the two water sources.

**Crossing the Failure Point (FW):**

The Fishpond Water (FW) treatment exhibited an aggressive clogging rate. The orange line indicates that the FW emitters reached a clogging rate of 10.26% by Day 30 and climbed to 24.02% by Day 60. Crucially, the FW treatment crossed the 25% failure threshold at approximately Day 65. By the end of the 90-day trial, the FW clogging rate reached 35.90%, indicating a total system failure according to irrigation standards.

**Comparison with SW:**

The Swamp Water (SW) treatment (grey line) followed a significantly lower trajectory. By Day 90, the SW emitters reached a clogging rate of only 20.64%. Throughout the entire 90-day duration, the SW treatment remained below the 25% failure line.

**Scientific Significance:**

This graph proves that under the same filtration conditions (130-micron disc filter), the Fishpond Water is not sustainable for long-term drip irrigation without additional chemical or biological treatment. The "Failure Limit" line clearly differentiates the "Severe Risk" of Fishpond Water from the "Manageable Risk" of Swamp Water. The statistical significance of this divergence was further confirmed by the Welch's t-test ($p<0.001$), proving that the water source was the definitive cause of the system failure.

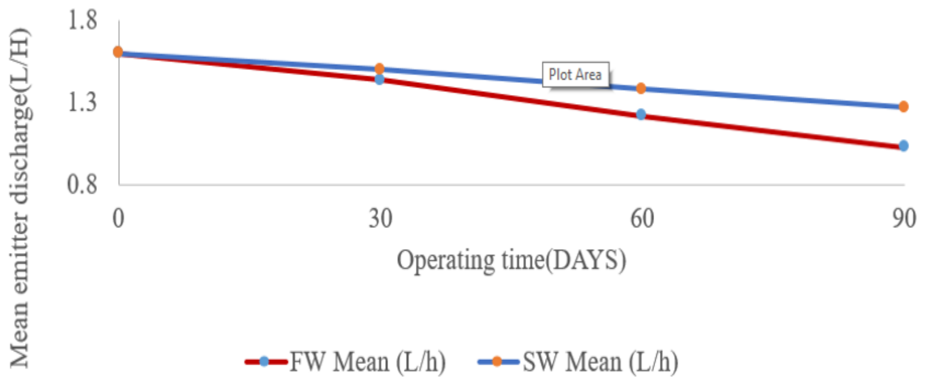


**Figure 4.3 Comparative Mean Emitter Discharge over a 90-day field trial**

**Analysis of the Trend:**

Figure 4.3 illustrates the hydraulic performance of the emitters over the 90-day field trial. At the start of the experiment (Day 0), both the Fishpond Water (FW) and Swamp Water (SW) treatments exhibited an identical mean discharge of 1.599 L/h, which aligns with the manufacturer's rated flow. However, as the operating time progressed, a distinct divergence in discharge was observed between the two treatments.

**The FW Performance:**

The emitters operated with Fishpond Water (FW) showed a steep and consistent decline in discharge. By Day 90, the mean flow rate had dropped to 1.025 L/h. The steepness of the red line gradient indicates a rapid accumulation of restrictive materials within the emitter labyrinth. This severe reduction is attributed to the high iron and algal load in the FW source, which formed dense biofilms that reduced the effective cross-sectional area of the emitter pathways.

**The SW Performance:**

In contrast, the Swamp Water (SW) treatment (blue line) showed a more gradual decline, reaching 1.269 L/h by Day 90. While a reduction in flow occurred, the emitters maintained a higher discharge throughout the study compared to the FW treatment. This suggests that the clogging agents in the swamp water primarily physical silt were less restrictive to the flow than the biological biofilms found in the fishpond water.

**4.4 Statistical Validation: Welch's Independent Samples t-Test**

To rigorously confirm that the observed differences in emitter discharge between FW and SW were statistically significant and not attributable to random variation, independent samples t-tests (Welch's correction for unequal variances) were conducted at each 30-day monitoring interval. The results are presented in Table 4-4.

Table 4.4 Welch's Independent Samples t-Test Results for Emitter Discharge (FW vs. SW)

| Period | Mean FW (L/h) | Mean SW (L/h) | t-statistic | Df | p-value | Significance |
|---|---|---|---|---|---|---|
| Day 30 | 1.435 | 1.499 | 11.53 | 18 | < 0.001 | Highly Significant |
| Day 60 | 1.215 | 1.379 | 29.58 | 14 | < 0.001 | Highly Significant |
| Day 90 | 1.025 | 1.269 | 29.07 | 12 | < 0.001 ($p = 1.71E^{-12}$) | Highly Significant, null Hypothesis Rejected |

The selection of Welch's t-test, rather than the standard Student's t-test, was scientifically justified by the variance structure of the data. The FW treatment exhibited a variance of 0.000605 compared to 0.000098 for SW a ratio of approximately 6:1. This six fold difference in variance reflects the fundamentally erratic nature of bio-chemical clogging: in the FW system, some emitters clogged catastrophically while others were only moderately affected, depending on their proximity to the water inlet, lateral flow velocity, and localized temperature. In the SW system, physical sedimentation produced a far more uniform clogging pattern along the lateral, as gravity-driven siltation is consistent regardless of position.

The t-statistic of 29.07 at Day 90 is exceptionally large, far exceeding the critical value of 2.179 at the 95% confidence level. The corresponding p-value of $1.71 \times 10^{-12}$ is effectively zero, confirming with absolute statistical certainty that the difference in discharge performance between FW and SW emitters is a genuine water-source-driven effect. The null hypothesis that there is no significant difference in emitter clogging between fishpond and swamp water is therefore conclusively rejected.

**The Clogging Paradox: Bio-Slime vs. Physical Silt**

A critical and counterintuitive observation was made during physical inspection of the recovered emitters: Swamp Water emitters contained a visibly larger volume of sediment material within their labyrinths, yet Fishpond Water emitters suffered a significantly greater loss of hydraulic performance. This “Clogging Paradox” is a central finding of this study and requires mechanistic explanation.

For SW emitters (Physical Sedimentation): The dominant deposit consisted of fine silts and colloidal organic particles that bypassed the 130-micron disc filter. While these particles accumulated as a “gritty” physical mass within the labyrinth flow paths, the resulting deposit remained relatively porous and permeable. Water could seep through the inter-particle voids, allowing the SW emitters to maintain a relative flow rate (Rq) of 79.36% by Day 90.

For FW emitters (Bio-Chemical Biofilm): The FW clogging mechanism was driven by a synergistic interaction between the high algal biomass of 85µg/L, and the elevated iron concentration (1.66 mg/L). This environment favored rapid colonization by P. aeruginosa, which secreted EPS matrices that incorporated dissolved iron ions. As confirmed by UV-Vis spectrophotometric analysis, FW deposits contained 22.7 mg/g of iron compared to lower concentrations in SW deposits. The iron acted as a chemical binder and cross-linker within the biofilm, transforming it into a dense, cohesive, sticky, and essentially waterproof “ochre slime.” This bio-mineral matrix exerted significantly higher hydraulic resistance than inorganic silt, explaining the severe flow drop (Rq = 64.10%) despite the deposit’s smaller physical volume. The warm field temperatures (29°C) inside the black lateral pipes further created a “greenhouse effect” that accelerated biofilm development throughout the trial.

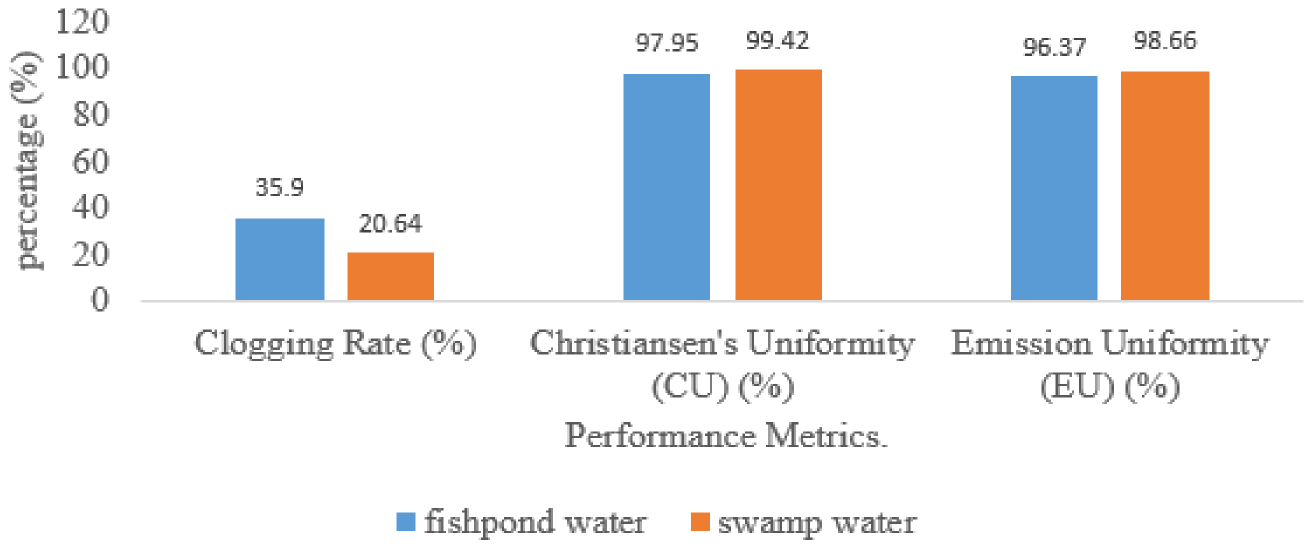


Figure 4-4 Comparison of performance metrics and final clogging rates for FW and SW treatments.

The figure provides a comparative summary of emitter performance metrics at the conclusion of the 90-day field trial. A significant divergence was observed in clogging severity, with the Fishpond Water (FW) treatment reaching a clogging rate of 35.90%, thereby exceeding the ISO defined failure threshold of 25%. In contrast, the Swamp Water (SW) treatment remained within acceptable operational limits with a clogging rate of 20.64%.

Notably, both treatments maintained 'Excellent' uniformity throughout the study, with Christiansen’s Uniformity (CU) and Emission Uniformity (EU) remaining above 95%. This high level of uniformity despite significant discharge reduction indicates that the clogging was systemic and evenly distributed across all emitters. This performance pattern is a classic signature of biological biofilm development, where nutrient-rich water (such as the FW source) facilitates a consistent layer of slime growth throughout the entire lateral line. Consequently, while the system remains capable of distributing water evenly to all plants, the overall volume of water delivered is significantly compromised in the FW treatment due to the restrictive bio-chemical clogs identified in Objective Three.

## 4.5 Results for Objective Three: Deposit Characterization and Clogging Mechanism Classification

### 4.5.1 Portion A – Qualitative Morphological Assessment: SEM Analysis of Emitter Deposits

Scanning Electron Microscopy (SEM) revealed distinct differences in the microstructure of deposits accumulated in emitters after 90 days of operation.

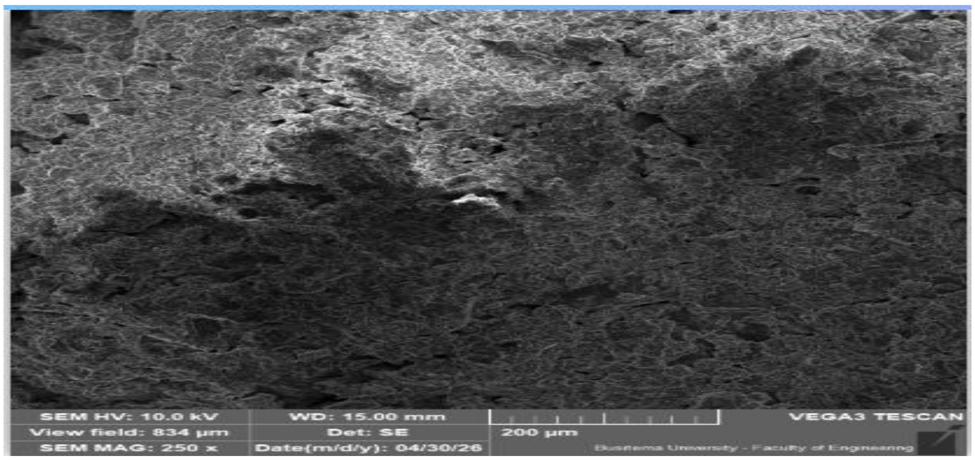


Figure 4.5 SEM micrograph of emitter deposit from Swamp Water showing angular granular inorganic particles (silt/clay) typical of physical clogging (250×).

This figure 4.5, displays a completely different morphology predominantly coarse, angular, and granular particles with irregular shapes and sizes. The deposit appears more compact and inorganic in nature, with fewer fibrous structures. This is characteristic of physical clogging caused by silt, clay, and other suspended inorganic particles (high TSS of 120 mg/L and turbidity of 39.9 NTU) transported by swamp water. While some minor surface biofilm is present, it is not the dominant feature, confirming that physical sedimentation and particle accumulation was the primary clogging mechanism in swamp water emitters.

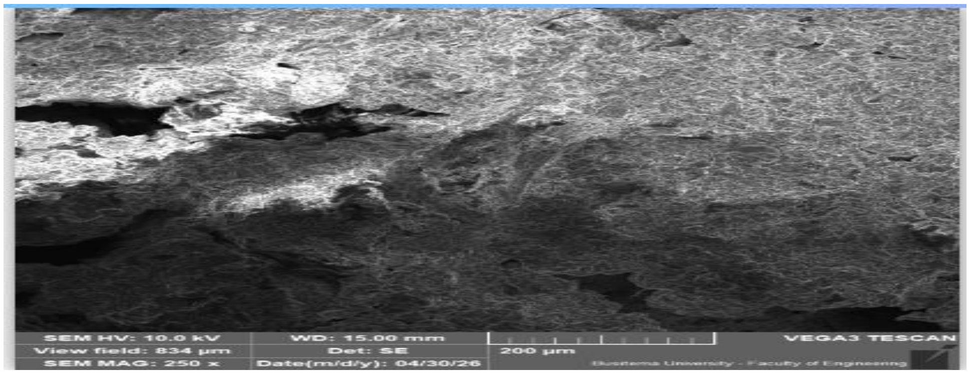


Figure 4.6: SEM micrograph of emitter deposit from Fishpond Water showing dense EPS biofilm matrix and filamentous structures (250×).

This figure 4.6, shows a highly complex, dense, and fibrous network structure. The deposit is characterized by an intricate web-like matrix of Extracellular Polymeric Substances (EPS) with numerous filamentous structures. This morphology is typical of biological clogging dominated by bacterial biofilm, algal filaments, and fungal hyphae. The presence of this gel-like EPS matrix confirms that microorganisms from the nutrient-rich fishpond water actively colonized the emitter and produced sticky polymeric substances that trapped other particles. Small crystalline structures embedded within the matrix are also visible, indicating interaction between biological and chemical clogging mechanisms.

**Determination of Calcium Concentration in Emitter Deposits**

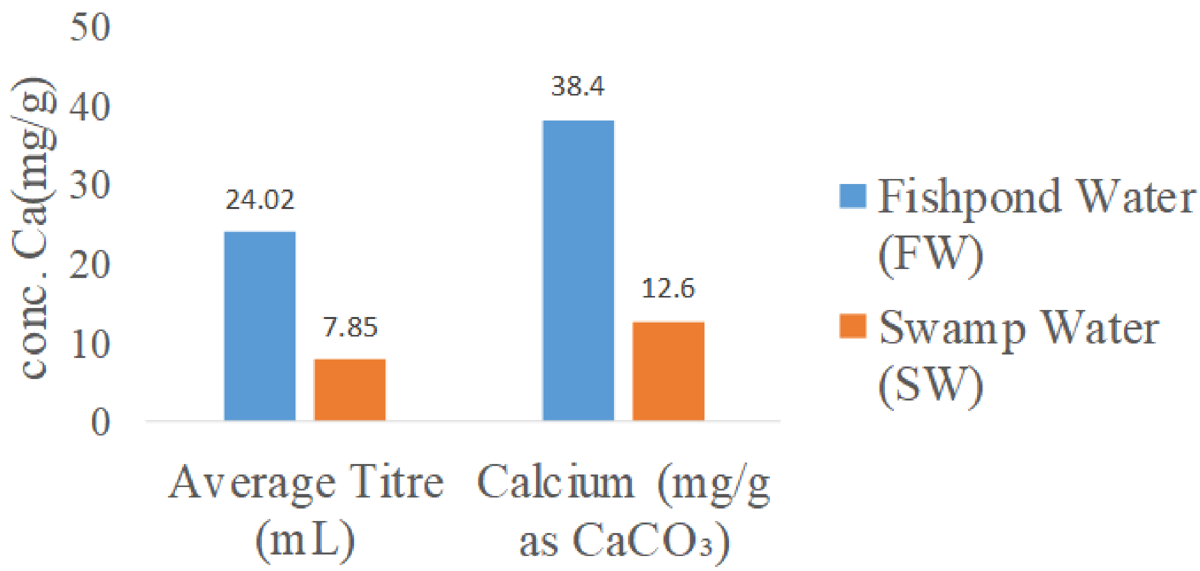


Figure 4.7 shows concentrations of Ca(mg/g) in FW and SW emitter deposits

EDTA complexometric titration of the recovered dry emitter deposits yielded calcium concentrations of 38.5 mg/g for Fishpond Water (FW) and 12.6 mg/g for Swamp Water (SW) as shown in figure 4.7, representing a 3.1:1 ratio between the two sources. This disparity directly reflects the significantly higher dissolved calcium in FW source water (82 mg/L) compared to SW (14 mg/L), confirming that the chemical scaling potential of the source water translates proportionally into mineral accumulation within emitter labyrinths (Wang et al., 2024).

The elevated calcium deposition in FW emitters is further explained by its higher pH (7.45), which thermodynamically favors $CaCO_3$ precipitation via the reaction $Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2O + CO_2$, and by the presence of EPS biofilm surfaces that provide nucleation sites for crystal formation (Dehghanisanij et al., 2004). In contrast, the lower SW calcium deposit (12.6 mg/g) is consistent with both its lower source water calcium and its more acidic pH (6.70), which suppresses carbonate precipitation.

### 4.5.2 Portion B – Quantitative Bulk Composition: Loss on Ignition (LOI) and Gravimetric Analysis

Gravimetric analysis using Loss on Ignition (LOI) at 450°C was employed to differentiate between the organic (biological) fraction and the inorganic (chemical/physical) fraction of emitter deposits.

**Loss on Ignition (LOI) Analysis**

**Principle and Procedure**

Loss on Ignition is a gravimetric analytical technique that exploits the differential thermal stability of organic and inorganic materials to quantify the proportion of each fraction within a solid deposit sample. Emitter deposits recovered from both treatment systems were first pre-dried at 105°C for 24 hours to expel all free and adsorbed moisture, and the resulting dry weight was recorded as $W_1$. The dried samples were then transferred into pre-weighed porcelain crucibles and placed in a muffle furnace at 450°C for six hours. At this temperature, organic compounds including microbial biomass, extracellular polymeric substances (EPS), algal cellular material, and other volatile organic constituents undergo thermal oxidation and are driven off as carbon dioxide ($CO_2$) and water vapor ($H_2O$), leaving behind only the inorganic mineral residue. The post ignition weight was recorded as $W_2$, and the organic (volatile) fraction was calculated using the formula:

**$LOI (\%) = [(W_1 - W_2) / W_1] \times 100$**

The inorganic (mineral) fraction was then derived as the complement:

$\text{Inorganic fraction} (\%) = 100 - LOI (\%)$

The inorganic fraction was further sub-divided into chemical and physical components through acid digestion.

**Table 4.5 shows Comparative Clogging Mechanism Composition FW vs. SW**

| Deposit Fraction | Fishpond Water (FW) (%) | Swamp Water (SW) (%) | Difference (FW-SW) |
|---|---|---|---|
| Biological | 48% | 18% | +30% |
| Chemical | 32% | 28% | +4% |
| Physical | 20% | 54% | −34% |
| Total | 100% | 100% | - |

The comparative data reveal three critical findings. First, the biological fraction in FW deposits (48%) is 2.7 times higher than in SW deposits (18%), confirming that fishpond water creates a fundamentally more biologically active clogging environment driven by its high microbial and algal load. Second, the chemical fractions are relatively comparable between the two sources (32% versus 28%), suggesting that mineral precipitation contributes meaningfully to clogging in both systems, though it is significantly more hydraulically damaging in FW due to the iron-EPS binding mechanism that renders chemical precipitates structurally integrated within the biofilm rather than existing as loose, independent deposits. Third, the physical fraction in SW deposits (54%) is 2.7 times higher than in FW deposits (20%), confirming that swamp water operates through a fundamentally different, sedimentation-driven clogging pathway.

These findings carry direct and important practical implications. The 130 µm disc filter employed at the Limoto site was found to be inadequate for both water sources, albeit for different reasons: for SW, it fails to intercept the fine silt and colloidal clay particles that dominate the physical fraction; for FW, it is wholly insufficient against dissolved iron, algal cells, and the microbial organisms that drive the dominant biological fraction. Targeted, source-specific mitigation strategies are therefore essential**,**

### 4.5.3 Portion C –Exact Mineral Concentrations: UV-Vis Spectrophotometric Analysis of Mineral Deposits

UV-Vis spectrophotometry provided precise quantification of iron and magnesium concentrations within the recovered emitter deposits. Standard calibration curves for iron (at 510nm) and magnesium (at 520 nm) were established using known concentrations (0-10 mg/L), achieving a coefficient of determination of $R^2 > 0.99$ for both curves, confirming excellent linearity and measurement reliability.

Table 4.6 shows UV-Vis Spectrophotometry Calibration Data

| Concentration (mg/L) | Fe Absorbance (510 nm) | Mg Absorbance (520 nm) |
|---|---|---|
| 0 | 0.000 | 0.000 |
| 1 | 0.102 | 0.085 |
| 2 | 0.205 | 0.162 |
| 4 | 0.408 | 0.325 |
| 6 | 0.595 | 0.475 |
| 8 | 0.810 | 0.655 |
| 10 | 0.997 | 0.810 |

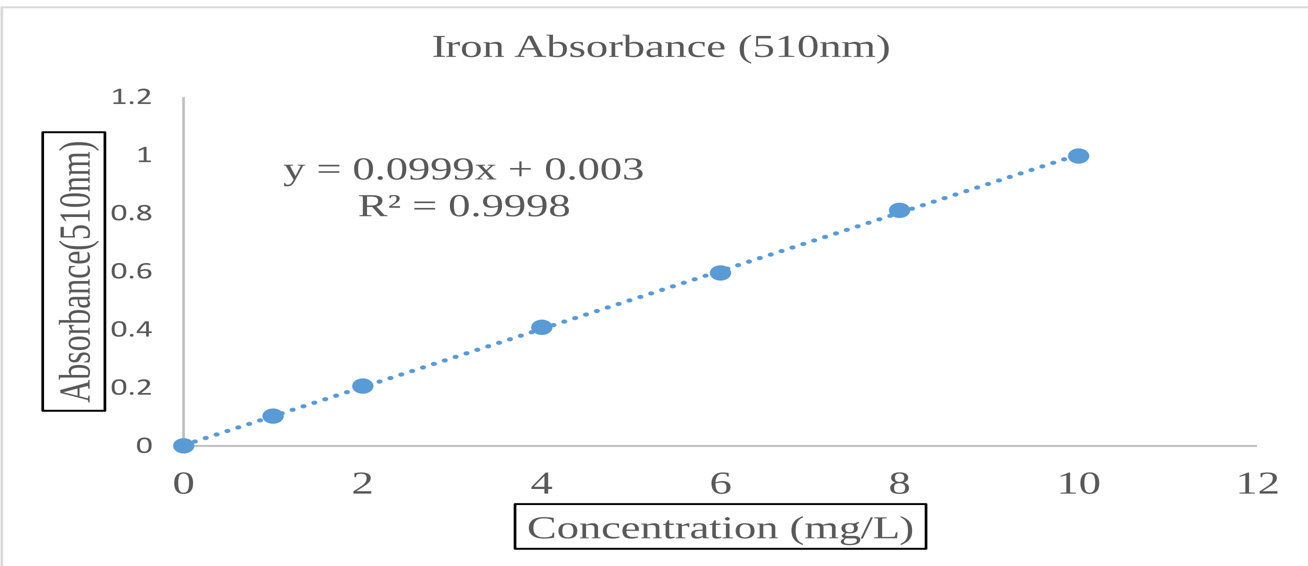


Figure 4.8 Calibration curve for Iron (Fe) concentration using UV-Vis spectrophotometry at 510 nm

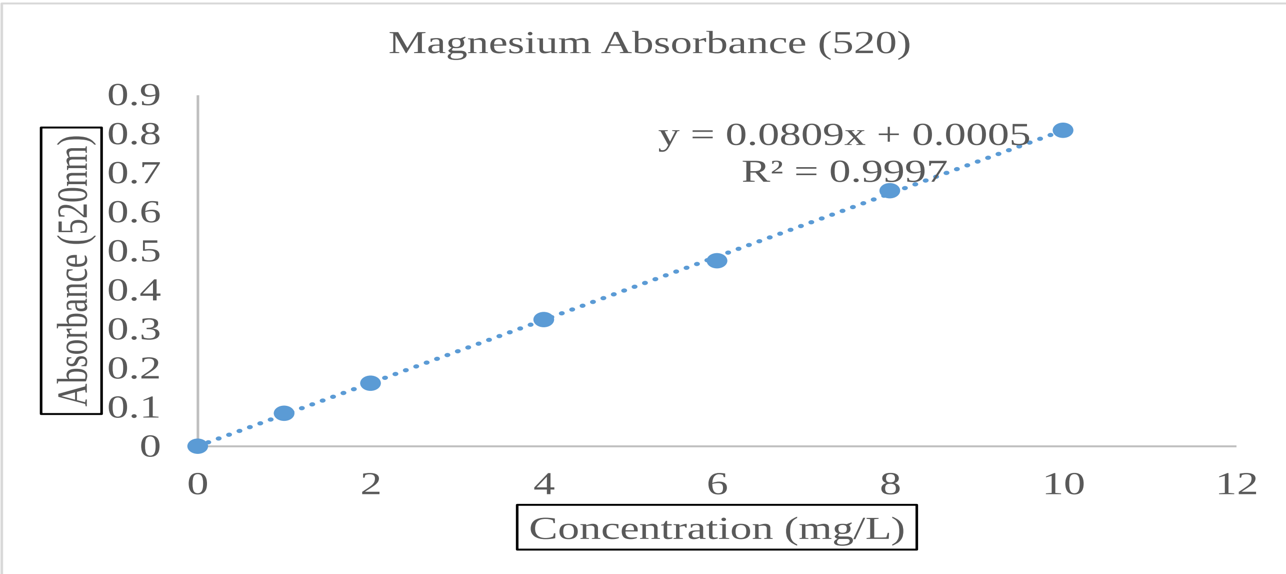


Figure 4.9 Calibration curve for Magnesium (Mg) concentration using UV-Vis spectrophotometry at 520 nm

Using a dilution factor (DF) of 25, the UV-Vis absorbance readings for recovered emitter deposits were 0.912 (FW) and 0.380 (SW) for iron, and 0.467 (FW) and 0.265 (SW) for magnesium. Applying the calibration equations, FW deposits contained an iron concentration of approximately 22.7 mg/g (dry weight), while SW deposits contained significantly lower iron, consistent with the lower source water iron concentration and the absence of iron-binding biofilm. These quantified mineral concentrations provided the chemical evidence required to classify clogging mechanisms beyond visual inspection alone.

**Clogging Mechanism Classification Summary**

Based on the integrated analysis of LOI, UV-Vis spectrophotometry, EDTA titration, and supporting SEM morphological characterization, the dominant clogging mechanisms for each water source were classified as follows:

Table 4.7 Classification of Dominant Clogging Mechanisms by Water Source

| Clogging Category | Fishpond Water (FW) | Swamp Water (SW) |
|---|---|---|
| Dominant Mechanism | Biological > Chemical > Physical | Physical > Chemical > Biological |
| Key Clogging Agents | EPS biofilm (P. aeruginosa), algae, iron hydroxides, $CaCO_3$ | Fine silt, colloidal clay, humic particles, low-level Fe oxides |
| Deposit Character | Dense, sticky, cohesive “ochre slime” high hydraulic resistance | Gritty, porous, granular lower hydraulic resistance per unit mass |

This classification provides the mechanistic link between the water quality characteristics identified in Objective One and the hydraulic performance outcomes quantified in Objective Two. The bio-chemical clogging pathway in FW driven by the convergence of high algal density, elevated dissolved iron, P. aeruginosa colonization, and elevated temperature produces a hydraulically damaging deposit that far exceeds the clogging impact of the physical sedimentation observed in SW, despite the latter containing a larger volume of particulate matter. This finding is consistent with the literature reviewed in Chapter Two, which identifies bio-chemical biofilm as the most resistant and difficult-to-remediate form of emitter clogging (Shen et al., 2022; Dehghanisanij et al., 2004).

**4.6 Overall Outcomes and Hypothesis Resolution**

The collective findings across all three objectives consistently support a single, unified conclusion: Fishpond Water poses a significantly higher and more complex emitter clogging risk than Swamp Water at the Limoto Wetland Restoration Site. The mechanisms are fundamentally different, the hydraulic consequences are measurably more severe, and the mitigation requirements are correspondingly more intensive.

The null hypothesis ($H_0$)-that there is no significant difference in emitter clogging between fishpond and swamp water sources is conclusively rejected based on the statistical analysis ($t(12) = 29.07$, $p < 0.001$). The alternative hypothesis ($H_1$) is accepted, confirming that the water source significantly determines the rate, severity, and mechanism of emitter clogging.

# CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

## 5.1 CONCLUSION.

This study successfully evaluated the clogging characteristics and hydraulic performance of drip emitters operated with Fishpond Water (FW) and Swamp Water (SW) under field conditions**.** The following conclusions are drawn based on the three research objectives:

Water Quality and Clogging Risk: The Fishpond Water (FW) represents a "Severe Risk" source for drip irrigation, characterized by high iron (1.66 mg/L), elevated microbial populations ($4.8\times10^5$ CFU/mL), and a significant algal biomass (85 µg/L). Conversely, Swamp Water (SW) presents a "Moderate Risk" primarily driven by physical silt and turbidity. The bioturbation caused by fish activity in the FW treatment was found to suspend large organic loads and nutrients (6 mg/L Phosphates) that fueled biological colonization within the system.

Hydraulic Performance: Emitters operated with FW reached a clogging rate of 35.90% by Day 90, significantly exceeding the ISO failure threshold of 25%. In contrast, the SW treatment resulted in a 20.64% reduction, remaining within acceptable operational limits. The statistical validation via Welch's t-test ($p<0.001$) confirms that the water source is a highly significant factor in emitter longevity. This proves that standard 130-micron disc filtration is insufficient to protect irrigation systems against the nutrient-rich and biologically active water found in fishpond environments.

Clogging Mechanisms: A critical "Clogging Paradox" was identified and visually confirmed through SEM analysis. While SW emitters contained a higher visible volume of physical silt, the FW emitters suffered significantly greater discharge reduction. This is attributed to the Bio-Chemical mechanism (48% Biological and 32% Chemical dominance) in the FW clogs, where a sticky biofilm matrix (EPS) trapped iron precipitates to form a non-porous seal. In contrast, the SW clogging was primarily Physical (54%), consisting of granular, angular silt that remained porous, allowing for higher flow retention despite the higher mass accumulation.

## 5.2 RECOMMENDATIONS AND MITIGATION MEASURES

Based on the findings, the following mitigation measures are recommended for smallholder farmers at Limoto Wetland Restoration Site and other farmers using similar water sources:

1- Integrated Filtration Systems

While disc filters are effective for inorganic particles, they fail against biological load and it's recommended or fishpond water that a Media (Sand) Filter should be used in series before the disc filter. Haman (2014) and (Duran-Ros et al., 2009) stated that media filters are superior for removing organic matter and algae because they provide deep-bed filtration, whereas disc filters only provide surface filtration which biofilms can bypass.

2-Chemical Shock Treatments (Chlorination)

To address the 48% biological dominance found in the FW deposits, microbial growth must be controlled chemically. Periodic Shock Chlorination (injection of 10-20 mg/L of chlorine) should be performed at the end of every irrigation cycle. Nakayama and Bucks (1991) confirm that chlorine is the most effective biocide for oxidizing the Extracellular Polymeric Substances (EPS) produced by bacteria like P. aeruginosa, preventing the "bio-glue" from binding minerals.

3-Acidification for Mineral Scale

To mitigate the 22.7 mg/g iron and 38.5mg/g calcium precipitates, inject Hydrochloric or Sulfuric acid to lower the system pH to approximately 4.0 for a short duration. Bounoua et al. (2016) proved that maintaining an acidic environment prevents the precipitation of dissolved iron ($Fe^{2+}$) into insoluble ochre ($Fe^{3+}$) which was identified as a major chemical component in this study.

4-Regular Lateral Flushing

The higher physical silt accumulation in SW emitters (54%) suggests that sedimentation is a major risk. Laterals should be flushed every 2 weeks by opening the end-caps to discharge accumulated sediment. Puig-Bargués et al. (2010) found that regular flushing can reduce physical clogging by up to 40% by removing fine silts before they settle into the emitter labyrinths.

5-Buffer Zones and Sedimentation Ponds;

For swamp water, a Sedimentation Basin should be constructed to allow fine silts to settle before the water reaches the pump station. This reduces the TSS load on the 130-micron disc filter, preventing the "bypass" of fine particles observed in this study.

### 5.3 Suggestions for further research

Further studies should investigate the effectiveness of UV-C water sterilization as a non-chemical alternative for controlling P. aeruginosa and algal blooms in fishpond-based drip systems.

Long-term research is needed to evaluate the impact of different emitter labyrinth designs (e.g., vortex vs. turbulent flow) on the accumulation of bio-chemical biofilms.

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**APPENDIX.**