

**Development of a Passive Filter for Polishing Municipal Lagoon Effluent -Lab and Field
Scale Studies**

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Abstract

The goal of this research is to create and assess a passive system for polishing municipal lagoon effluent. The study's goals include identifying the best media type and hydraulic loading rate for an unsaturated filter, evaluating the hydraulic retention time (HRT) and adsorptive capacity for a saturated filter, and pilot-scale testing of the technology. The experimental variables include unsaturated media, filter depth, loading rate, and Direct Reduced Iron (DRI) adsorptive media HRT. The lab study consisted of a series of column tests with synthetic wastewater, while the field study involved three 1 m³ pilot filters dosed with municipal lagoon effluent. Two sources of coarse sand media in the column study exhibited clogging while a crushed glass media did not under conditions of continuous dosing. A 45-cm layer of crushed glass media at 25 cm/d continuous loading provided optimum treatment for BOD and NH₄⁺. Also, the column study demonstrated that increased hydraulic loading rate at constant organic loading rate increases filter clogging and reduces treatment efficiency. The field study, on the other hand, polishing a low solids and low carbon lagoon effluent with 29 cm/d intermittent dosing found better COD and ammonium reduction with a 45 cm layer of coarse sand compared to crushed glass, and with no signs of clogging. Both lab and field studies found 15 cm of 12.5 mm dia. DRI with 5.7-5.9 hr HRT was effective at phosphorus reduction. A recommended passive filter design to polish municipal lagoon effluent consists of a 45 cm layer of coarse sand and 15 cm of saturated DRI at an intermittent loading rate of 25 cm/d. Crushed glass can be considered as an alternative to coarse sand where intermittent dosing is not viable or high solids or organic loading could contribute to premature filter clogging.

Keywords: municipal lagoon effluent polishing, intermittent sand filter, crushed glass, continuous dosing, clogging, direct reduced iron, phosphorus, ammonium, BOD

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List of Abbreviations

ASBR: Anaerobic Sequencing Batch Reactor

ASS: Activated Sludge System

BOD: Biochemical Oxygen Demand

COD: Chemical Oxygen Demand

C_U: Uniformity coefficient

DO: Dissolved Oxygen

DRI: Direct Reduced Iron

EDS: Energy dispersive X-ray spectroscopy

EJ: Eljen Sand

FM: Filter media sand

HFCW: Horizontal flow-built wetland

HLR: Hydraulic Loading Rate

HRT: Hydraulic Retention Time

ISF: Intermittent Sand Filters

MBR: Membrane Bioreactor

MLSS: Mixed Liquor Suspended Solids

NO₃-N: Nitrate Nitrogen

NO₂-N: Nitrite Nitrogen

NH₄-N: Ammonia Nitrogen

OLR: Organic Loading Rate

PAHs: Polycyclic Aromatic Hydrocarbons

RG: Recycled Glass

RPM: Revolutions Per Minutes

SEM: Scanning Electron Microscope

SRP: Soluble Reactive Phosphorus

SS: Suspended Solids

TDS: Total Dissolved Solids

TAN: Ammonia Nitrogen

TN: Total Nitrate

TN: Total Nitrogen

TOC: Total Organic Carbon

TP: Total Phosphate

TP: Total Phosphorus

UASB: Upflow Anaerobic Sludge Blanket

VFCW: Vertical flow-built wetland

CHAPTER 1

1.0 Introduction

Lagoon-based sewage treatment systems are the most common type of municipal wastewater treatment technology in Canada with 1048 systems (Environment and Climate Change Canada, 2017). In Canada, municipal lagoon system discharges are regulated by both the federal and provincial governments. The Federal regulation stipulates maximum effluent concentrations of 25 mg/L for TSS and cBOD₅ and 1.25 mg/L NH₃ at 15°C ± 1°C (Government of Canada, 2012). Provincial discharge criteria are site specific and based on the attenuation capacity of the receiving water body, which can be more stringent than the federal criteria. The federal regulations as well as increasingly strict provincial requirements are requiring many municipalities to upgrade their lagoon systems. The presence of algae in the effluent during warm months can increase TSS to above 30 mg/L (USEPA, 2002). Cold weather and ice cover greatly reduces nitrification, limiting the ability to meet NH₃ limits during winter months or spring discharge periods and meeting increasingly stringent TP limits of less than 1.0 mg/L is a challenge for conventional coagulation practices (Federation of Canadian Municipalities, 2004). Add-on polishing technologies can provide cost-effective means of addressing these issues. Intermittent Sand Filters (ISF) are a proven technology that can address lagoon effluent BOD, TSS and TAN (USEPA, 1999), although appropriate sources of coarse sand are becoming scarce. Recent work has shown the potential of direct reduced iron (DRI) as an effective P sorption media with synthetic phosphate solution (Qin.H, 2019).

1.1 Research Objectives

The research topics and goals of this thesis are intended to address the difficulties and problems associated with municipal lagoon polishing and to explore the possibility of passive filters as a

practical and long-term improvement to municipal wastewater treatment. The following are the study's goals and research questions:

The goal of this research study is to develop a passive filter to polish municipal lagoon effluent combining an intermittent sand filter to polish BOD, TSS, and TAN and a saturated DRI bed to polish TP.

Hypotheses are:

- 1) Removal of BOD and TAN increases with increased ISF media depth and temperature.
- 2) BOD and TAN treatment efficiency as well as filter clogging will increase with increasing ISF media % Fines and Coeff. Of Uniformity (D_{60}/D_{10}) and will increase with decreasing Effective Diameter (D_{10}).
- 3) Crushed recycled glass can provide an effective replacement media to coarse sand with less biofilm development reducing clogging potential, however, also reducing treatment efficiency.
- 4) Organic fouling will not significantly impact optimum HRT and phosphorus removal efficiency of the DRI media.

1.1.1 Specific Research Objectives

At the Lab Column-Study Scale:

1. Evaluate two coarse sand materials utilized by the Ontario onsite wastewater industry and a crushed recycled glass product at high organic and hydraulic loading rates to polish municipal lagoon effluent for BOD, TSS, and TAN, considering filter depth and temperature at continuous dosing condition (for situations where no electricity is available for intermittent dosing).

2. Evaluate the impact of temperature, OLR and DRI depth/HRT on the removal of SRP with simulated lagoon effluent.

At the Field Pilot-Study Scale:

1. Evaluate two coarse sand materials utilized by the Ontario onsite wastewater industry and a crushed recycled glass product to remove TSS and TAN with real lagoon wastewater.

2. Evaluate the effectiveness of ISF/DRI combined filter at removing TP and SRP as a function of HRT/media depth.

1.2 Thesis Organization

The thesis comprises five chapters as described below:

Chapter 1: Introduction; The background and importance of the topic, the research questions and objectives, the study's scope and constraints, and the structure of the thesis are all covered in this chapter's summary of the study.

Chapter 2: Literature Review; the literature on passive filters for cleaning municipal wastewater is reviewed in this chapter. The evaluation of the literature includes information on the fundamentals of passive filtration, filtration medium, design considerations, and the effectiveness of passive filters in terms of nutrient removal, hydraulic loading rate, influent wastewater quality, and filter bed depth.

Chapter 3: Column study; the techniques used to build and assess passive filters at lab scales are covered in this chapter. The chapter discusses choosing filtering medium, designing and building columns, setting up experiments, using sample and analysis procedures, data processing methods, and conclusion of the column study.

Chapter 4: Field Study; the techniques used to build and assess passive filters at field scales are covered in this chapter. The chapter discusses choosing filtering medium, designing and building filters, setting up experiments, using sample and analysis procedures, data processing methods, and conclusion of the field study.

Chapter 5: Overall Conclusions and Future Research.

1.3 References

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CHAPTER 2

2.0 Literature Review

Passive filters have become a potential solution for polishing municipal lagoon effluent in recent years. Pollutants are removed from wastewater by passive filters using natural processes such as physical filtration, adsorption, and biological degradation (Salzmann, Ackerman & Cicek, 2022). Passive filters are more ecologically friendly than traditional treatment techniques because they consume less energy, use fewer chemicals, and produce less sludge than alternatives including mechanical aeration and chemical coagulation /flocculation. This issue is important because of the possible effects it might have on the environment, public health, and the economy. Municipalities risk penalties, legal action, and reputational harm if they do not adhere to regulatory criteria for pollution removal from municipal lagoons. Furthermore, excess nutrient contamination can have detrimental effects on the environment including the deterioration of ecosystems and potential harm to human health.

The purpose of this chapter is to assess the present research on passive filters used to treat municipal lagoon wastewater. The performance of passive filters in terms of nutrient removal, hydraulic loading rate, influent wastewater quality, and filter bed depth are covered in detail, along with a review of the fundamentals of passive filtering, filtration media, design considerations, and performance metrics. Additionally, this chapter reviews effects of ammonia on aquatic creatures and the eutrophication induced by the release of nutrients into the water.

2.1 Principles of Passive Filtration

Pollutants are removed from wastewater by the natural process of passive filtering, which combines physical, chemical, and biological processes. To capture suspended particles, colloids, and dissolved organic materials, the method uses a bed of porous media, such as sand, gravel, or another filter medium. The filter medium also act as a substrate for the development of microorganisms, which are essential for removing ammonium from wastewater (Bezirgianidis et al, 2019). Municipal wastewater can be polished using the low-cost, low-maintenance treatment technology of passive filtering.

2.1.1 Filtration Media

The effectiveness of passive filters depends on the choice of filtering medium. High surface area, homogenous particle size distribution, and high porosity are characteristics of the perfect medium. Sand is the most often utilized filtering medium because it is readily available, inexpensive, and simple to handle. Passive filters have also been employed with various filter media, including gravel, crushed glass, and other recyclable materials (Bezirgianidis et al, 2019). The preferred treatment goals, the properties of the wastewater, and the media's accessibility all influence the choice of medium.

2.1.2 Design Parameters

Filter bed depth, filtration media, hydraulic loading rate, and influent wastewater quality are design factors for passive filters. The depth of the filter bed impacts how long the wastewater is in contact with the filter material, which has an impact on how effectively contaminants are removed. While a deeper bed depth lengthens contact time, it may also cause media clogging. A shallow bed depth reduces contact time and lowers removal efficiency. The quality of the influent wastewater,

including the quantity of nutrients and organic matter, has an impact on the filter's efficiency and must be taken into account during the design phase.

2.1.3 Performance of Passive Filters

Numerous studies have been done on the effectiveness of passive filters in terms of nutrient removal, hydraulic loading rate, influent wastewater quality, and filter bed depth. Passive filters have been proven to be highly effective in removing nutrients like nitrogen and phosphorus, with some studies reporting removal rates of up to 90% (Hamisi et al, 2022). It has been discovered that the performance of passive filters is influenced by the hydraulic loading rate, with lower rates leading to better removal efficiency. Passive filters have been discovered to be affected by the quality of influent wastewater, including the amount of nutrients and organic debris. Another crucial factor that affects how well passive filters work is the depth of the filter bed. Treatment increases with bed depth until oxygen transfer is impeded.

2.2 Nitrifying filters

Nitrifying filters are designed to remove nitrogen compounds, specifically ammonia (NH_4^+) and nitrite (NO_2^-), from wastewater. These filters play a crucial role in maintaining water quality by preventing the discharge of harmful ammonium nitrogen into the environment (Peng et al., 2020).

The mechanisms of nitrification involve the conversion of ammonia to nitrite and then to nitrate through the activity of specific microorganisms—ammonia-oxidizing bacteria and nitrite-oxidizing bacteria. This biological process, known as nitrification, occurs in nitrifying filters where the microbial community establishes and thrives (Manirakiza & Sirotkin, 2021). Nitrification is vital for wastewater treatment as it transforms nitrogen compounds into less harmful forms, preventing their adverse effects on aquatic ecosystems.

2.2.1 Sand Grain Size in Nitrifying Filters

The choice of sand grain size in nitrifying filters holds significance in determining the filter's performance (Lee et al., 2017). Sand provides a substrate for microbial attachment and biofilm formation, creating an environment conducive to nitrification. The grain size influences the surface area available for microbial colonization and the void spaces for wastewater flow through the filter bed.

The impact of sand grain size on nitrification efficiency is two-fold. Finer grains offer increased surface area for microbial attachment, potentially enhancing nitrification rates. However, smaller grains may also lead to increased head loss and reduced permeability, affecting the overall hydraulic performance of the filter. Balancing these factors is crucial to optimize nitrification efficiency in the filter system.

2.2.2 Loading Rates in Nitrifying Filters

Loading rates refer to the quantity of nitrogen-containing compounds applied to the nitrifying filter per unit area over a specific time. This parameter is crucial for controlling the nutrient load and ensuring that the microbial community can effectively convert ammonia to nitrate. Loading rates are typically expressed as mass or concentration of nitrogen compounds per unit area per day (Karia et al., 2023).

The effects of loading rates on nitrifying filter performance are multifaceted. High loading rates may overwhelm the microbial population, leading to incomplete nitrification and the release of unconverted nitrogen compounds. Conversely, low loading rates may underutilize the filter's capacity. Finding the optimal loading rate is essential for maintaining stable nitrification and preventing nitrogen discharge beyond regulatory limits.

2.3 Phosphorus Adsorption Media

Phosphorus is a critical nutrient present in wastewater, and its excessive discharge can lead to eutrophication in receiving water bodies. Eutrophication promotes algal blooms, depleting oxygen levels and negatively impacting aquatic ecosystems. Efficient removal of phosphorus is thus crucial for preventing these adverse environmental effects.

2.3.1. Environmental Implications of Phosphorus Discharge

The environmental implications of phosphorus discharge extend beyond eutrophication. Phosphorus runoff contributes to water quality degradation, impacting both surface water and groundwater (Haque, 2021). Addressing the importance of phosphorus removal is fundamental to sustainable wastewater treatment practices and environmental conservation.

2.3.2 Types of Phosphorus Adsorption Media

Phosphorus adsorption media are materials designed to capture and retain phosphorus from wastewater through adsorption processes. Various types of media, such as activated alumina, iron-based materials, and modified clays, are employed for their ability to selectively adsorb phosphorus ions.

Different adsorption media possess specific characteristics influencing their phosphorus removal efficiency. Surface area, chemical composition, and the presence of reactive sites are key factors determining the efficacy of these media in capturing phosphorus. Understanding the specific characteristics of each media type is essential for selecting the most appropriate option based on the wastewater composition and treatment objectives.

2.4 Types of Lagoons

Anaerobic, facultative, and aerobic lagoon types are important types of municipal wastewater treatment systems. These lagoons are made to provide diverse environmental conditions that make it easier for various biological and physical processes to remove contaminants.

2.4.1 Anaerobic Lagoons

Anaerobic lagoons are made to function in an environment without oxygen, where microorganisms decompose organic materials. Anaerobic digestion is the process by which organic pollutants are broken down into less harmful substances and biogas (methane and carbon dioxide) is produced. In municipal wastewater treatment systems, anaerobic lagoons are frequently employed as the initial stage, where the primary treatment takes place. Anaerobic lagoons may remove up to 60% of organic pollutants, including BOD and TSS (Siregar & Romaito, 2020).

2.4.2 Facultative Lagoons

Facultative lagoons are designed to function with both aerobic and anaerobic layers forming a stratified ecosystem. This makes it possible for many kinds of bacteria to coexist and carry out various tasks. Anaerobic microbes continue the degradation of organic materials by anaerobic digestion, whereas aerobic microorganisms destroy organic matter through oxidation. In municipal wastewater treatment systems, facultative lagoons are often utilized during the secondary treatment stage, when further removal of organic matter and nutrients takes place. Facultative lagoons may remove BOD and TSS by up to 70–90% (Majumder et al, 2021).

2.4.3 Aerobic Lagoons

Aerobic lagoons are created to function in oxygen-rich environments where microbes oxidize organic debris. These lagoons are often employed as the last stage in municipal wastewater treatment systems, where the last of the nutrients and organic materials are further removed to

comply with regulations. When rigorous effluent quality standards must be satisfied, such as in sensitive environmental areas or for wastewater reuse, aerobic lagoons are frequently employed. Aerobic lagoons may remove BOD and TSS up to 90–95% of the time (Guerra et al, 2019).

The choice of lagoon type is influenced by a number of variables, including the properties of the wastewater, the requirements for effluent quality, the availability of land, and the climate. Every kind of lagoon has benefits and drawbacks. Anaerobic lagoons, for instance, are good at reducing organic matter but may need longer retention durations and may create biogas that has to be controlled (Uddin & Wright, 2022). Although facultative lagoons may need more space than other types of lagoons, they provide a balance between anaerobic and aerobic conditions. Although they produce high-quality effluent, aerobic lagoons require more energy for aeration. To improve the effectiveness of different types of lagoons in removing contaminants from municipal wastewater, there has been considerable interest in mixing passive filtration systems, such as constructed wetlands or sand filters, with them in recent years. These hybrid systems have showed encouraging improvements in treatment efficacy and effluent quality overall. It is necessary to do more research and statistical analysis in order to assess the effectiveness and cost-effectiveness of these combination systems in various contexts.

2.5 Municipal Lagoon Treatment Systems

Due to its simplicity and low cost as compared to other wastewater treatment techniques, municipal lagoons are frequently employed for the treatment of municipal wastewater in rural and isolated places. However, these lagoons frequently have problems including high levels of total suspended solids (TSS), biochemical oxygen demand (BOD), and nutrients like nitrogen and phosphorus, which can have a negative influence on the ecosystem and the water quality. Different treatment solutions have been suggested and put into practice to improve the efficiency of municipal lagoons

in order to deal with these problems (Hellal et al., 2021). Due to its low cost, simple installation and maintenance, and efficiency in eliminating TSS, BOD, and nutrients, passive filtering systems have grown in popularity.

A constructed wetland is a typical passive filter utilized to polish municipal lagoon effluent. Numerous studies have demonstrated that TSS, BOD, nitrogen, and phosphorus may be effectively removed from municipal wastewater by constructed wetlands. Sand filters are an additional passive filter type utilized to polish municipal lagoon effluent. A bed of sand or other porous material, acts as both a physical barrier to trap suspended particulates and a biological layer to break down organic materials. TSS, BOD, nitrogen, and phosphorus may all be effectively removed using sand filters (Hellal et al., 2021). Municipal lagoons find widespread use in various settings, from small communities to large urban areas. They are often employed as cost-effective alternatives for treating domestic and industrial wastewater. The simplicity of their design and reliance on natural processes make them particularly attractive for regions with limited resources or infrastructure.

2.5.1 Limitations of Municipal Lagoons

Municipal lagoons, while effective in wastewater treatment, encounter specific challenges in achieving optimal removal of key pollutants. This section examines the limitations associated with Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), Total Phosphorus (TP), and Ammonium (NH_4) removal in municipal lagoon systems.

Achieving efficient Biological Oxygen Demand (BOD) reduction in municipal lagoons is challenged by the complex kinetics of microbial activity. The rates of decomposition are influenced by factors such as temperature, pH, and the composition of the influent wastewater (Chen et al., 2017). Variability in these parameters can lead to inconsistent BOD removal,

impacting the overall effectiveness of lagoon systems. The composition of incoming wastewater, particularly the presence of complex organic compounds, poses a challenge to the microbial communities responsible for BOD reduction. Lagoons may struggle to maintain consistent removal rates when faced with influent variations, leading to periodic deviations in effluent quality.

Municipal lagoons rely on physical mechanisms such as sedimentation and filtration for the removal of Total Suspended Solids (TSS). Sedimentation allows heavier particles to settle to the bottom, forming sludge, while filtration through aquatic vegetation aids in the entrapment of suspended solids (LeBlond, 2020). These mechanisms are effective to a certain extent but have inherent limitations. Factors like wind action and turbulence can lead to resuspension of settled solids in the lagoon, diminishing the efficiency of sedimentation. Hindered settling, where smaller particles take longer to settle, further hampers TSS removal (LeBlond, 2020). These limitations result in challenges in achieving consistently low TSS levels in the treated effluent.

Total Phosphorus (TP) removal in municipal lagoons is often hindered by the inefficient precipitation of phosphates. The chemical processes involved in phosphorus precipitation are sensitive to pH, and variations in lagoon conditions can lead to incomplete removal (Luo et al., 2017). This challenge is particularly pronounced in lagoons receiving influents with elevated phosphorus concentrations. While algae and aquatic plants contribute to phosphorus removal, their effectiveness may be limited by factors such as light availability and nutrient competition (Rezania et al., 2021). This biological uptake is insufficient to meet stringent TP discharge limits, necessitating supplementary treatment measures.

Ammonium (NH_4) removal in municipal lagoons relies on microbial nitrification processes, where ammonia is converted to nitrate through biological oxidation. However, achieving optimal

nitrification rates can be challenging due to factors such as temperature fluctuations, inhibitory substances, and variations in microbial populations. The limitations of municipal lagoons in BOD, TSS, TP, and NH_4 removal highlight the need for innovative solutions. The subsequent section outlines the objectives of a study focused on passive filter development, aiming to address these limitations and enhance the efficiency of wastewater treatment in municipal lagoons.

2.5.2 Filter Media

In the design of a passive filter, the selection of filter material is critical. The media should be highly permeable, have a sizable surface area, and have a high capacity for pollutant adsorption. Gravel, sand, zeolite, and compost are examples of frequently used filter media (Xiao et al, 2018). The HLR and retention time of the filter are influenced by the particle size of the filter medium. Smaller particle size often results in longer retention times and lower HLR. The ability of the filter medium to absorb contaminants, particularly heavy metals and nutrients, is also crucial. The proposed technology includes two components: an unsaturated filter for TSS, BOD and NH_4^+ removal above a saturated phosphorus sorption bed comprised on Direct Reduced Iron (DRI) media. In our case we will focus on covering both unsaturated and saturated filter media.

2.5.2.1 Unsaturated Filter media

Intermittent sand filters (ISFs) are amongst the oldest wastewater treatment technologies developed and have been used extensively for small-flow wastewater treatment applications including septic tank effluent, polishing and nitrifying secondary effluents. Almost complete removal of BOD_5 and almost complete nitrification were achieved treating domestic primary settled wastewater across multiple studies at very low hydraulic loading rates of 0.04-0.06 m/d (Crites and Tchobanoglous 1998). The application of ISFs to polish municipal lagoon effluent is less well understood with several studies summarized in Table 2.2. The critical design factors

include the filter media (D_{10} , D_{60}/D_{10} , % fines, particle surface roughness and angularity), filter, HLR and dosing frequency. Oxygen transfer to the filters is dependent upon DO in the wastewater and most importantly oxygen diffusion between doses. As the dose frequency increases, the batch volume decreases, decreasing the effluent velocity and increasing residence time. However, as dose frequency increases, diffusion decreases. This favours biofilm development in the top layer of the filter, which further reduces hydraulic conductivity (Bancole et al, 2003), and can lead to premature filter clogging. HLRs and loading cycles reported in the literature (Table 2.2) vary from 0.1 m/d (24 doses/day) to 0.28 m/d (14 doses/d) to 0.70-0.80 m/d with 3-4 days loading followed by a 7-d rest period (30-32 doses/d), while design guidelines for algae removal specify 0.37-0.56 m/d (Crites and Tchobanoglous, 1998).

The typical media utilized is coarse sand ($D_{10} = 0.2-0.3$ mm, $CU < 5$, fines $< 1\%$ and filter depths > 450 mm (Crites and Tchobanoglous, 1998). Potential replacement media to sand, which is in short supply in many jurisdictions, include recycled crushed glass (Salzmann et al, 2022, Healy et al, 2010) or crushed limestone (Torrens et al, 2009). A pilot system treating facultative lagoon effluent compared sand to crushed glass (Salzman et al, 2022) as described in Table 2.1. The sand and glass had a D_{10} , UC and % fines of 0.17 and 3.59 mm, 3.13 and 4.18, and 2.8 and 0.8%, respectively. Both filters had similar removal of TSS (94 vs 92%), while sand provided better removal for both ammonium (99.8 vs 90.4%) and COD (55 vs 45%). Importantly the crushed glass provided good removal with a D_{10} 20x higher than that of the sand. Healy et al (2010) achieved complete TSS removal and nitrification at both 200 and 400 mm depth in a column study with synthetic secondary effluent comparing sand ($D_{10} = 0.15$ mm) to crushed glass (0.5-1.1 mm dia.) at a low HLR of 0.1 m/d. Torrens et al (2009) in a field study showed improved treatment at 650 mm compared with 250 mm filter depths with both crushed limestone and river sand at a high HLR of 0.70-0.80 m/d

(with periodic rest periods). River sand (D_{10} : 0.25 mm, CU: 4.7, Fines: 2.1 %) provided similar removal of COD and better removal of TSS and KN than crushed limestone (D_{10} : 0.19 mm, CU: 9.3, Fines: 4.0 %), possibly due to lower biofilm development on the angular surfaces of the crushed limestone compared with the smooth surfaces of the river sand. However, both materials provided good removal efficiency for the parameters of interest (Table 2.2). Torrens et al (2009) also reported 50 and 65 % nitrification during winter operating conditions (wastewater $T \sim 2^{\circ}\text{C}$) with filter depths of 250 and 650 cm, respectively, at an HLR of 40 cm/d and 8 doses/d. Chmielowski et al (2023) analyzes the feasibility of utilizing recycled shredded ABS plastic (acrylonitrile butadiene styrene) as packing media in an experimental vertical flow filter for on-site wastewater treatment plants. Research has indicated that shredded recycled ABS is a highly promising filtration material due to its significant attributes in the treatment process, including a substantial surface area, strong mechanical properties, and chemical inertness. The system was operated with a hydraulic load of 0.5 m/d for three months. The primary effluent demonstrated a high reduction efficiency for BOD_5 , COD and TSS, with rates of 94.4%, 77.8%, and 92.8%, respectively.

Salzmann et al (2022) assessed the effectiveness of sand (with an effective size of 0.17 mm and uniformity coefficient of 3.13) and crushed recycled glass (with an effective size of 3.59 mm and uniformity coefficient of 4.18) in pilot-scale ISFs to polish secondary lagoon effluents from the Village of Dunnottar, located on the southwestern shore of Lake Winnipeg, Manitoba. The filters were operated with a HLR of 0.28 m/d and 14 doses/day from May to September. The system's performance was evaluated for a duration of two years (2017 - 2018) concerning TSS, COD, N, and P. The removal of TSS was similarly effective in both sand and glass filters, with removal efficiencies above 90%. The elimination of dissolved COD was 29% lower in glass, mostly

because of the reduced surface area of the media. The $\text{NH}_4^+\text{-N}$ reductions achieved a rate above 90% in both filters. Sand filters consistently complied with the Effluent N criteria, but glass filters exceeded the limit on 33% of occasions in 2018. Neither sand nor glass was able to decrease the concentration of P below 1 mg/L. It appears that sand filters primarily eliminate phosphorus through mineral precipitation involving calcium and magnesium molecules. This led to the solidification (hardening) of the upper layers of the sand filter. The elimination of P was noticeably lower in glass, mainly because of the reduced availability of Ca in the media. The results obtained demonstrate that crushed recycled glass is a suitable filter media for tertiary wastewater treatment systems, particularly for the removal of total suspended solids (TSS), chemical oxygen demand (COD), and ammonium nitrogen ($\text{NH}_4^+\text{-N}$).

Gherairi et al (2015) compared crushed glass to coarse sand with identical D_{10} (0.12 mm) in 60 cm columns treating synthetic secondary effluent. At low HLR of 0.1 m/d and 13 doses per day, both columns were successful at reducing COD and BOD5 by greater than 90%.

Gill et al. (2011) made a comparison over a two-year period to assess the treatment efficacy of two parallel stratified filters, one using sand as a medium and the other using recycled glass. Both filters received secondary treated effluent from a single property that simultaneously functioned as a Bed & Breakfast. Both filters had a 100 mm layer of limestone sand specifically designed to remove phosphorus. The glass filter exhibited comparable performance to the sand filter across all tested parameters, on average. Nevertheless, there were variations in the process kinetics between the two systems, specifically with nitrogen removal. The glass filter removed about 1.5 times the total nitrogen load compared to the sand filter. Phosphorus removal was more significant in the sand filter than in the recycled glass filter, with 51% and 40% removal efficiency, respectively.

Horan et al (2007) tested three grades of recycled glass as tertiary filter media for total suspended solids removal (TSS) in domestic wastewater treatment facilities. Fine glass produced the highest effluent quality, while coarse glass could process three times the flow but had lower effluent quality. Medium glass had similar flow characteristics to coarse glass but achieved considerable particle removal, though less than fine glass. Full-scale experiments compared medium glass performance to sand medium, finding minimal difference in TSS removal. Glass medium showed superior flow properties and treated 8-10% more influent after the backwash cycle. Recycling offers benefits such as reduced CO₂ emissions, sustainable products, and positive publicity and environmental reporting, though these are harder to quantify.

The sand trench onsite wastewater treatment system is a cost-effective solution for rural or rural areas without centralized sewage infrastructure. Ramezaniapour et al. (2023) study aims to compare the effectiveness of crushed glass (CG) to sand in treating primary treated effluent from a septic tank. A test rig was built to replicate actual conditions in a discharge control trench. The results showed that CG loaded at 25 mm per day and 50 mm per day resulted in an average increase of 13% and 6% in total nitrogen reduction, respectively. The CG50 media showed comparable performance to the sand media in terms of removing 95% of total suspended solids and 96% of biochemical oxygen demand. However, sand is known for its early obstruction and is not the most sustainable option. The paper concluded that substituting CG with sand in a three-bedroom residence could save up to \$500 and reduce annual CO₂ emissions.

To our knowledge, the literature has not addressed a direct comparison of similar crushed glass to sand materials. The existing literature reports good removal efficiencies and consistent filter operation at dosing frequencies of 3-32 doses per day and variable HLRs (Table 2.1). However, it

does not address continuous loading situations where electricity for time-dosed pumping is not available or is cost prohibitive.

Table 2.1 Municipal Lagoon Polishing with Intermittent Sand Filters with Alternative Media

Purpose	Filter Media	Loading Rate & Loading Cycle	Treatment	Reference
Facultative Lagoon Effluent	Material: Sand D ₁₀ : 0.17 mm CU: 3.1 Fines: 2.8 % Depth: 1000 mm	HLR: 0.28 m/d 14 doses/d	COD _{in} = 44 mg/L COD _{out} = 20 mg/L TSS _{in} = 41 mg/L TSS _{out} = 2 mg/L NH ₄ ⁺ -N _{in} =6.7 mg/L NH ₄ ⁺ -N _{out} =0.01 mg/L	Salzman et al, 2022
	Material: Crushed Glass D ₁₀ : 3.59 mm CU:4.2 Fines: 0.8 % Depth: 1000 mm		COD _{in} = 44 mg/L COD _{out} = 24 mg/L TSS _{in} = 41 mg/L TSS _{out} = 3 mg/L NH ₄ ⁺ -N _{in} =6.7 mg/L NH ₄ ⁺ -N _{out} =0.6 mg/L	
Facultative Lagoon Effluent	Material: Sand D ₁₀ : 0.25 mm CU: 4.7 Fines: 2.1 % Depth: 250 mm	0.70-0.80 m/d 30-32 doses/d with 3-4 days operation / 7- day rest period	COD _{in} = 140 mg/L COD _{out} = 97 mg/L TSS _{in} = 44 mg/L TSS _{out} = 21 mg/L KN _{in} =19 mg/L KN _{out} =4.0 mg/L	Torrens et al, 2009
	Material: Sand D ₁₀ : 0.25 mm CU: 4.7 Fines: 2.1 % Depth: 650 mm		COD _{in} = 140 mg/L COD _{out} = 58 mg/L TSS _{in} = 44 mg/L TSS _{out} = 8 mg/L KN _{in} =19 mg/L KN _{out} =2.4 mg/L	
	Material: Crushed Limestone D ₁₀ : 0.19 mm CU: 9.3 Fines: 4.0 % Depth: 250 mm		COD _{in} = 140 mg/L COD _{out} = 97 mg/L TSS _{in} = 44 mg/L TSS _{out} = 24 mg/L KN _{in} =19 mg/L KN _{out} =5.6 mg/L	

Purpose	Filter Media	Loading Rate & Loading Cycle	Treatment	Reference
Wastewater (Septic tank)	Material: Crushed Limestone D ₁₀ : 0.19 mm CU: 9.3 Fines: 4.0 % Depth: 650 mm		COD _{in} = 140 mg/L COD _{out} = 65 mg/L TSS _{in} = 44 mg/L TSS _{out} = 15 mg/L KN _{in} =19 mg/L KN _{out} =4.4 mg/L	
	Material: Recycled shredded ABS plastic (acrylonitrile butadiene styrene) Dia: 4.75 mm Fines:0.11% Depth: 1300 mm	HLR: 0.50 m/d Depth:110 mm	COD _{in} = 400 mg/L COD _{out} = 94.7 mg/L TSS _{in} = 426.3 mg/L TSS _{out} = 25.90 mg/L BOD _{in} = 246.7 mg/L BOD _{out} = 12.30 mg/L	Chmielowski et al, 2023
Synthetic secondary effluent	Material: Crushed Glass Dia: 0.5-1.1 mm Depth: 200 mm	HLR: 0.10 m/d 24 doses/d	COD _{in} = 98 mg/L COD _{out} = 57 mg/L TSS _{in} = 22 mg/L TSS _{out} = ND NH ₄ ⁺ -N _{in} =5.1 mg/L NH ₄ ⁺ -N _{out} =0.1 mg/L	Healy et al, 2010
	Material: Sand D ₁₀ : 0.15 mm Depth: 200 mm		COD _{in} = 98 mg/L COD _{out} = 54 mg/L TSS _{in} = 22 mg/L TSS _{out} = ND NH ₄ ⁺ -N _{in} =5.1 mg/L NH ₄ ⁺ -N _{out} =0.1 mg/L	
	Material: Crushed Glass Dia: 0.5-1.1 mm Depth: 400 mm		COD _{in} = 98 mg/L COD _{out} = 43 mg/L TSS _{in} = 22 mg/L TSS _{out} = ND NH ₄ ⁺ -N _{in} =5.1 mg/L NH ₄ ⁺ -N _{out} =0.1 mg/L	
	Material: Sand D ₁₀ : 0.15 mm Depth: 400 mm		COD _{in} = 98 mg/L COD _{out} = 54 mg/L TSS _{in} = 22 mg/L TSS _{out} = ND NH ₄ ⁺ -N _{in} =5.1 mg/L NH ₄ ⁺ -N _{out} =0.03 mg/L	

Purpose	Filter Media	Loading Rate & Loading Cycle	Treatment	Reference
Synthetic secondary effluent	Material: Crushed Glass D ₁₀ : 0.12 mm Depth: 600 mm	HLR: 0.1 m/d 13 doses/d	COD _{in} = 878.47 mg/L COD _{out} = 70.28 mg/L BOD _{in} = 480 mg/L BOD _{out} = 33.6 mg/L	Gherairi et al. (2015)
	Material: Sand D ₁₀ : 0.12 mm Depth: 600 mm		COD _{in} = 878.47 mg/L COD _{out} = 61.49 mg/L BOD _{in} = 480 mg/L BOD _{out} = 19.2 mg/L	
Secondary treated effluent	Material: Crushed Glass D ₁₀ : 0.23 mm CU: 2.3 Depth: 400 mm	HLR=0.038 m/d 9 doses/d	COD _{in} = 144 mg/L COD _{out} = 36 mg/L Total N _{in} = 54.6 mg/L Total N _{out} = 43.0 mg/L SRP _{in} = 9.9 mg/L SRP _{out} = 6.4 mg/L	Gill et al. (2011)
	Material: Granite sand D ₁₀ : 0.15 mm CU: 3.84 Depth: 400 mm		COD _{in} = 144 mg/L COD _{out} = 34 mg/L Total N _{in} = 54.6 mg/L Total N _{out} = 49.3 mg/L SRP _{in} = 9.9 mg/L SRP _{out} = 5.5 mg/L	
Secondary Domestic wastewater	Material: Fine Glass Dia: 0.2-1 mm Depth: 900 mm	Loading=24 hrs HLR=16.36 m/d Residence time=2 to 2.4 min	COD _{in} = 109.7 mg/L COD _{out} = 84.3 mg/L TSS _{in} = 32.9 mg/L TSS _{out} = 13.4 mg/L	Horan et al (2007)
	Material: Medium Glass Dia: 0.5-1.45 mm Depth: 900 mm		COD _{in} = 109.7 mg/L COD _{out} = 92.4 mg/L TSS _{in} = 32.9 mg/L TSS _{out} = 17.3 mg/L	
	Material: Coarse Glass Dia: 1.5-2.5 mm Depth: 900 mm		COD _{in} = 109.7 mg/L COD _{out} = 78.0 mg/L TSS _{in} = 32.9 mg/L TSS _{out} = 19.9 mg/L	

Purpose	Filter Media	Loading Rate & Loading Cycle	Treatment	Reference
Septic Tank	Material: Rounded Sand Dia: 1-2 mm Depth:900 mm		COD _{in} = 109.7mg/L COD _{out} = 100.5 mg/L TSS _{in} = 32.9 mg/L TSS _{out} = 23.0 mg/L	Ramezaniapour et al (2023)
	Material: 2A Sand D ₅₀ : 0.35 mm CU:3.79 Depth:600 mm	HLR=0.05 m/d 3 doses/d	TSS _{in} = 56.1 mg/L TSS _{out} = 2.2 mg/L BOD _{in} = 107 mg/L BOD _{out} = 5.6 mg/L TN _{in} =43.8 mg/L TN _{out} = 18.4 mg/L	
	Material: Crushed Glass D ₅₀ : 2.2 mm CU:6.91 Depth:600 mm		TSS _{in} = 56.1 mg/L TSS _{out} = 3.6 mg/L BOD _{in} = 107 mg/L BOD _{out} = 5.5 mg/L TN _{in} =43.8 mg/L TN _{out} = 15.2 mg/L	
	Material: Crushed Glass D ₅₀ : 2.2 mm CU:6.91 Depth:600 mm	HLR=0.03 m/d 3 doses/d	TSS _{in} = 56.1 mg/L TSS _{out} = 5 mg/L BOD _{in} = 107 mg/L BOD _{out} = 8.9 mg/L TN _{in} =43.8 mg/L TN _{out} = 15.8 mg/L	

2.5.2.2 Saturated DRI Filter Media

There are two main potential processes of phosphorus removal by DRI: chemical adsorption and surface precipitation and crystallization. During the process of adsorption, the dissolved phosphorus species $H_xPO_4^{(3-x)-}$ are carried into the porous DRI through diffusion and subsequently concentrated on the solid surface through a chemical reaction known as chemisorption. In most situations, this chemisorption process is restricted by concentration (John C Crittenden et al., 2012). Crystallization can occur as a result of decreased solubility of the solute, which can be caused by processes such as evaporation, cooling, or the introduction of a second solvent.

Qin (2019) performed the SEM examination on DRI which revealed the presence of crystal/phosphate precipitation on the medium surface, while the EDS was used to determine the elemental composition of the crystal/surface precipitation. Two primary crystal formations were detected on the DRI surface, as depicted in (a) and (b). The crystal in (a) exhibits a distinct plate-like shape, with lengths ranging from 10 to 100 μm . The EDS examination revealed that the plate form crystal is predominantly constituted of 80% Fe, 15% O, 4% P, and 1% K by weight. Based on stoichiometry, it can be inferred that the crystal is primarily composed of ferric oxide hydroxide. The precipitate contained plate crystals that were identified as ferric oxide hydroxide ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$) through PXRD analysis conducted using a Rigaku Ultima IV diffractometer (Tokyo, Japan). In scenario (b), the crystal takes the shape of clustered spherical material with sphere diameters of around 1 μm . This observation is consistent with the findings of Song et al. (2015), who also discovered sphere-like iron phosphorus crystals with a diameter of roughly 1 μm . The EDS analysis revealed that the crystal consisted of 61% oxygen, 14% phosphorus, 14% iron, and 12% potassium. According to stoichiometric calculation, the most probable form is $\text{KFe}(\text{PO}_4)_2(\text{H}_x\text{O}_8)$. The $\text{KFe}(\text{PO}_4)_2(\text{H}_x\text{O}_8)$ crystal was seen to be more prevalent than other crystal species on the fully saturated DRI surface. Based on the scanning electron microscope (SEM) images, it is evident that surface precipitation/crystallization is the main process occurring, with adsorption perhaps playing a role in the initial phases. According to Li and Stanforth (2000), differentiating between chemical adsorption and surface precipitation is challenging, despite the adsorption isotherm displaying a strong correlation. This study posited that both systems had a role in the process of maintaining phosphorus.

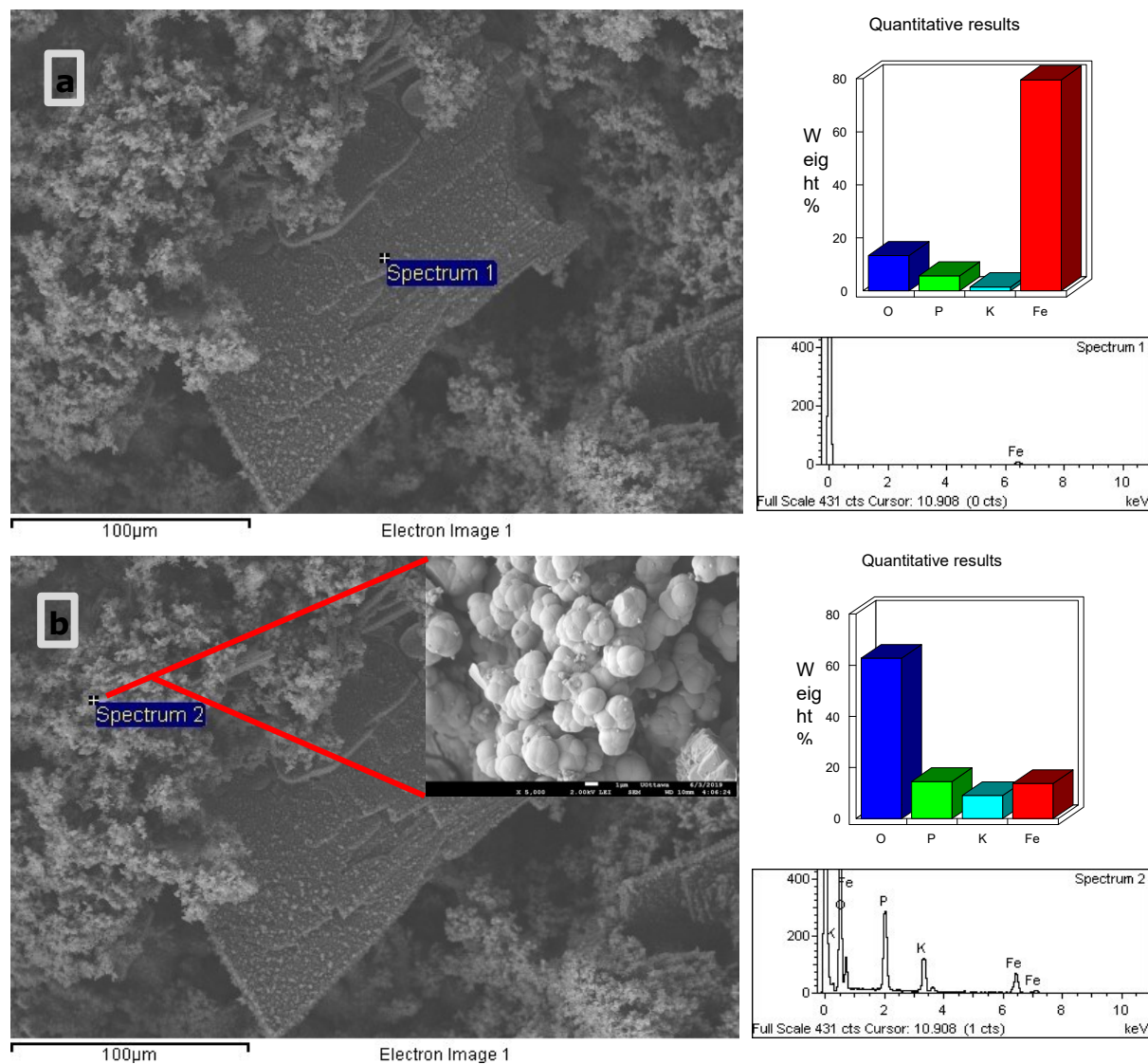


Figure 2.1 SEM and EDS analysis on the saturated DRI surface (from Qin, 2019)

Sun et al (2023) investigated the feasibility of using a sponge-iron-based denitrifying filter at room temperature to remove nitrate and phosphorus from simulated secondary effluent simultaneously. Batch test findings indicate that 70.0% of the overall nitrate reduction was attributed to biological nitrate denitrification. Furthermore, the experiment successfully achieved high-efficiency phosphorus removal by utilizing the chemical reaction between liberated iron and phosphorus. The removal efficiencies exceeded 90% when the hydraulic retention times were longer than 2 hours.

However, Sun et al. (2023) concluded that HRT played a critical role in the phosphorus removal of iron-based denitrifying filters, while 3 h was beneficial for phosphorus removal.

Xue et al (2018) research focuses on the process of phosphate removal using Sponge iron in both batch and fixed-bed operations. Experiments were carried out to analyze isotherms and kinetics. The isotherm data is characterized by the Freundlich and Langmuir models, while the adsorption kinetic data is fitted using the pseudo-second-order kinetic model. The Langmuir isothermal equation has a saturated adsorption capacity of around 3.25 mg/g. The presence of accompanying anions negatively impacts the process of phosphate adsorption, with the following sequence of effects: $\text{NO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$. According to the Adams-Bohart model, the column height decreased from 0.135 to 0.105 m when the contact time increased from 10 to 30 minutes, while the influent concentration remained at 1.0 mg/L. According to the BDST model, the minimum depth of the bed required is 0.15 m when the initial concentration of phosphate in the influent is 1.0 mg/L and the contact time is 20 minutes.

Qin (2019) quoted studies conducted by “Barca et al. (2014) and Mortula et al. (2007), which employed EAF slag and basic oxygen furnace steel slag as filter media, together with a sand filter. These filter media were treated with a synthetic solution containing 10 mg P/L, and the hydraulic retention time (HRT) was set at 24 hours (Barca et al., 2014). Both filters had a removal rate of over 98% throughout a span of 52 weeks. In Mortula et al.'s (2007) study, slag demonstrated a treatment efficiency of 50% when applied to municipal influent with total phosphorus concentrations of 3.7 mg/L. The slag exhibited removal efficiency of 99.4%, 54.1%, and 59.2% for influent phosphorus concentrations of 0.9 ± 0.3 , 0.03 ± 0.01 , and 0.05 ± 0.03 mg/L, respectively (Cameron et al., 2003). Weber et al. (2007) employed an EAF slag filter to treat dairy wastewater. They achieved an average phosphorus removal efficiency of 75% by using influent concentrations

of dissolved reactive phosphorus at 29 mg/L. The treatment was carried out over a time span of 259 days, with a hydraulic retention time (HRT) ranging from 12 to 24 hours. Over time, there was a decrease in the efficiency of retaining P, with a 12% decline at a 12-hour hydraulic retention time (HRT) and a 63% decline at a 24-hour HRT. These findings clearly demonstrate that slag filters experience a decline in effectiveness as time goes on. The limited number of regeneration trials suggests that the filter media may not be reusable and has a predetermined lifespan”.

Direct Reduced Iron (DRI), a promising media to remove phosphorus from effluent streams, has been investigated in adsorption capacity jar tests and lab-scale scale columns (+300 days) using synthetic phosphate solution (Qin, 2019). DRI is an intermediate product within the steel-making industry which is produced from the direct reduction of iron oxide to high content metallic iron pellets by direct chemical reduction (Stephenson and Smailer, 1980). During direct reduction process, the oxygen in the feed stock is removed from the system via reducing-gases, leaving the DRI produced with a more porous physical form than the original iron oxide feed stock utilized and is often called sponge iron (Qin, 2019).

Qin (2019) found that the optimum DRI diameter was 12.5 mm to maximize P removal while minimizing risk of clogging. The material has a maximum sorption capacity of 1.2 ± 0.4 mg P/ g DRI (at 200 mg/L initial P) and minimum 4 hr HRT to remove >80% of 4 mg/L effluent. Qin (2019) did not consider the impact of organic matter or biofilm fouling on P removal and did not apply the technology at field-scale.

2.5.3 Inlet and Outlet Structures

The regularity of wastewater distribution and collection across the filter medium is impacted by the design of input and outflow structures. The buildings should be built to distribute wastewater evenly across the whole surface of the filter material (Prodanovic et al, 2017). For horizontal flow

filters, the cleaned wastewater is collected in a collecting drain at the bottom of the filter, whereas a perforated distribution pipe is frequently utilized for vertical flow filters.

2.5.4 Depth of Filter Bed

When designing passive filters, the filter bed's depth is a crucial factor. It establishes the pollutant removal filter media's effective depth and retention time. Longer retention periods and greater removal efficiency result from a deeper filter bed (Dhamodharan et al, 2019). But a deeper filter bed also adds to the filter's cost and raises the risk of clogging and hydraulic failure. Based on the quality of the wastewater and the required removal effectiveness, the depth of the filter bed should be carefully chosen.

2.5.5 Filter Clogging

Leverenz et al. (2009) investigated the clogging phenomenon in intermittent sand filter (ISF) systems. The sand characteristics used in the ISF study are $D_{10}=0.45$ mm, $C_U=3$, with a depth of 0.15 m. The study utilized a combination of an unsaturated flow model and a reactive transport model. The model sensitivity analysis identified many key variables that play a significant role in the clogging phenomena observed in ISFs. These variables include hydraulic loading rate, influent chemical oxygen demand (COD) concentration, filter dosing frequency, and operation time. Multiple operational modes were discovered that effectively reduce bacterial growth on the filter surface. After doing the sensitivity analysis, the model was used to simulate many case studies where ISF blockage was observed. The findings from the case study model simulations demonstrated a correlation between the total suspended solids loading rate and the occurrence of clogs at a specific location. Ruppe (2005) noted that sand filters ($D_{10}=0.44$ mm, $C_U=2.4$, Depth=0.15 m), which were subjected to the same hydraulic loading rates (HLRs) and influent wastewater source but were dosed at varied frequencies, experienced clogging at varying intervals.

The ISF, which was dosed at a frequency of 96 doses per day, became clogged after 55 days of operation. In contrast, the filter, which was dosed at a frequency of 48 doses per day, became clogged on day 93, suggesting that a dosing frequency of 15 minutes is too short, reducing oxygen transfer and wastewater diffusion. Rodgers et al. (2004) conducted an experiment where they applied synthetic dairy wastewater (a high strength waste) over a medium sand ($D_{10}=0.45$ mm, $CU=3.0$, $Depth=0.35$ m) at a rate of 0.06 m/d in 4 dosages per day. They observed that the filter became clogged after only 35 days of operation.

A study by Grace et al (2016) compared a multi-media filter comprising combinations of Bayer residue, zeolite, fly ash and granular activated carbon to sand filters, subject to continuous and intermittent loading. The study showed that the innovative filter configurations reached a maximum removal rate of 97% for aluminum, 71% for total organic carbon (TOC), and 88% for ammonium nitrogen (NH_4^+-N) in the most successful configuration. However, these configurations were not as permeable as sand. Analysis of the filters showed that the primary cause of blockage was the accumulation of organic material at the top layer of the filters. The formation of the clogging layer occurred at a faster rate on the surface of the new media compared to the sand filters. However, the clogging layer reached deeper into the sand filters with continuous loading than intermittent loading. Interestingly, Petitjean et al. (2016) concluded that the occurrence of physical blockage in vertical flow sand filters for on-site wastewater treatment resulted in a change in the hydraulic characteristics of the column prior to an observed decrease in oxygen levels, suggesting that treatment efficiency will continue until there a hydraulic failure.

2.5.6 Maintenance and Operation

For best effectiveness, passive filters need routine maintenance. Replacement of the filter media, backwashing, and cleanup of sludge buildup are maintenance tasks. In order to loosen and remove

collected particles, backwashing entails turning around the flow through the filter material. The HLR, medium type, and influent wastewater quality all affect how often backwashing is required. For the removal of contaminants from wastewater to be effective and dependable, careful consideration of these elements is important. The design of a passive filter is influenced by a number of variables, including the filter type, the medium employed, the hydraulic loading rate, and the properties of the effluent. The filter's ability to treat contaminants effectively depends on the choice of filter material. High porosity, high permeability, and adequate adsorption capacity are required of the media. To achieve effective treatment and avoid blockage, the hydraulic loading rate needs to be regulated. The right vegetation must be chosen for hybrid filters in order to maximize nutrient removal and offer extra treatment. The effectiveness of passive filters for treating municipal wastewater has been examined in several research. Luukkonen et al.'s (2019) study assessed the effectiveness of a VFF loaded with zeolite for treating secondary wastewater. According to the study, the VFF successfully removed COD (89.4%), $\text{NH}_4^+\text{-N}$ (99.4%), and TP (82.4%). Laforest et al, (2017) evaluation of an HFF loaded with zeolite for treating synthetic wastewater was part of a separate investigation. According to the study, the HFF successfully removed substantial amounts of COD (90.6%), $\text{NH}_4^+\text{-N}$ (99.9%), and TP (80.6%). Generally, the design and effectiveness of a passive filter depend on a number of elements, including the filter type, the medium utilized, the hydraulic loading rate, and the properties of the effluent. By use of physical, chemical, and biological processes, passive filters eliminate contaminants. For hybrid filters, choosing the right vegetation is essential since it improves nutrient removal and offers extra treatment.

2.6 Research Studies on Passive Filters for Lagoon Polishing

The effectiveness of passive filters for treating municipal wastewater has been examined in several research. Luukkonen et al.'s (2019) study assessed the effectiveness of a VFF loaded with zeolite for treating secondary wastewater. According to the study, the VFF successfully removed COD (89.4%), NH₄⁺-N (99.4%), and TP (82.4%). Laforest et al, (2017) evaluation of an HFF loaded with zeolite for treating synthetic wastewater was part of a separate investigation. According to the study, the HFF successfully removed substantial amounts of COD (90.6%), NH₄⁺-N (99.9%), and TP (80.6%).

Three different types of filter media, including zeolite, perlite, and sand, were used in research by Zulkifi et al. (2022) to assess how well passive filters performed at removing nitrogen and phosphorus from municipal lagoon effluent. According to the findings, zeolite had the highest removal efficiency for both nitrogen and phosphorus, at 66.5% and 75.8%, respectively. With nitrogen removal efficiencies of 43.5% and 38.9%, respectively, and phosphorus removal efficiencies of 42.6% and 38.2%, respectively, perlite and sand performed less well.

The effectiveness of passive filters is also greatly influenced by the width and depth of the filter bed. The effects of filter bed size and depth on the removal of nitrogen and phosphorus from municipal wastewater were examined in research by Zheng et al. (2018). According to the study, increasing the filter bed's size and depth increased the removal effectiveness of both nitrogen and phosphorus. The removal effectiveness of phosphorus increased from 46.9% to 74.6% for the same range of filter bed sizes, whereas the removal efficiency of nitrogen improved from 45.5% for a small filter bed to 74.7% for a big filter bed.

The effects of influent concentration on the removal of nitrogen and phosphorus using a horizontal subsurface flow constructed wetland was examined in a study by Liu et al. (2020). The study

discovered that as the influent concentration rose, so did the effectiveness of nitrogen and phosphorus removal. For instance, at a 50 mg/L influent concentration, the removal efficiency of nitrogen declined to 69.5%, and at a 200 mg/L influent concentration, it reduced to 35.5%.

Li et al. (2023) assessed how well a hybrid passive filter performed in removing impurities from the effluent of a municipal wastewater treatment facility. Organic matter, suspended particles, and nutrients were successfully removed from the effluent by the filter, with removal rates of 68.2%, 79.6%, and 50.0%, respectively, according to the research. The authors also noticed that the filter performance was significantly influenced by the hydraulic retention time and the filter medium. The effectiveness of using a vertical constructed wetland as a passive filter for polishing treated municipal wastewater was examined in another study by AbeSon et al. (2022). They discovered that the filter had removal rates of 93%, 80%, and 93% for contaminants including nitrogen, phosphorus, and suspended particles, respectively. The adsorption of a substrate with a high surface area-to-volume ratio, according to the authors, enhanced the filter's effectiveness. The effectiveness of a horizontal constructed wetland as a passive filter for cleaning residential wastewater was also assessed in a study by Ribas (2017). The filter had removal rates of 84%, 72%, and 72%, respectively, for contaminants such total suspended solids, biological oxygen demand, and chemical oxygen demand, according to the research. The depth and size of the filter bed had a big effect on how well the filter worked, according to the authors.

Additionally, Yu et al. (2022) assessed how well a hybrid constructed wetland (HCW) system polished the wastewater from a Chinese urban lagoon. Cattails and reeds were added to the horizontal and vertical flow wetland portions of the HCW system. The outcomes demonstrated that the HCW system was efficient in removing pathogens, heavy metals, and nutrients from the lagoon effluent, including up to 4.2 logs of removal for *E. coli*, up to 78% removal for total

nitrogen, and up to 91% removal for total phosphorus. In separate research, Otieno et al. (2017) assessed how well a horizontal subsurface flow (HSSF) wetland polished the wastewater from a municipal lagoon in Ghana. A gravel layer and a bed of sand made up the HSSF system. The results demonstrated that the HSSF system was efficient in removing pathogens, heavy metals, and nutrients from the lagoon effluent, 90% removal for total nitrogen and up to 87% removal for total phosphorus. According to the study, the removal effectiveness of the HSSF system was significantly influenced by the size, depth, and type of the filter medium.

In order to polish the effluent from a municipal lagoon in Chile, AbeSon et al. (2022) examined the efficacy of a hybrid system made up of a horizontal subsurface flow wetland and granular activated carbon (GAC) filter. The outcomes demonstrated that the hybrid system was efficient in removing up to 85% removal for total nitrogen and up to 96% for total phosphorus). The study also discovered that the hydraulic loading rate of the system, type, and concentration of pollutants in the influent all significantly impacted the hybrid system's ability to remove pollutants.

2.6.1 Laboratory Studies

It has been determined through laboratory tests how effective passive filters are at polishing lagoons. Small-scale filter systems are employed in this research to evaluate the efficiency of various filter media and design configurations in removing contaminants from wastewater. To mimic real-world settings, the influent water in these tests is often spiked with a known quantity of contaminants.

Wei et al. (2022) carried out one such study in which they assessed the efficacy of a vertical flow constructed wetland (VFCW) in polishing lagoon effluent. The study made use of laboratory-scale VFCWs with gravel and other organic materials as filter medium. According to the findings, the VFCW with organic media removed COD, TSS, and $\text{NH}_4^+\text{-N}$ with a better removal efficiency than

the VFCW using only gravel media. The study also discovered that the VFCW's ability to remove pollutants was significantly influenced by the hydraulic loading rate and influent pollutant concentration. The efficacy of a hybrid constructed wetland (HCW) system for treating secondary effluent from a municipal wastewater treatment plant was examined in a further laboratory investigation by Zorai et al. (2023). A horizontal flow wetland was the first component of the HCW system, followed by a vertical flow wetland. With removal efficiencies ranging from 73.7% to 96.8%, the results demonstrated that the HCW system was successful in eliminating COD, TSS, TN, and TP from the secondary effluent. The study also discovered that the HCW system's removal effectiveness was significantly impacted by the depth and composition of the filter medium. Laboratory research has demonstrated that passive filters are capable of removing pollutants from lagoon effluent, while removal efficiencies vary depending on design details, the make-up of the filter medium, and the quantity of influent pollutants. These research studies offer crucial information on the creation and improvement of passive filters for lagoon polishing.

Pilot-scale experiments have also been carried out to assess the efficacy of passive filters for lagoon polishing. These studies make use of larger-scale filter systems to evaluate the performance of passive filters in more practical working scenarios. Weerakoon et al.'s (2020) investigation into the effectiveness of a horizontal subsurface flow (HSSF) constructed wetland for cleaning lagoon effluent was one such research. The filter bed size for the study's HSSF system was 5 m x 3 m x 0.5 m, and the filter medium utilized was made up of gravel and sand. With removal efficiencies of 98.1% for COD, 96.9% for TSS, 84.5% for TN, and 90.8% for TP, the results demonstrated that the HSSF system was efficient in removing pollutants from lagoon effluent. The study also discovered that the hydraulic loading rate and influent pollutant concentration had a sizable effect on the HSSF system's removal effectiveness. Parde et al.'s (2021) employed a pilot-scale HFCW

system with a 5 m × 5 m x 0.5 m filter bed with gravel and wood chips as the filter material. The findings demonstrated that the lagoon effluent pollutants could be effectively removed by the HFCW system, with removal efficiencies of 89.9% for COD, 91.2% for TSS, 83.8% for TN, and 69.6% for TP. The study also discovered that the HFCW system's removal effectiveness was significantly impacted by the depth and composition of the filter medium.

Ji et al. (2020) investigated a vertical flow system followed by a horizontal flow system with 97% removal of nitrogen and 92% removal of phosphorus. Liu et al. (2021) looked at several filter media for lagoon effluent pollution including zeolite, gravel, and sand served in a small-scale horizontal flow system. The zeolite filter, which had removal rates of up to 98% for nitrogen and 96% for phosphorus, was discovered by the researchers to be the most efficient media. An investigation carried out in South Africa assessed the effectiveness of vertical flow filter using recycled shredded plastic. With average removal efficiencies of 94.4% for BOD, 77.8% for COD and 92.8% for TSS, the study indicated that the passive filter system was successful in removing carbon compounds (Chmielowski et al., 2023).

2.6.2 Field Studies

The effectiveness of passive filters in various environments has been assessed through field experiments. In one Brazilian research, the efficacy of a vertical flow constructed wetland (VFCW) system for treating dairy farm wastewater was assessed (Pinninti et al, 2022). The filter media for the VFCW system was crushed stone of various sizes in a four-stage filter bed. Total suspended solids (TSS), biological oxygen demand (BOD), and total nitrogen (TN) were among the contaminants that the system was able to effectively eliminate. TSS, BOD, and TN removal efficiencies were determined to be 87.7%, 93.4%, and 83.8%, respectively. A study within the United States assessed how well a hybrid horizontal subsurface flow (HHSF) wetland system

handled septic tank wastewater (Rahi et al., 2020). The filter bed used in the HHSF system had a gravel and sand combination as the filter media. TSS, BOD, and TN were among the contaminants that the system was able to effectively eliminate. TSS, BOD, and TN were found to have removal efficiencies of 94.6%, 93.3%, and 68.8%, respectively.

The efficacy of a hybrid vertical flow (HVF) constructed wetland system in treating municipal wastewater was assessed in a study carried out in Spain (Nuamah et al, 2020). The HVF system had two layers of filter beds with various filter media, such as zeolite, gravel, and sand. TSS, BOD, TN, and TP removal efficiencies were determined to be 91.3%, 94.3%, 91.4%, and 89.9%, respectively.

Field studies have also examined the long-term upkeep and operation of these systems in addition to the performance of passive filters. In one American research, the long-term efficacy of a subsurface flow constructed wetland (SSFCW) system for treating municipal wastewater was assessed (Zhong et al., 2022). The study discovered that the system could continue to remove pollutants at a constant rate for ten years. The study did discover, however, that the hydraulic conductivity of the system was decreased as a result of the buildup of organic matter and particles in the filter bed. The SSFCW system's long-term effectiveness was shown to depend on routine maintenance, which includes the removal of accumulated solids.

Another South Africa research assessed the efficacy of a passive horizontal flow filter for polishing wastewater from a facultative lagoon system (Tebitendwa & Cowan, 2023). Sand, gravel, and discarded coal were employed as the filter material in this investigation. According to the study, the passive filter had removal efficiency for organic matter and suspended particles of 90% and 70%, respectively.

2.7 Effect of Filter Media Characteristics

The size and characteristics of the filter are critical to effective treatment. Larger surface area to volume ratios is often seen in smaller filter media particles, allowing for better interaction between the filter media and the effluent. This greater contact may improve the adsorption and filtering of contaminants, increasing the effectiveness of their removal. For instance, Wang et al.'s (2022) study found that using sand of 0.3 to 0.5 mm diameter compared with a diameter of 0.5 to 0.7 mm improved the removal efficiency of nitrogen and phosphorus. According to research by Tondera et al. (2018), the size of the filter medium can influence how effectively nutrients are removed from horizontal flow reed beds. In comparison to bigger sizes (10-14mm), they discovered that lower media sizes (2-5mm) produced better removal rates of nitrogen and phosphorus. The removal effectiveness of passive filters can also be impacted by the filter media's composition. The capacity of various filter media types to absorb contaminants might vary depending on their chemical and physical characteristics. Forbis-Stokes et al.'s (2018) study compared the removal effectiveness of a passive filter made of sand and granular activated carbon (GAC) to one made of simply sand. The findings demonstrated that, in comparison to a sand-only filter, the filter adding GAC had considerably greater removal efficiency for both organic matter and nitrogen.

In a vertical flow constructed wetland system, a research by Wu et al. (2019) assessed the efficacy of two distinct types of filter media (ceramic and zeolite) in terms of organic matter removal. They discovered that when compared to zeolite media, ceramic media had a better removal efficiency for both chemical oxygen demand (COD) and total organic carbon (TOC). The filter bed's depth can also affect the effectiveness of pollutant removal. According to research by Al-Wahaibi et al. (2021), a horizontal flow reed bed system with deeper filter beds removed nitrogen and phosphorus

at greater rates. Beyond a certain depth, however, removal efficiency did not considerably improve.

2.8 Impact of Hydraulic Loading Rates

The effectiveness of passive filters for lagoon polishing is significantly influenced by the hydraulic loading rate (HLR), which is the quantity of wastewater applied to the filter per unit area and time. Numerous studies have examined how HLR affects the effectiveness of pollution removal in various kinds of passive filters. A vertical flow constructed wetland (VFCW) was utilized in a study by Mimis et al. (2007) to treat the effluent from a facultative lagoon. The HLR ranged from 0.015 to 0.114 m³/m²/day, and the filter bed was filled with gravel and sand. The findings demonstrated that whereas removal of biological oxygen demand (BOD) and ammonia-nitrogen (NH₃-N) was unaffected by HLR, removal efficiency of total suspended solids (TSS) declined with increasing HLR. The HLR was varied from 0.04 to 0.32 m³/m²/day in research by Li et al. (2023) that employed a horizontal subsurface flow constructed wetland (HSFCW) to treat wastewater from a facultative lagoon. The findings demonstrated that when HLR increased, the effectiveness of total nitrogen (TN) and phosphorus (TP) removal reduced.

In hybrid constructed wetlands (HCWs), the impact of HLR on pollution removal has also been investigated. A hybrid constructed wetland with a vertical flow (VF) portion and a horizontal subsurface flow (HSF) section was utilized to treat effluent from a facultative lagoon in a study by Herrera-Melain et al. (2023), and the HLR was adjusted from 0.1 to 1.2 m³/m²/day. The findings demonstrated that while the removal efficiency of TN and TP in the HSF section rose with increasing HLR, it decreased in the VF section with rising HLR. The best HLR for eliminating contaminants in passive filters may differ based on the filter media type, the size and depth of the filter bed, and the kind and quantity of pollutants in the influent, it is crucial to note. Therefore,

through pilot-scale research or field trials, it is vital to ascertain the suitable HLR for each unique scenario. In addition, longer contact times between the wastewater and filter material might lead to lower pollutant removal efficiency at higher HLRs. On the other side, lower HLRs may result in a clogged filter bed and a diminished ability to cure. Jenkins, (2017) determined that a vertical flow constructed wetland using gravel as the filter medium performed best at an HLR of 0.01 m³/m²/d. Another study by Saeed & Sun, (2017) discovered that a hybrid vertical-horizontal flow constructed wetland with zeolite and blast furnace slag as the filter medium worked best for eliminating nitrogen and phosphorus from swine wastewater when the HLR was between 0.5 and 1.5 m³/m²/d.

Gaballah et al., (2020) looked at the impact of HLR on the elimination of nitrogen and phosphorus in a horizontal subsurface flow wetland. The study determined that raising the HLR from 0.05 m/d to 0.15 m/d caused a drop in the effectiveness of removing nitrogen and phosphorus, which was linked to a reduction in the amount of time wastewater was in contact with the filter medium. The effectiveness of a hybrid vertical-flow constructed wetland for treating swine wastewater was also assessed by Wang et al. (2018) under various HLRs. According to the study, while total nitrogen removal efficiency was not significantly impacted by the HLR, total phosphorus removal efficiency declined as HLR increased.

2.9 Comparative Analysis of Passive Filters with other Polishing Methods

More research is being done on passive filters as a practical way to polish municipal wastewater treatment lagoon effluent. To evaluate the relative efficacy of passive filters compared to other cleaning techniques, it is crucial to compare their performance. This section will examine and contrast the effectiveness of passive filters with that of other polishing techniques including artificial wetlands, activated sludge, and sand filters. A popular technique for wastewater treatment

that effectively removes organic contaminants, nitrogen, and phosphorus is activated sludge. Activated Sludge System (ASS) consists of a reactor where wastewater's organic content is broken down by microorganisms. The cleaned water is subsequently released or subjected to further treatment. However, activated sludge systems might have expensive capital and running expenses. Chaves-Barquero et al., (2018) conducted research to examine the efficacy of passive filters and activated sludge in polishing wastewater treatment lagoon effluent. The study discovered that while the removal efficiency for total suspended particles was comparable for both techniques, passive filters had a greater removal efficiency for total nitrogen and total phosphorus than the activated sludge system. The effectiveness of ASS and passive filters for lagoon cleaning has been examined in several research. In one research, the performance of a hybrid ASS made up of a sequencing batch reactor (SBR) and a membrane bioreactor (MBR) was compared to that of a passive filter. Both systems showed good removal efficiencies for nutrients and organic materials, according to the study, while the passive filter had a greater removal efficiency for pathogens and heavy metals.

Another often used technique for wastewater treatment is constructed wetlands. These systems are renowned for their low running costs and capacity to create habitat for animals. They employ natural processes to remove contaminants. The effectiveness of passive filters and artificial wetlands for cleaning the effluent from a municipal wastewater treatment facility was compared in research by Alsawi, Ray & Scholz., (2017). The research discovered that compared to artificial wetlands, passive filters had a greater removal effectiveness for total nitrogen, total phosphorus, and total suspended particles.

Another common technique for polishing wastewater effluent is the use of sand filters. These systems consist of a sand bed or other filtering medium that removes contaminants as wastewater

flows over it. Greenleaf's (2019) study examined the effectiveness of passive filters and sand filters for polishing wastewater treatment lagoon effluent. The removal effectiveness for total suspended particles was similar for both techniques, however the study indicated that passive filters had a greater removal efficiency for total nitrogen and total phosphorus than the sand filter system. Based on the aforementioned investigations, Table 2.2 lists the removal efficiency for various contaminants attained by passive filters and other polishing techniques.

Table 2.2 Comparison of pollutant removal efficiencies for passive filters and other polishing methods

<i>Polishing Method</i>	<i>Total Nitrogen</i>	<i>Total Phosphorus</i>	<i>Total Suspended Solids</i>
	<i>(%)</i>	<i>(%)</i>	<i>(%)</i>
<i>Passive Filters</i>	57-90	50-80	53-87
<i>Activated Sludge</i>	37-83	40-80	50-85
<i>Constructed Wetlands</i>	40-75	25-60	40-70
<i>Sand Filters</i>	30-70	35-60	53-87

Adapted from: (Jin et al., 2017)

According to Table 2.2, all polishing techniques remove total suspended particles equally well, however passive filters are more effective than other polishing techniques at removing total nitrogen and total phosphorus. It is crucial to remember that the effectiveness of these techniques might change based on elements including the kind and quantity of pollutants present in the influent, the size and depth of the filter bed, and the hydraulic loading rate.

Passive filters provide a number of advantages over conventional polishing techniques in terms of sustainability. Compared to artificial wetlands and activated sludge systems, they require less

energy and maintenance. Passive filters may also be created to replicate natural systems, which helps animal habitat and has aesthetic advantages. It is crucial to remember that passive filters need their filter material to be replaced on a regular basis, which might cause disposal problems.

2.10 Cost-effectiveness and Feasibility of Passive Filters

Passive filters are receiving more and more attention as a practical and long-lasting water treatment option, particularly for lagoon polishing. Because passive filters don't need energy or chemicals and have low maintenance, they can considerably save operating expenses. In comparison to other traditional treatment techniques, the affordability and viability of passive filters will be examined in this section. The efficiency of passive filters in terms of cost has been examined in several research. Fernandez-Gatell et al. (2022) evaluated the feasibility of using horizontal subsurface flow (HSSF) to treat swine wastewater. HSSF built wetlands were found to be cost-effective, with an estimated cost of \$1.28/m³ of treated water, according to the study. This is less expensive than the predicted cost of other traditional wastewater treatment techniques including sequencing batch reactors and activated sludge. The efficiency of hybrid constructed wetlands for the treatment of residential wastewater was also assessed in a research by Truu et al. (2022). The study discovered that hybrid constructed wetlands had a low cost of \$1.35/m³ of treated water. This is less expensive than other typical wastewater treatment techniques, such membrane bioreactors and oxidation ponds, which are predicted to cost more.

Additionally, it has been shown that passive filters are more practical in rural and distant places where installing traditional wastewater treatment systems may not be practicable because of their high initial capital and ongoing maintenance expenses. Upadhyay & Singh (2020) examined the viability of using vertical flow constructed wetlands to treat greywater in Israel's rural regions. According to the study, vertical flow constructed wetlands were practical, had cheap initial and

ongoing expenses, and had a significant amount of potential to treat greywater. Additionally, passive filters have a lower carbon footprint than other traditional wastewater treatment techniques. The carbon footprint of HSSF built wetlands for the treatment of urban stormwater was assessed in a study by Freeman et al. (2018). The study discovered that when compared to other traditional wastewater treatment techniques like membrane filtration and chemical treatment, HSSF built wetlands had a reduced carbon footprint. Passive filters' cost-effectiveness in comparison to other wastewater treatment techniques has also been assessed in a number of studies. According to 2017 research by Oladoja et al. in Nigeria, the capital cost of a passive filter is almost 70% less than that of a traditional wastewater treatment facility. Additionally, because passive filters use less energy and require less maintenance, their operating costs are predicted to be 50% cheaper than those of traditional treatment plants.

Passive filters are a more sustainable solution for wastewater treatment since they also have a little impact on the environment and may be made to fit in with the surrounding environment. However, depending on a number of variables, including the kind of filter media employed, the size and depth of the filter bed, and the kind and quantity of pollutants in the influent, the cost-effectiveness and viability of passive filters may change. Wang et al. (2020) observed that the kind of filter media employed affected how cost-effective HSSF constructed wetlands were, with media based on limestone being more cost-effective than media based on zeolite. Conclusively, passive filters offer a practical and affordable solution for treating wastewater, especially in places with limited infrastructure and resources. Compared to alternative treatment options, they use less energy, need less upkeep, and have a longer lifespan.

2.11 References

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CHAPTER 3

3.0 Development of a passive filter to polish municipal lagoon effluent – column studies

3.1 Abstract

A filter design with unsaturated media and saturated reactive media layers was evaluated to polish synthetic municipal lagoon effluent under conditions of continuous dosing. Two coarse sand media were compared with crushed recycled glass in the unsaturated layer at varying depths and hydraulic loading rates. The sand media observed biofilm clogging at both 25 and 55 cm/d loading, while the crushed glass did not. A 45 cm layer of crushed glass at 25 cm/d loading provided optimum treatment, reducing cBOD₅ and NH₄⁺-N concentrations by 87 and 93%, respectively. This study demonstrated that increased hydraulic loading rate at constant organic loading rate increases filter clogging and reduces treatment efficiency. Direct Reduced Iron was evaluated as a reactive media for soluble phosphorus reduction at varying depths and HRTs. A 15 cm layer of 12.5 mm dia. saturated DRI with 5.9 hr HRT was effective at reducing soluble phosphorus by 89% with no apparent impact of biofouling on removal efficiency.

Keywords: column study, municipal lagoon effluent polishing, continuous dosing, clogging, direct reduced iron, phosphorus, ammonium, BOD.

3.2 Introduction

Lagoon-based sewage treatment systems are the most common type of municipal wastewater treatment technology in Canada with over 1000 systems in operation (Environment and Climate Change Canada, 2017). Federal regulation stipulates maximum effluent concentrations of 25 mg/L for TSS and cBOD₅ and 1.25 mg/L NH₃ at 15°C ± 1°C (Government of Canada, 2012), while

Provincial discharge criteria are site specific, can be more stringent than the federal criteria and include phosphorus. The presence of algae in the effluent during warm months can increase TSS to above 30 mg/L (USEPA, 2002). Cold weather and ice cover inhibits nitrification during winter and early spring, resulting in NH₃ exceedances. Additionally, it is a challenge for lagoon systems to meet increasingly stringent total phosphorus (TP) limits of less than 1.0 mg/L with conventional coagulation practices (Federation of Canadian Municipalities, 2004). Add-on polishing technologies can provide cost-effective means of addressing these issues.

Intermittent Sand Filters (ISF) have been demonstrated to effectively polish lagoon effluent for BOD, TSS and NH₄⁺ at hydraulic loading rates (HLRs) and dosing frequencies varying from 0.1 m/d with 24 doses/day (Healy et al, 2010) to 0.28 m/d with 14 doses/d (Salzman et al, 2022) to 0.70-0.80 m/d with 30-32 doses/d, albeit with 3-4 days loading followed by a 7-d rest period (Torrens et al, 2009) with media depths of between 0.4 to 1.0 m. In the studies by Salzman et al (2022) and Healy et al (2010), coarse sand was also compared to crushed glass, with the crushed glass exhibiting somewhat lower nitrification rates but at higher D₁₀ values.

Oxygen transfer to ISFs is dependent upon dissolved oxygen (DO) in the wastewater and most importantly on oxygen diffusion between doses. As the dose frequency increases, the batch volume decreases, decreasing the effluent velocity and increasing residence time. However, as dose frequency increases, diffusion decreases. This favours biofilm development in the top layer of the filter, which further reduces hydraulic conductivity (Bancole et al, 2003), and can lead to premature filter clogging. The reported literature does not consider the case of continuous loading, where electricity for time dosed pumping may not be available.

Various media with high cation content have been studied for passive phosphorus removal including calcium-based materials such as waste steel slag (Drizo et al, 2006; Cameron et al, 2003),

aluminum-based materials such as activated aluminum oxide (Xie et al, 2015) and many iron based materials (Zhu et al, 2024). Direct Reduced Iron (DRI) has been shown to be a promising media to remove phosphorus from effluent streams (Qin, 2019). DRI is an intermediate product in the steel-making industry produced from the direct reduction of iron oxide to high content metallic iron pellets with a porous media (Stephenson and Smailer, 1980). Qin (2019) proposes an optimum DRI diameter of 12.5 mm to maximize P removal while minimizing risk of clogging. DRI has an equilibrium sorption capacity of 1.2 ± 0.4 mg P/g DRI (at 200 mg/L initial P) and minimum 4 hr HRT to remove >80% of 4 mg/L effluent. The sorption capacity is similar to other active media including blast-furnace slag (Han et al., 2016), which has been studied extensively. However, Qin (2019) did not consider the impact of organic matter or biofilm fouling on P removal.

The goal of this study is to develop a passive filter to polish municipal lagoon effluent consisting of an unsaturated media layer to remove BOD, TSS and NH_4^+ and a saturated media layer to remove P. The first objective of the study is to optimize the unsaturated media layer for BOD and NH_4^+ removal, comparing two sand media utilised in the Ontario onsite wastewater industry to crushed recycled glass under continuously loading conditions. It is hypothesised that the smooth surfaces of the crushed glass will reduce biofilm development and filter clogging compared to sand, however, with potentially lower removal efficiencies. The second objective is to evaluate DRI media for soluble P reduction under conditions of organic loading and biofilm fouling.

3.3 Materials and Methods

3.3.1 Columns Setup

A series of 9 columns (6-inch PVC) was established to operate at room temperature and a further 3 columns at cold temperature in the UOttawa Environmental Engineering Laboratory to evaluate the treatment of synthetic municipal lagoon effluent for BOD, $\text{NH}_4^+\text{-N}$ and SRP (Figures 3.1 and

3.2). A sample collection port was installed in the transition layer between the unsaturated and saturated media to collect samples from the nitrifying layer. A standpipe from the bottom outlet port maintains saturated conditions to the top of the transition layer and allows for effluent sampling. Column media and operating temperature details are described in Table 3.1.

Each column from the top comprises:

- 1.0 A 5 cm gravel layer (1.2 cm dia.)
- 2.0 30, 45 or 60 cm nitrifying media layer (Filter Media Sand (FM), Eljin Sand (EJ), Recycled Glass (RG))
- 3.0 A 5 cm transition gravel layer (1.2 cm dia.)
- 4.0 5, 10 or 15 cm layer of Direct Reduced Iron (DRI)
- 5.0 A 10 cm gravel layer (3.8 cm dia.)

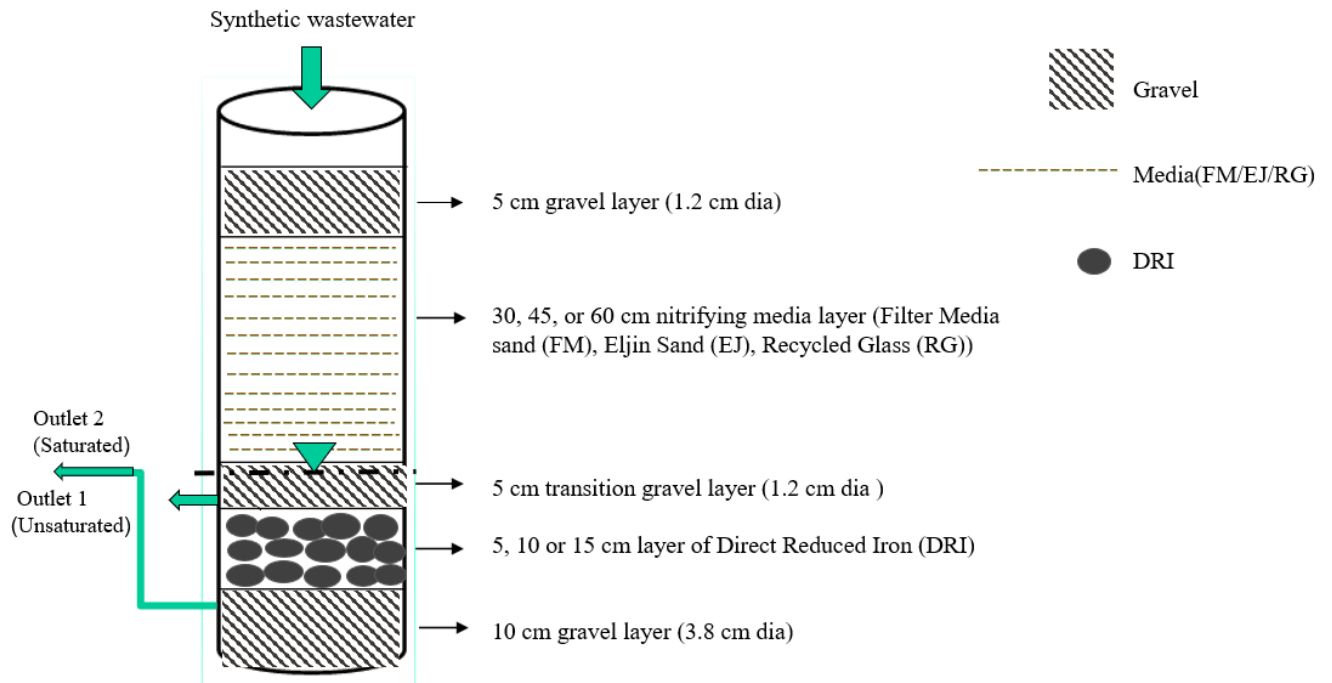


Figure 3.1 Column Setup Diagram



Figure 3.2 Column Set Up Photo

Table 3.1 Column details used in Laboratory

Column Number	Nitrifying Media	DRI Depth	Temperature
	cm	cm	°C
1	FM – 30	15	4.5±0.7
2	FM – 45	10	4.5±0.7
3	FM – 60	5	4.5±0.7
4	FM – 30	15	21.3±1.5
5	FM – 45	10	21.3±1.5
6	FM – 60	5	21.3±1.5

Column Number	Nitrifying Media	DRI Depth	Temperature
	cm	cm	°C
7	EJ – 30	5	21.3±1.5
8	EJ – 45	10	21.3±1.5
9	EJ – 60	15	21.3±1.5
10	RG – 30	5	21.3±1.5
11	RG – 45	10	21.3±1.5
12	RG – 60	15	21.3±1.5

3.3.2 Media

Three ISF media were selected for this study. Two represent coarse sand specifications utilised for high-rate onsite wastewater treatment applications in Ontario (Filter Media Sand (FM) (OBC s. 8.7.5) (Ontario Ministry of Municipal Affairs and Housing, 2012) and Eljen Inc. specified sand (EJ) (www.eljen.com). These were acquired from Brissenden Pit (Mountain, ON). The crushed recycled glass (RG) product was obtained from Enviro Grit-Abrasives (Abbotsford, BC). To ensure uniform packing, media was loaded into the columns in 10 cm layers, and then a metal stick with a flat rubber head was used to compact sand in columns as per Prochaska et al., (2003). Particle size analysis of the ISF media was conducted following ASTM D422 and is presented in Table 3.2. The DRI media was acquired from ArcelorMittal’s direct reduction plant in Contrecoeur, Québec with a nominal diameter of 12.5 mm and presented in Table 3.2. Figure 3.3 below depicts the porous characteristics of DRI, as observed through scanning electron microscopy imaging of the surface of DRI pellets (Qin, 2019).

Table 3.2 ISF Media Specifications

ISF Media	Effective size (D ₁₀) mm	U _c (D ₆₀ /D ₁₀)	% Fines (<0.075mm)
FM	0.43	2.6	4.5
EJ	0.18	5.8	2.1
RG	0.45	2.2	0.04

Table 3.3 DRI characteristics

Elemental Analysis (%)	Bed density (kg/m ³)	Density (g/cm ³)	Specific area (m ² /g) (Avg. ± SD)	Bed porosity (%)
Fe: 92.2 O: 2.6 C: 1.8	1653	2.93	0.27 ± 0.04	41.1

Source from: (Qin, 2019)

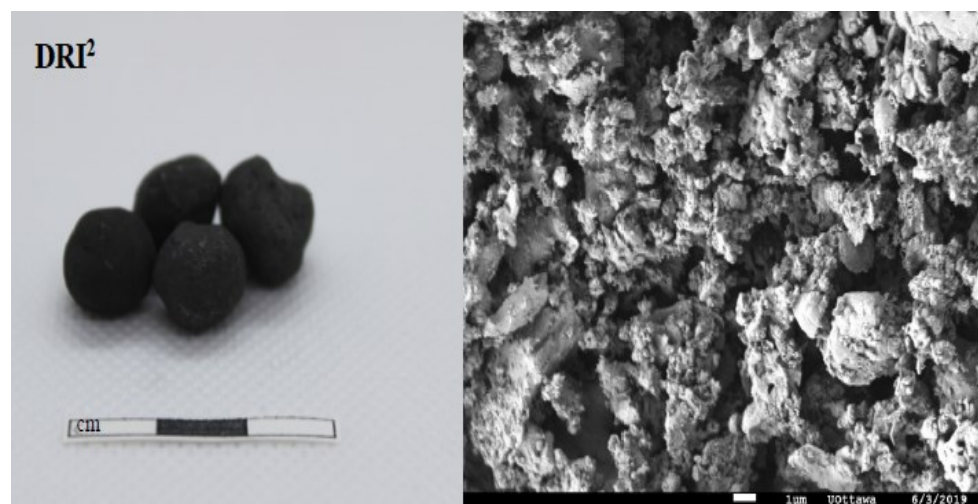


Figure 3.3 DRI media and SEM surface imaging (Qin, 2019)

3.3.3 Synthetic Wastewater Preparation, Dosing and Sample Collection

The synthetic wastewater was prepared by weighing and dissolving appropriate quantities of ≥ 99% ACS certified KH₂PO₄, NH₄Cl and MicroC® 2000 to obtain nominally 25 mg/L ammonium

as N, 4 mg/L phosphorus as P and 25/50 mg/L cBOD₅, respectively. 10L of lagoon effluent from the Alfred Municipal lagoon (Alfred, ON) was added periodically to the feed water to seed the columns. The two containers were used to prepare the synthetic feed of 300 Litres. They were switched every three days, to allow the containers to be consecutively washed and dried to minimize biofilm development and biological activity in the feed container. Multiple head peristaltic pumps were used to dose the columns with continuous loading rates of 6.94 mL/min for the 55 cm/day loading condition and 3.04 mL/min for the 25 cm/day loading condition.

Samples were collected from the influent containers as well as the 1st and 2nd sample points from each column. The pH and temperature were immediately measured, and samples were analyzed for cBOD₅, NH₄⁺, and OPO₄³⁻. Sample collection commenced at a frequency of 2 times/week and was reduced to once a week once nitrification was established.

3.3.4 Water Analytical Methods

The collected samples were kept in the refrigerator at a temperature of 4±2°C. The following Standard Methods (APHA, 2012) were used for analyzing the samples: 5-day cBOD (cBOD₅) as per method 5210 B; NH₄⁺-N according to method 4500-NH₃ D; orthophosphate (PO₄³⁻-P) as per method 4500-P E. The room temperature columns were operated for 135 days with 55 cm/day loading rate and 65 days with loading rate of 25 cm/day. The cold room temperature columns were operated from 60 days with loading rate of 55 cm/day and 65 days with loading rate of 25 cm/day.

The column performance was calculated in terms of concentration (%Removal) as:

$$\%R = \frac{C_{in} - C_{out}}{C_{out}} \times 100 \quad \text{Equation 3.1}$$

where C_{in} and C_{out} were the concentrations of a given contaminant inflow and outflow sample.

3.3.5 Statistical Analysis

A one-way analysis of variance (ANOVA) test was employed to examine significant differences in parameter concentrations. The t-test: Paired Two Sample for Means, was performed to examine significant differences in cBOD_5 and $\text{NH}_4^+\text{-N}$ concentrations.

3.4 Results and Discussion

Columns were operated at both room temperature ($21\pm 2^\circ\text{C}$) and cold temperature ($5\pm 1^\circ\text{C}$) with loading rates 55 cm/day and 25 cm/day. The room temperature columns were operated for 135 and 65 days with loading rates of 55 cm/day and 25 cm/day, respectively. The cold temperature columns were operated for 60 and 65 days with hydraulic loading rates of 55 cm/day and 25 cm/day, respectively. The pH of influent samples for room temperature columns was 7.6 ± 0.4 and pH for cold temperature columns was 7.8 ± 0.3 which is neutral to slightly basic.

The characteristics of the ISF media are critical to the filter performance. The FM and RG had similar Effective Size ($D_{10}= 0.43$ and 0.45 mm) and Coeff. of Uniformity ($C_u=2.6$ and 2.2), respectively, while FM had 4.5% fines compared with virtually no fines in RG. Comparing FM to RG would suggest FM could have more risk of clogging due to higher % Fines, while the smooth surfaces of RG (made from crushed glass) could reduce biofilm development and adhesion, reducing both treatment and clogging. EJ, on the other hand, had a lower Effective Size ($D_{10}=0.18$ mm), higher Coef. Of Uniformity ($C_u=5.8$), and 2.1% fines. This suggests that EJ is more prone to compaction due to a higher C_U value than FM and RG and more prone to clogging than FM and RG due to a lower Effective Size, while the impact of % Fines is between that of FM and RG. Both FM and RG are within the guidelines for ISFs treating primary settled domestic wastewater (D_{10} 0.25-0.75 mm and $C_u<4$; (Crites and Tchobanoglous, 1998)), while EJ is not (D_{10} is lower and C_u is higher).

3.4.1 Filter Clogging

The key operational constraint with ISFs is filter clogging. In this study, challenging conditions representing a “worst-case” scenario of high hydraulic and organic loading rates and continuous dosing were applied to three types of filter media. Filter clogging was defined as standing water observed above the top gravel layer. When a filter became clogged, the filter was drained, and compressed air was applied through the unsaturated sampling port for approximately 15 minutes and kept open for an hour to restore permeability. Clogging events were observed for all EJ filter depths as well as FM45 and FM60 (Table 3.4). After 90 days of continuous operation EJ30 and EJ60 became clogged and were treated with compressed air. EJ45, FM45 and FM60 became clogged toward the end of the 55 cm/d loading condition and were treated with compressed air prior to changing the hydraulic loading to 25 cm/d. FM45 and FM60 as well as EJ60 again became clogged after 30 days operation at the 25 cm/d loading and were treated with compressed air. No clogging issues were observed with FM30 as well as all depths of RG indicating that RG is the superior media from a clogging perspective.

These results reinforce the importance of intermittent dosing, when feasible, as studies by both Salzman et al (2022) and Florrens et al (2009) found long-term removal of COD and NH_4^+ with similar coarse sand filtration at HLRs of 28 cm/d and 70-80 cm/d (with a 7-day rest period following 3-4 days of operation), respectively, while this study observed clogging issues at both 55 and 25 cm/d loading for both sand types. However, crushed recycled glass did not exhibit clogging even at the higher 55 cm/d continuous loading condition, suggesting that this material is advantageous when intermittent dosing cannot be accommodated.

Table 3.4 Clogging/Rejuvenation Events

Filter	Clogging/Rejuvenation (Compressed Air) Dates
EJ30	Day 92 (55 cm/d loading)
EJ45	Day 177 (55 cm/d loading)
EJ60	Day 92 (55 cm/d loading) Day 30 (25 cm/d loading)
FM45	Day 177(55 cm/d loading) Day 30 (25 cm/d loading)
FM60	Day 177(55 cm/d loading) Day 30 (25 cm/d loading)

Leverenz et al. (2009) investigated the clogging phenomenon in intermittent sand filter (ISF) systems, with the sand characteristics used in the ISF study being $D_{10}=0.45$ mm, $C_U=3$, with a depth of 0.15 m. The ISF simulation model evaluated the parameters in the sensitivity analysis, including HLR (0.041-0.163 m/d), influent COD (200-800 mg/L), and dosing frequency (1-48 doses/d). Dosing frequencies 1-8 doses/day achieved steady-state bacterial concentrations under the various loading conditions. Filter clogging is probable in situations that encourage continuous growth instead of the constant state. The current study applied continuous dosing with higher HLR (0.25 and 0.55 m/d) but lower COD influent concentrations (~25-50 mg/L). This suggests that the recycled glass at 0.25 m/d loading achieved steady-state bacterial concentrations, while the two sand media did not and experienced clogging issues.

A study by Grace et al. (2016) considered a single-layer sand filter that was 1 meter thick comparing intermittent 12 doses/day (HLR=0.68 m/d) to constant loading (1.42 m/d). The sand in this filter had a D_{10} of 0.18 mm and a C_U of 2.19. The low organics (DOC = 5.7 mg/L and low solids (Turbidity = 19 NTU) effluent caused both filters to clog after 90 days of operation, with the clogging layer reaching deeper into the sand filters with continuous loading than intermittent

loading. This suggests that that an intermittent loading rate of 0.68 m/d is too high, even with a weak effluent and confirms that the present study loading condition of 0.55 m/d is too high, particularly under continuous loading.

3.4.2 Biological Oxygen Demand (BOD₅)

The cBOD₅ column study results are summarized in Table 3.5 with data presented in Figures 3.4-3.6. At 55 cm/d loading rate and 21°C, FM performed better at 30 and 45 cm depths, compared to 60 cm depth, with 74, 74 and 26 removal efficiency, respectively (Fig. 3.4A). This suggests clogging in the 60 cm column reduced oxygen transfer to the filter more than at the lower column depths. However, variances were relatively large at all depths, indicating that 55 cm/d was too high to achieve stable effluent quality under these experimental conditions. At 55 cm/d loading and 5°C, all three FM filter depths produced consistent but marginal results with only 14-21% removal efficiency, demonstrating a clear temperature effect (Fig. 3.4C). Reducing the hydraulic loading rate but maintaining equivalent organic loading had a positive effect on treatment with the 30 cm depth exhibiting consistently good removal with 87% removal efficiency (Fig. 3.4B). Both 45 and 60 cm depths observed poor removal due to clogging, but provided good treatment after rejuvenation treatment. At 25 cm HLR and 5°C, the FM filters performed better with increasing depth from 61-80% removal efficiency (Fig. 3.4D), which was a significant improvement compared with 55 cm/d HRT ($P < 0.05$), again reinforcing the observation that HLR is more critical than OLR and implies higher HLRs can induce clogging conditions which impede atmospheric oxygen transfer to the filters.

Table 3.5 cBOD₅ Concentration (mg/L) after 14 days of operation (Avg ± SD)

55 cm/day loading

21°C				5°C			
Influent	FM-30	FM-45	FM-60	Inf	FM-30	FM-45	FM-60
19±6	6±5	6±5	14±8	28±2	24±2	22±2	22±2
	EJ-30	EJ-45	EJ-60				
	19±6	11±7	20±5				
	RG-30	RG-45	RG-60				
	12±4	10±7	4±3				

25 cm/day loading

21°C				5°C			
Influent	FM-30	FM-45	FM-60	Influent	FM-30	FM-45	FM-60
39±6	5±4	19±13	19±9	48±3	19±9	15±4	9±4
	EJ-30	EJ-45	EJ-60				
	18±10	27±13	14±7				
	RG-30	RG-45	RG-60				
	17±5	5±1	1±1				

At 55 cm/d loading, EJ exhibited no significant removal at 30 and 60 cm depths ($P>0.05$), while only 42% average removal was observed at 45 cm depth and effectively no removal during the last 20 days of operation (Fig 3.5A). EJ performance improved at 25 cm/d loading with 31-64% removal efficiency but with relatively high variances (Fig. 3.5B).

RG showed good results at both HLRs with removal efficiency increasing with filter depth from 37 to 79% at 55 cm/d loading rate and 56 to 97% at 25 cm/d loading rate (Fig. 3.6). Stable and low effluent quality was observed at 60 cm depth at 55 cm/d loading (4 ± 3 mg/L) as well as at 45 cm depth at 25 cm/d loading (5 ± 1 mg/L) and 60 cm depth at 25 cm/d loading (1 ± 1 mg/L) (Table 3.4).

Reducing the HLR from 55 to 25 cm/d at equivalent OLRs had a significant effect on removal efficiencies across all filter medias, media depths and temperatures ($P<0.05$). This indicates that HLR has a significant effect on ISF performance and clogging at constant OLR. The relatively poor performance of EJ at all depths and hydraulic loading rates can be due to the combination of a smaller D_{10} and higher Cu ($D_{10}=0.18\text{mm}$, $Cu = 5.8$) resulting in compaction and filter clogging,

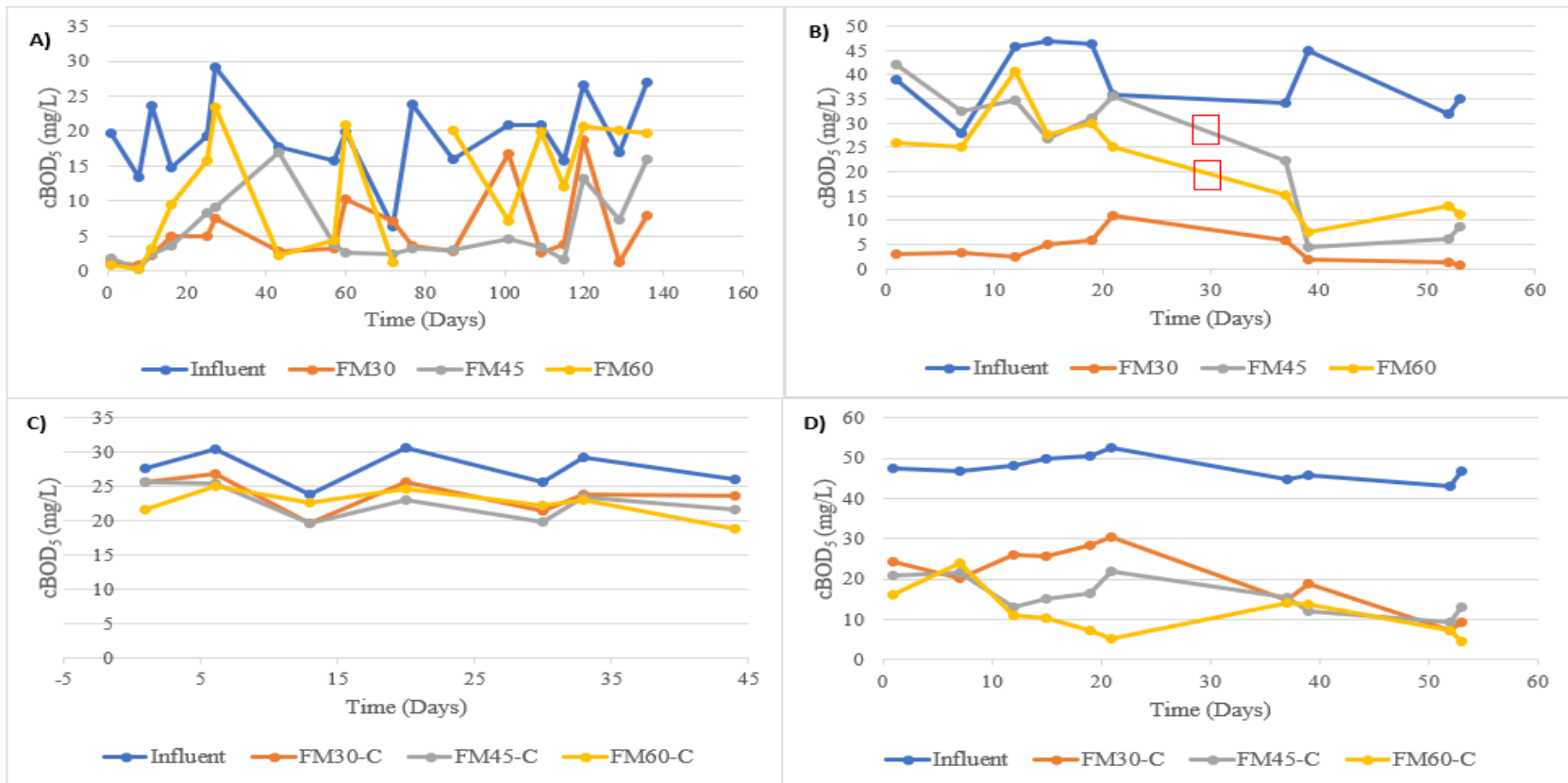
cutting off oxygen transfer and reducing BOD oxidation. FM exhibited better BOD removal than RG at 30 cm depth, but poorer removal at 60 cm depth ($P < 0.05$). FM and RG had respectively similar D_{10} (0.43 and 0.45mm) and Cu (2.6 and 2.2) but different % Fines (4.5 versus 0.0 %), as well as different surface roughness (sand versus glass). This suggests that the higher % Fines and increased surface roughness of FM increased retention time and likely biofilm development, resulting in improved treatment at 30 cm depth, while also fostering clogging, which was observed at higher depths, and reduced treatment efficiency. RG, with no fines and smooth particle surfaces did not experience clogging effects at either hydraulic loading rate and demonstrated a clear improvement in BOD removal with increased filter depth due to longer liquid retention times and contact with aerobic biofilms without clogging observed in the filter. This produced consistent and very good effluent quality at 60 cm depth at 55 cm/d HLR and both 45 and 60 cm depths at 25 cm/day HLR.

The effect of media depth on $cBOD_5$ effluent concentration is presented in Figure 3.7A. FM experienced clogging at 45 and 60 cm depths and is reflected in poorer treatment compared to 30 cm depth, while EJ exhibited better treatment at 60 cm depth, although this media experienced clogging issues at all depths. The RG columns did not exhibit clogging and clearly demonstrated the effect of increasing depth on reducing $cBOD_5$ effluent concentration with significant differences observed between each depth ($P < 0.05$). RG60 provided the best overall treatment of $cBOD_5$. The effect of media type on $cBOD_5$ effluent concentration is presented in Figure 3.7B at three depths. FM provided superior treatment at 30 cm depth, while RG provided superior treatment at both 45 and 60 cm depths ($P < 0.05$). This suggests that the media surface area and % fines of FM at 30 cm provided good conditions for biofilm development without clogging, while

insufficient biofilm had developed in RG at 30 cm; however, at 45 and 60 cm clogging issues impacted FM and EJ, while increased removal without clogging was observed with RG.

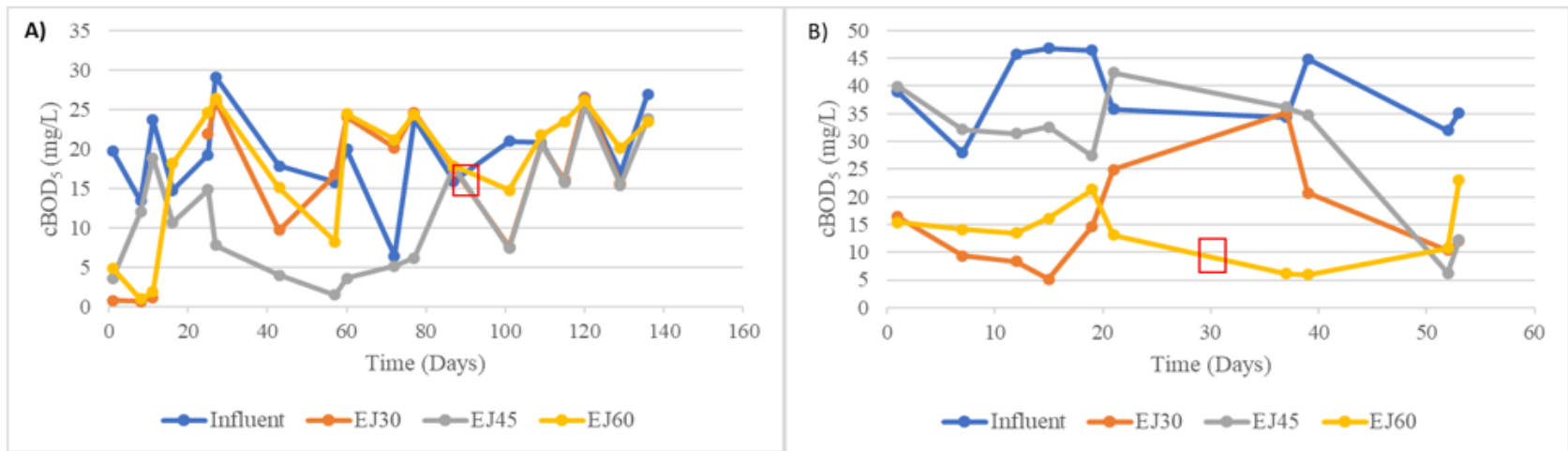
The effect of hydraulic loading rate at constant organic loading rate is compared in Figure 3.8 for the RG columns, where clogging was not a confounding factor. The organic reduction rate increased with filter depth and was higher at a 25 cm/d hydraulic loading rate than at 55 cm/d hydraulic loading rate across all depths. The RG at 25 cm/day was significant ($P < 0.05$) over RG at 55 cm/day across all depths. A lower HLR should result in higher liquid retention time within the filter, resulting in higher removal rates. The difference between the two HLRs diminishes at 60 cm depth, as increased filter depth provides sufficient HRT at both HLRs to achieve high organic removal efficiencies.

According to Gherairi et al. (2015), a comparative study between two granular materials, crushed glass and sand, with a 60 cm depth loaded intermittently (HLR 10 cm/d). The results showed that sand was slightly better than recycled glass, which is 96 and 93 %, respectively. Ramezaniapour et al. (2023) studied the treatment of septic tank discharge using crushed glass and sand media with a depth of 60 cm, which was loaded intermittently (HLR 5 cm/day) and performed similarly for both media in BOD removal (94 %). This study, with continuously loading, observed clogging in the sand media, but no clogging and 96% removal efficiency with a 60 cm of crushed glass at 25 cm/d loading rate. Comparing to the literature and to the sand media, this suggests that a 25 cm/d loading is approaching an optimum value for the crushed glass media under the conditions tested.



* Declogging action on FM45 & FM60

Figure 3.4 FM Inlet and Outlet of cBOD₅ Concentrations with Time (A – 55 cm/d, 10.5 g BOD/m²·d, 21°C; B - 25 cm/d, 9.8 g BOD/m²·d, 21°C; C – 55 cm/d, 15.4 g BOD/ m²·d, 5°C; D – 25 cm/d, 12.0 g BOD/ m²·d, 5°C)



* Declogging action on EJ30 & EJ60

Figure 3.5 EJ Inlet and Outlet of cBOD₅ Concentrations with Time (A – 55 cm/d, 10.5 g BOD/m²·d, 21°C; B - 25 cm/d, 9.8 g BOD/m²·d, 21°C)

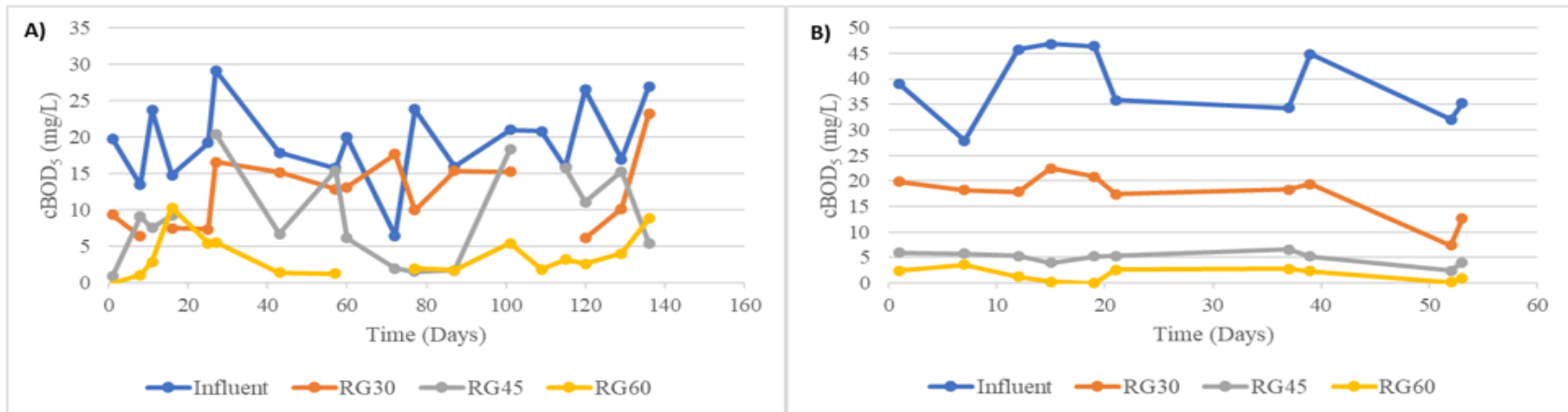


Figure 3.6 RG Inlet and Outlet of cBOD₅ Concentrations with Time (A – 55 cm/d, 10.5g BOD/m²·d, 21°C; B - 25 cm/d, 9.8 g BOD/m²·d, 21°C)

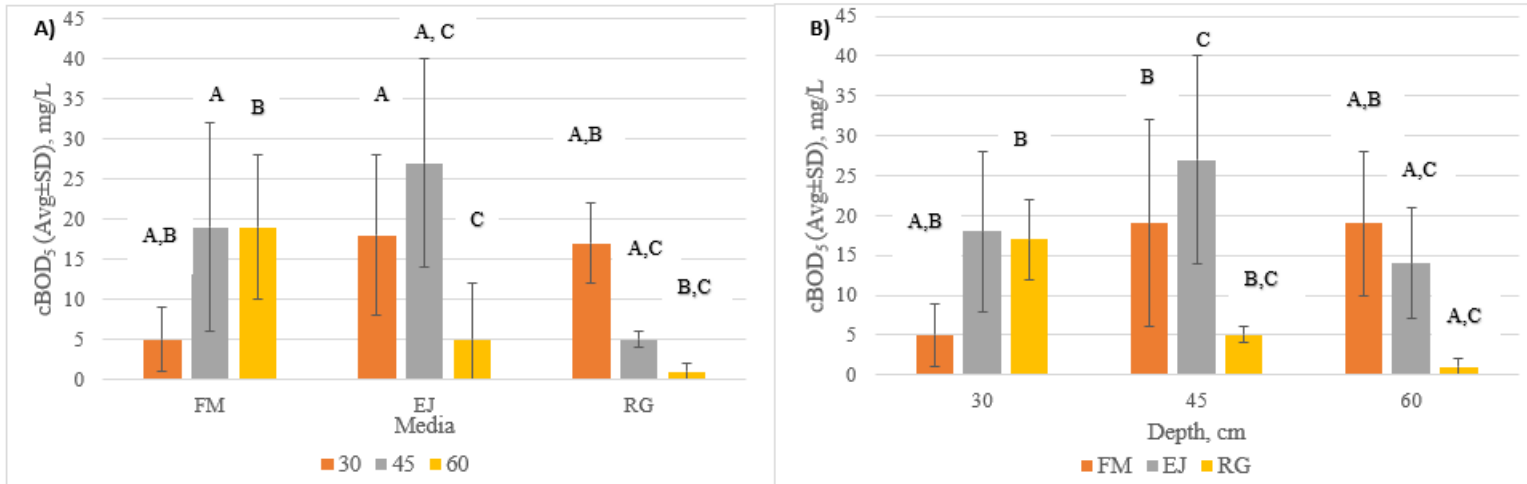


Figure 3.7 cBOD₅ Concentrations at 25 cm/d loading rate (A – Effect of media depth; B – Effect of media type at same depth)(matching pairs represent significant differences using a Paired-T test (P<0.05))

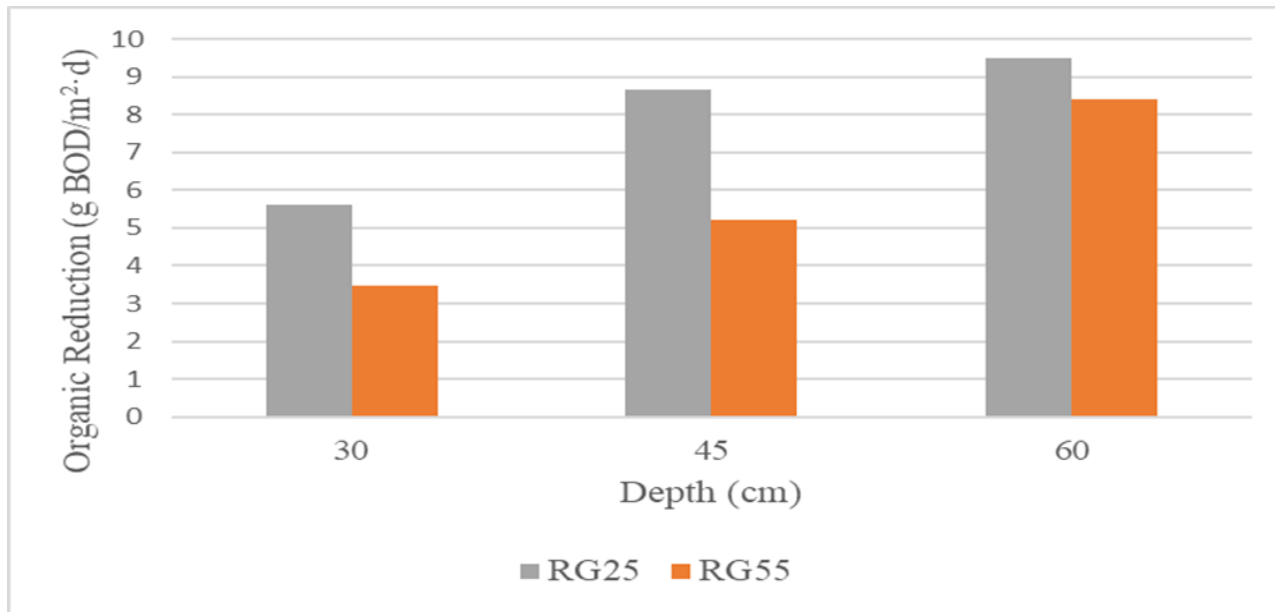


Figure 3.8 Column Study of RG Organic reduction (g BOD/ m²·d) at 25 and 55 cm/d loading rate

3.4.3 Ammonium Nitrogen

Ammonium reduction was only considered in the 25 cm/d loaded columns as the 55 cm/d columns did not achieve consistent BOD removal. The FM columns at 21°C (Fig. 3.9A) demonstrated very similar trends between NH_4^+ and BOD removal. Consistent and excellent nitrification (92%) was observed at the lowest depth (30 cm), coinciding with no observed clogging, while both 45 and 60 cm depths exhibited limited nitrification until a filter rejuvenation action was initiated, after which nitrification increased to 62 and 65%, respectively (Table 3.6). The FM filters demonstrated limited nitrification at 5°C of 17-26% with no clear impact of filter depth on performance (Fig. 3.9B). This demonstrates the strong temperature dependence of nitrifying bacteria.

EJ columns showed nitrification decreasing with increasing filter depth from 83 to 63% (Fig. 3.10A). This suggests a relationship between filter depth and filter clogging, which in turn affects oxygen transfer and nitrification. As with BOD, RG demonstrated very consistent results at the three depths with the lowest nitrification efficiency observed at the 30 cm depth (31%) followed by 67% at 60 cm depth and 91% at 45 cm depth (Fig. 3.10B). As RG was the only material that did not exhibit clogging tendencies, these results suggest that increased depth provides more biofilm contact and liquid retention time to nitrify the effluent and that RG requires an optimum 45 cm depth for nitrification at the loading conditions of this experiment, although better BOD reduction was observed at 60 cm depth. The much higher nitrification efficiencies observed with FM compared with RG at 30 cm depth, suggest that the combination of increased fines and surface roughness of the FM media compared with recycled glass supported increased biofilm development and liquid retention time in FM without clogging occurring.

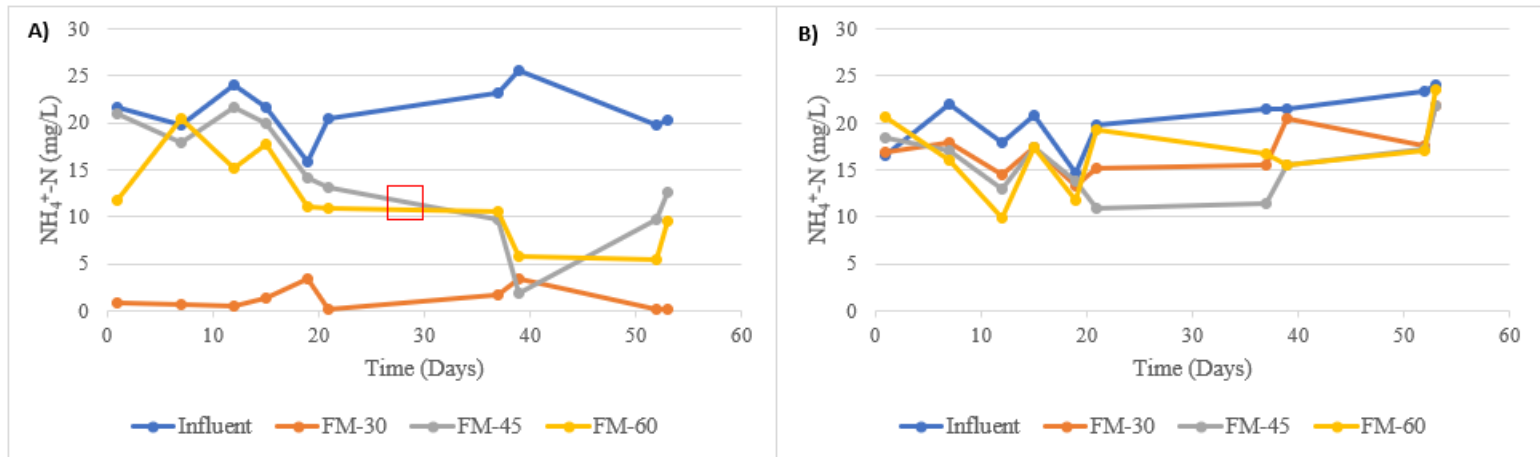
The effect of media depth on $\text{NH}_4^+\text{-N}$ effluent concentration is presented in Figure 3.11A. FM experienced clogging at 45 and 60 cm depths and is reflected in poorer treatment compared to 30 cm depth ($P < 0.05$). EJ also exhibited significantly higher nitrification at 30 cm depth ($P < 0.05$), although this media experienced clogging issues at all depths. This suggests increased liquid retention times increased clogging and limited oxygen transfer at 45 and 60 cm depths in both FM and EJ columns. The RG columns did not exhibit clogging and exhibited the optimum ammonium removal at 45 cm depth ($P < 0.05$), suggesting that higher liquid retention at 60 cm depth impeded oxygen transfer to the filter, while 30 cm depth did not provide sufficient liquid retention time for nitrification. The effect of media type on $\text{NH}_4^+\text{-N}$ effluent concentration is presented in Figure 3.11B at three depths. FM and EJ provided superior treatment at 30 cm depth, while RG provided superior treatment at 45 cm depths ($P < 0.05$). This suggests that the media surface area and % fines of FM at 30 cm provided good conditions for biofilm development without clogging, while insufficient biofilm had developed in RG at 30 cm; however, at 45 cm clogging issues impacted FM and EJ, while increased removal without clogging was observed with RG, and finally at 60 cm depths, increased liquid retention reduced oxygen transfer and nitrification at all 3 depths.

Healy et al (2010) compared sand, soil, and crushed glass for polishing domestic synthetic wastewater with influent $\text{NH}_4^+\text{-N}$ concentrations of 5.1 ± 3.4 mg/L and observed complete nitrification at both 38 and 65 cm depths with all media types with an HLR of 10 cm/d loaded intermittently. This compares to the current study, where a 45 cm filter of recycled glass continuously loaded at 25 cm/d achieved a 91% removal efficiency with 21.0 ± 3.0 mg/L $\text{NH}_4^+\text{-N}$ influent concentration, indicating that the present study effectively treated ammonium at a relatively high loading rate under continuous loading conditions.

Table 3.6 NH_4^+ -N Concentration (mg/L) after 14 days of operation (Avg \pm SD)

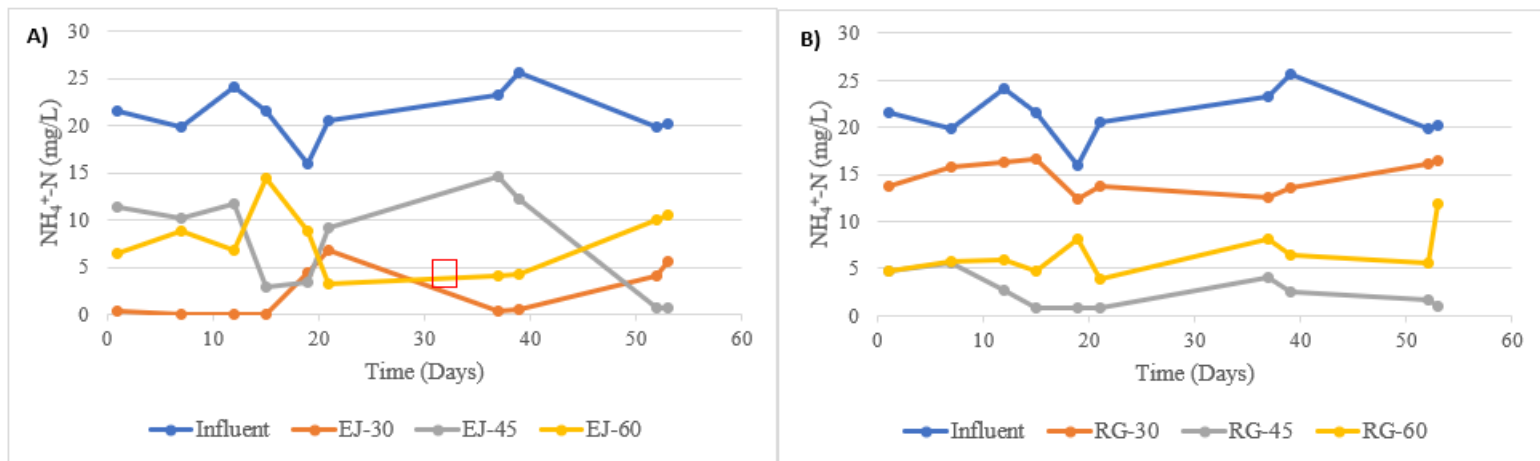
25 cm/day loading

21°C				5°C			
Influent	FM-30	FM-45	FM-60	Influent	FM-30	FM-45	FM-60
21.0 \pm 3.0	1.7 \pm 1.5	11.6 \pm 5.5	10.1 \pm 4.1	20.8 \pm 3.1	17.3 \pm 3.0	15.4 \pm 3.8	17.3 \pm 3.6
	EJ-30	EJ-45	EJ-60				
	3.5 \pm 2.8	6.2 \pm 5.7	7.9 \pm 4.2				
	RG-30	RG-45	RG-60				
	14.5 \pm 1.9	1.8 \pm 1.3	7.0 \pm 2.7				



* Declogging action on FM45 & FM60

Figure 3.9 FM Inlet and Outlet $\text{NH}_4^+\text{-N}$ Concentrations with Time (A - 25 cm/d, 9.8 g BOD/ $\text{m}^2\cdot\text{d}$, 21°C; B - 25 cm/d, 12.0 g BOD/ $\text{m}^2\cdot\text{d}$, 5°C)



* Declogging action on EJ60

Figure 3.10 Inlet and Outlet $\text{NH}_4^+\text{-N}$ Concentrations with Time (25 cm/d, 9.8 g BOD/ $\text{m}^2\cdot\text{d}$, 21°C) (A - EJ; B - RG)

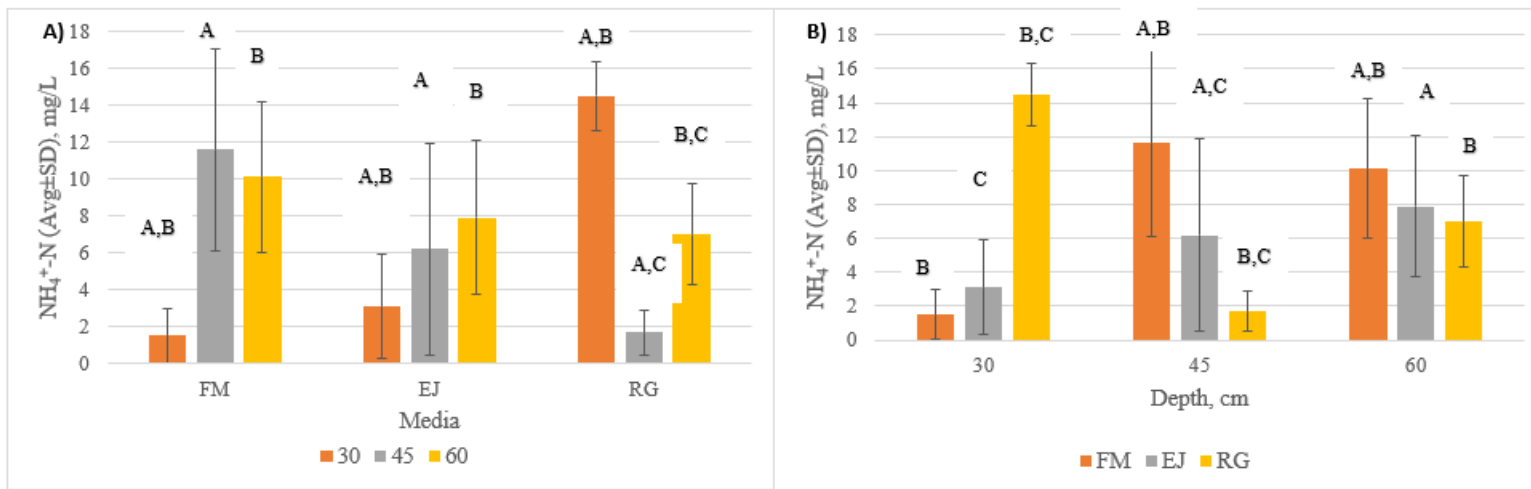


Figure 3.11 $\text{NH}_4^+\text{-N}$ Concentrations at 25 cm/d loading rate (A – Effect of media depth; B – Effect of media type at same depth)(matching pairs represent significant differences using a Paired-T test ($P < 0.05$))

3.4.4 Soluble Reactive Phosphorus

The two treatment effects studied were the effect of DRI depth/HRT on SRP removal assuming that sorption capacity was not reached and the impact of organic fouling on SRP removal. It was hypothesized that temperature would have no significant effect on SRP removal as the sorption mechanisms are not thought to be strongly temperature dependent. The effect of the overlying media could also play a role in SRP reduction through adsorption to any cations present in the media.

The FM/DRI columns exhibited no significant differences in outlet SRP concentrations at 21 and 5°C ($P>0.05$) (Table 3.7), indicating that temperature does not play a significant role in the removal mechanisms. With the exception of FM-10 outlet concentration at 25 cm/d loading (SRP=1.2±0.7 mg/L), all average outlet concentrations varied between 0.3 and 0.7 mg/L with no effect of DRI depth on SRP removal and suggests average outlet concentrations of below 1.0 mg/L are achievable under the conditions tested. Contrarily, both the EJ/DRI and RG/DRI columns exhibited effects of DRI depth and HLR with the lowest outlet concentrations of 0.3±0.2 and 0.4±0.2 mg/L, respectively, observed with the lower 25 cm/d loading rate and highest DRI depth of 15 cm and HRT of 5.9 hrs. The time series data for FM are presented in Figure 3.13, while data for EJ and RG are presented in Figure 3.14.

The effect of DRI HRT and overlying unsaturated media can be observed in the Figure 3.12. The RG curve shows a strong trend of increasing SRP removal with HRT ($R^2=0.98$). This can be attributed to the DRI, as it is unlikely that the overlying crushed glass media would contribute to phosphate removal. A smaller effect of HRT on SRP removal was observed with EJ, indicating a combined effect of the overlying sand media ($R^2=0.92$). No effect of HRT was observed with FM ($R^2=0.04$), suggesting a strong effect of the overlying sand media. However, values from all media

combinations converged at an HRT of 5.9 hrs and 15 cm DRI depth with $89\pm 3\%$ removal, indicating optimum DRI design parameters.

The impact of organic loading on the columns on DRI performance appears to be minimal as optimum removal efficiencies, and HRT is comparable to the minimum 4 hr HRT and $> 80\%$ removal, as reported by Qin (2019), with columns loaded solely with phosphate solution.

Table 3.8 presents the P retained in the unsaturated media/DRI columns after both 55 and 25 cm/d loading periods. The P retained in the RG/DRI columns can be attributed largely to the DRI, as it is likely that glass will adsorb soluble phosphorus. The P retention ranged from 2.3 to 3.8 mg P/gm DRI, which is considerably higher than the 1.2 ± 0.4 mg P/gm media as reported by Qin (2019) study under 200 ppm initial concentration jar tests. These results further support the long-term application potential of DRI as a passive P removal filter. The FM and EJ columns reported ranged of P retention from 2.5-7.3 mg P/g DRI, but these values include P retention in sand media.

Sun et al (2023) utilized the sponge iron for phosphorus removal from simulated secondary effluent with influent P concentration ranging from 2.5-5 mg/L. Removal efficiency increased from 76 to 95% as HRT increased from 1-1.5 hrs to 4 hrs. These results indicate that a 4 hr HRT is optimum for P removal. These are similar findings to Qin (2019) and further support the conclusions of the present study, which found 88% removal of SRP from the RG/DRI column with a 15 cm DRI layer and a 5.9 hr HRT.

Table 3.7 SRP Concentration (mg/L) after 14 days of operation (Avg ± SD)

55 cm/day loading				5°C			
21°C							
Influent	FM-5	FM-10	FM-15	Inf	FM-5	FM-10	FM-15
4.0±0.8	0.3±0.5	0.7±0.5	0.3±0.5	3.3±0.6	0.4±0.3	0.3±0.3	0.5±0.4
	EJ-5	EJ-10	EJ-15				
	1.2±1.0	0.8±0.5	0.6±0.7				
	RG-5	RG-10	RG-15				
	2.0±2.0	1.2±0.6	1.1±0.5				
25 cm/day loading				5°C			
21°C							
Influent	FM-5	FM-10	FM-15	Influent	FM-5	FM-10	FM-15
3.3±0.3	0.6±0.6	1.2±0.7	0.5±0.1	4.0±0.3	0.6±0.3	0.6±0.2	0.5±0.1
	EJ-5	EJ-10	EJ-15				
	1.6±1.8	0.5±0.4	0.3±0.2				
	RG-5	RG-10	RG-15				
	2.5±1.4	0.6±0.2	0.4±0.2				

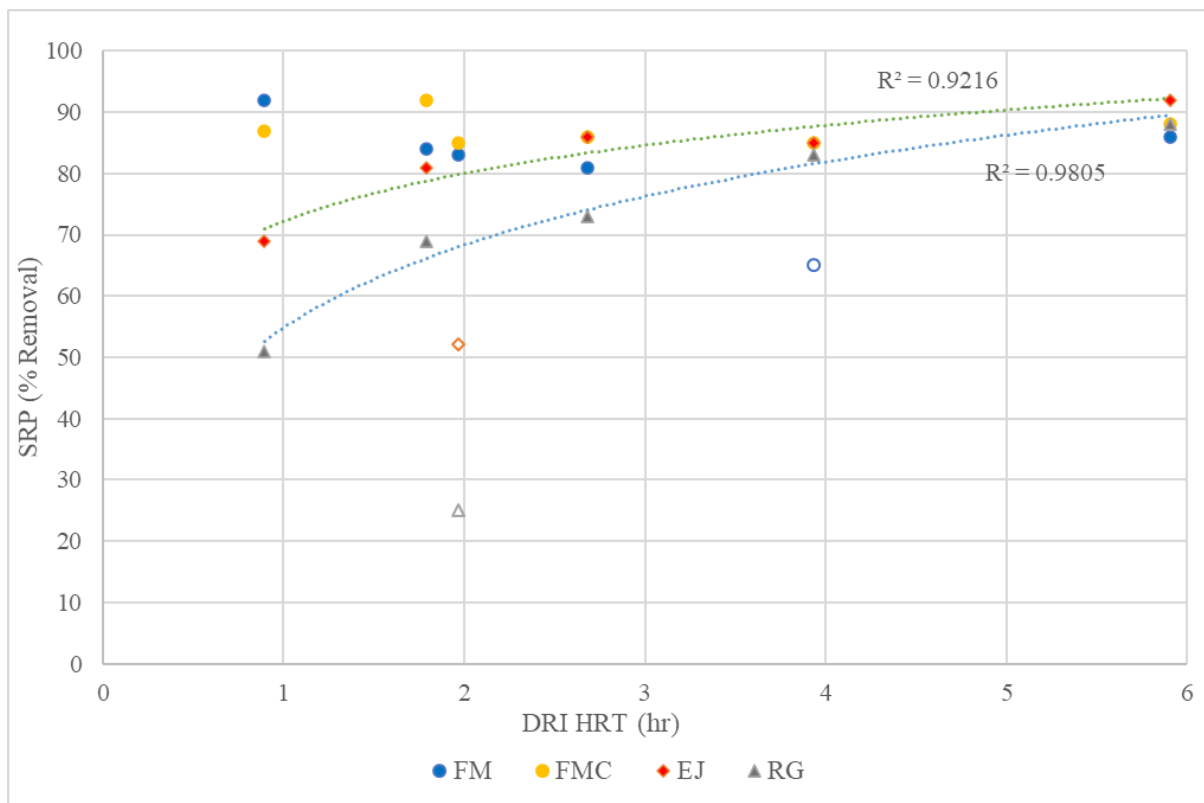


Figure 3.12 SRP Removal Efficiency with DRI HRT (FM, EJ and RG at 21°C; FMC at 5°C). Unfilled data points represent outliers where short-circuiting may have contributed to reduced removal efficiencies.

Table 3.8 Total P retained in unsaturated media/DRI filters at 21°C at the end of after 200 days of filter operation following 55 and 25 cm/d loading periods.

Media	DRI Depths, cm	Total P retained mg P/g DRI
FM	15	2.5
	10	3.3
	5	7.3
EJ	5	5.4
	10	3.3
	15	2.6
RG	5	3.8
	10	2.8
	15	2.3

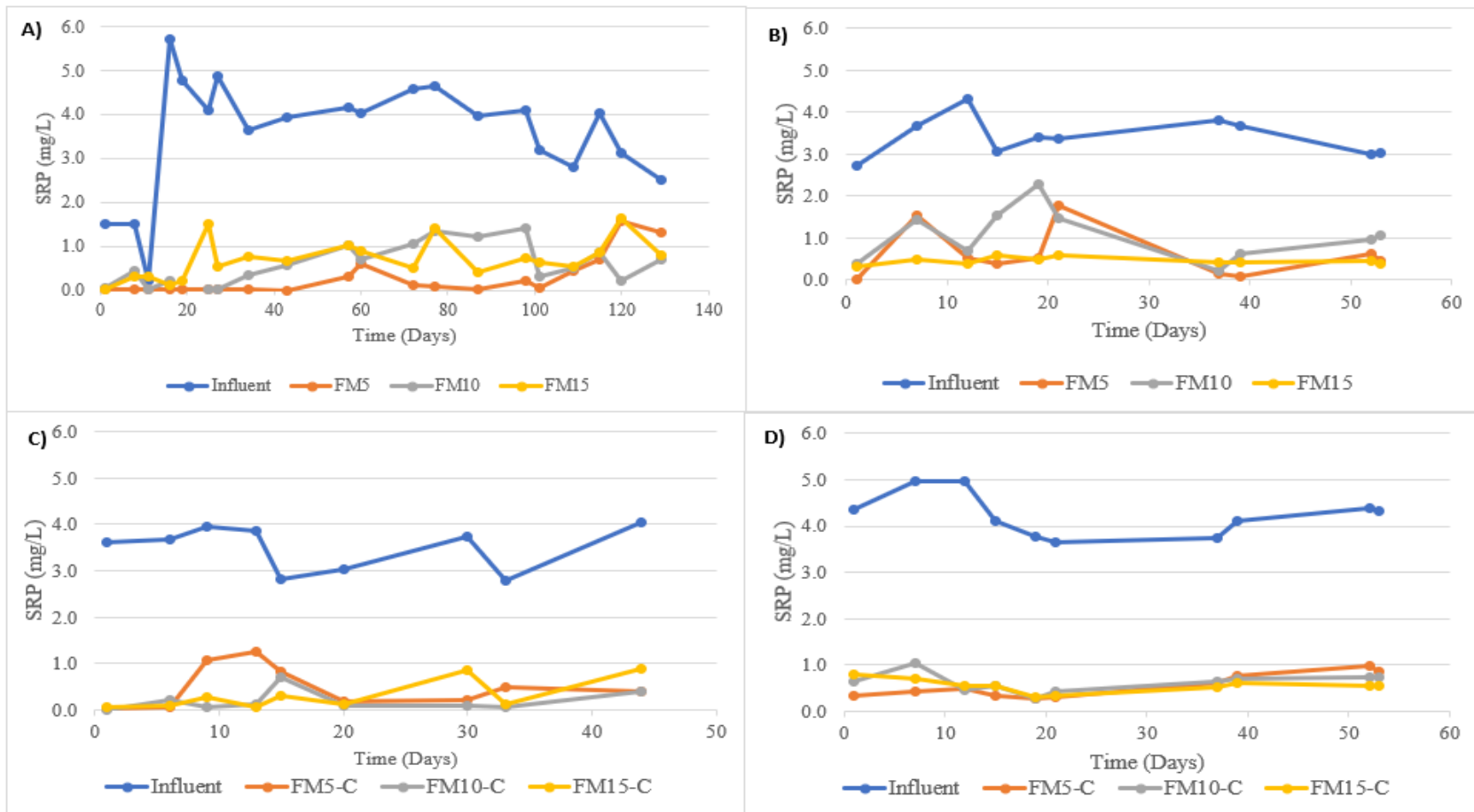


Figure 3.13 FM Inlet and Outlet SRP Concentration with Time (A – 55 cm/d, HRT 0.9-2.7 hrs, 21°C; B - 25 cm/d, HRT 2.0-5.9 hrs, 21°C; C – 55 cm/d, HRT 0.9-2.7 hrs, 5°C; D – 25 cm/d, HRT 2.0-5.9 hrs, 5°C)

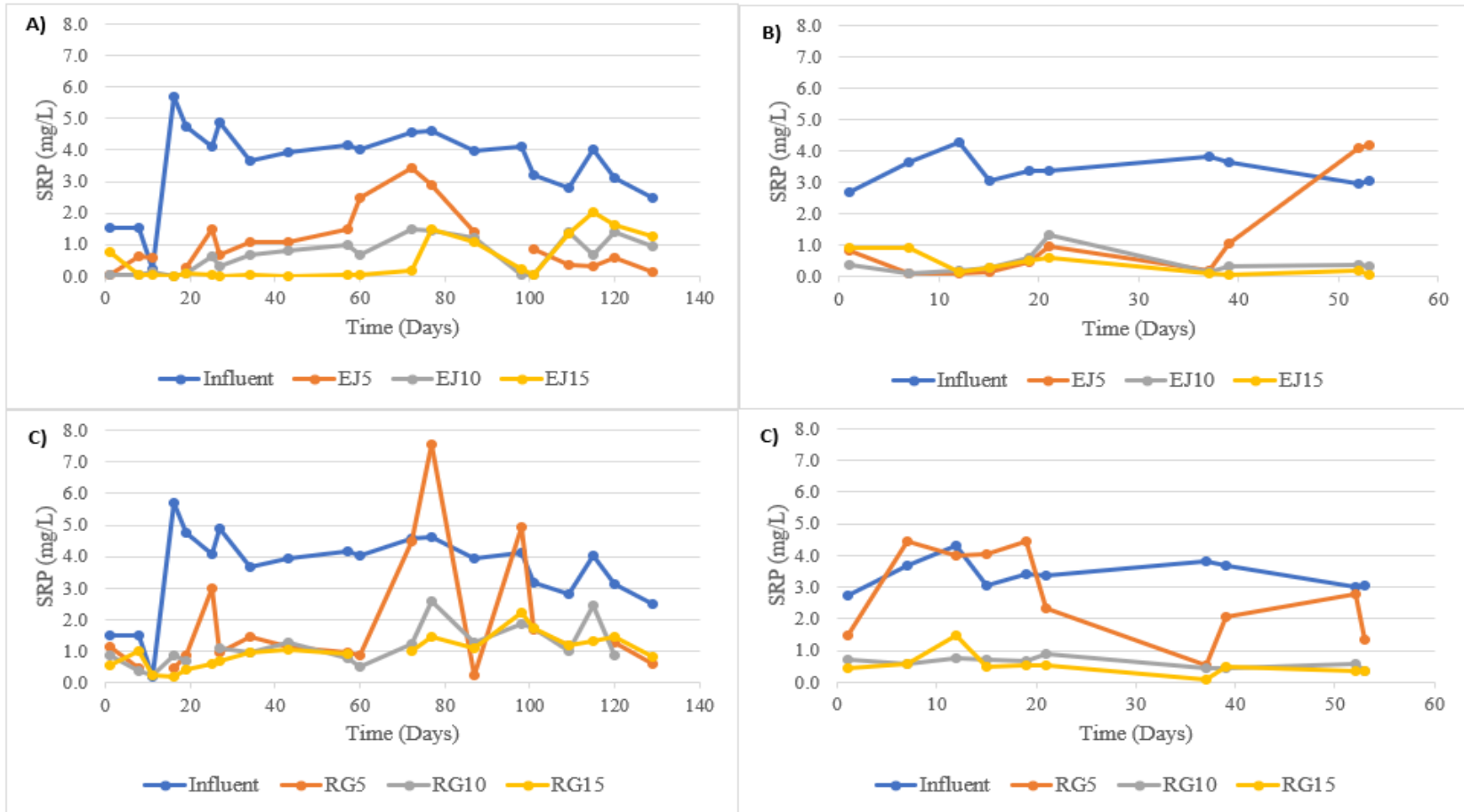


Figure 3.14 Inlet and Outlet SRP Concentration with Time (A – EJ, 55 cm/d, HRT 0.9-2.7 hrs, 21°C; B – EJ, 25 cm/d, HRT 2.0-5.9 hrs, 21°C; C – RG, 55 cm/d, HRT 0.9-2.7 hrs, 21°C; D – RG, 25 cm/d, HRT 2.0-5.9 hrs, 21°C)

3.5 Conclusion

Two coarse sand media and crushed recycled glass were compared under conditions of continuous dosing at hydraulic loading rates of 55 and 25 cm/d. The sand media ($D_{10} = 0.43$ mm, $CU = 2.6$, %fines = 4.5; $D_{10} = 0.18$ mm, $CU = 5.8$, %fines = 2.1) observed biofilm clogging at both loading rates, while the crushed glass ($D_{10} = 0.45$ mm, $CU = 2.2$, %fines = 0.04) did not. This suggests that for conditions where intermittent dosing is not feasible, crushed glass can provide an appropriate filter media to polish lagoon effluent for BOD and NH_4^+ . The optimum crushed glass filter depth was found to be 45 cm at 25 cm/d loading rate, reducing $cBOD_5$ and NH_4^+-N concentrations by 87 and 93%, respectively. With all unsaturated media types and depths, a 15 cm layer of saturated DRI was effective at reducing soluble phosphorus by 89%, with no apparent impact of biofouling on removal efficiency.

This study also demonstrated that the hydraulic loading rate plays an independent role to the organic loading rate, with $cBOD_5$ treatment reduced at increased HLR under conditions of constant organic loading.

The proposed passive filter for lagoon effluent polishing, where intermittent dosing is not feasible, consists of a 45 cm deep unsaturated trickling filter comprised of crushed glass ($D_{10}=0.43$ mm) above a 15 cm saturated layer of 12.5 mm dia. DRI (5.9 HRT) with a design hydraulic loading rate of 25 cm/d.

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CHAPTER 4

4.0 Development of a Passive Filter for Polishing Municipal Lagoon Effluent – Field-Scale Study

4.1 Abstract

A passive filter comprising an unsaturated coarse sand or crushed recycled glass layer and a saturated layer of Direct Reduced Iron (DRI) was evaluated to polish municipal lagoon effluent in a field trial. At a loading rate of 29 cm/d over a 7-month operating season, the filters were successful at polishing a low carbon municipal lagoon effluent with no signs of clogging. Coarse sand media performed better than crushed recycled glass with similar D_{10} in terms of TSS removal (57 vs 28%), COD removal (39 vs 24%) and NH_4^+ removal (68 vs 42%). Average TP concentrations were reduced to below 0.2 mg/L and average SRP concentration to below 0.04 mg/L with DRI depths ranging from 5-15 cm. A recommended design would include a 0.45 m unsaturated coarse sand layer over a 0.15 m saturated DRI layer (12.5 mm dia.) at a loading rate of 29 cm/d.

Keywords: Municipal lagoon effluent polishing, intermittent sand filters, crushed recycled glass, direct reduced iron, phosphorus, ammonium.

4.2 Introduction

Lagoon-based sewage treatment systems are the most common type of municipal wastewater treatment technology in Canada with over 1000 systems in operation (Environment and Climate Change Canada, 2017). Federal regulation stipulates maximum effluent concentrations of 25 mg/L for TSS and cBOD_5 and 1.25 mg/L NH_3 at $15^\circ\text{C} \pm 1^\circ\text{C}$ (Government of Canada, 2012) , while Provincial discharge criteria are site specific, can be more stringent than the federal criteria and

include phosphorus. The presence of algae in the effluent during warm months can increase TSS to above 30 mg/L (USEPA, 2002). Cold weather and ice cover inhibits nitrification during winter and early spring, resulting in NH₃ exceedances. Additionally, it is a challenge for lagoon systems to meet increasingly stringent total phosphorus (TP) limits of less than 1.0 mg/L with conventional coagulation practices (Federation of Canadian Municipalities, 2004). Add-on polishing technologies can provide cost-effective means of addressing these issues.

Intermittent Sand Filters (ISF) have been demonstrated to effectively polish lagoon effluent for BOD, TSS and NH₄⁺ at hydraulic loading rates (HLRs) and dosing frequencies varying from 0.1 m/d with 24 doses/day (Healy et al, 2010) to 0.28 m/d with 14 doses/d (Salzman et al, 2022) to 0.70-0.80 m/d with 30-32 doses/d, albeit with 3-4 days loading followed by a 7-d rest period (Torrens et al, 2009) with media depths of between 0.4 to 1.0 m. In the studies by Salzman et al (2022) and Healy et al (2010), coarse sand was also compared to crushed glass, with somewhat lower nitrification rates observed but with higher crushed glass D₁₀ values.

Various media with high cation content have been studied for passive phosphorus removal including calcium-based materials such as waste steel slag (Drizo et al, 2006; Cameron et al, 2003), aluminum-based materials such as activated aluminum oxide (Xie et al, 2015) and many iron based materials (Zhu et al, 2024). Direct Reduced Iron (DRI) has been shown to be a promising media to remove phosphorus from effluent streams (Qin, 2019). DRI is an intermediate product in the steel-making industry produced from the direct reduction of iron oxide to high content metallic iron pellets with a porous media (Stephenson and Smailer, 1980). Qin (2019) proposes an optimum DRI diameter of 12.5 mm to maximize P removal while minimizing risk of clogging. DRI has an equilibrium sorption capacity of 1.2 ±0.4 mg P/g DRI (at 200 mg/L initial P) and minimum 4 hr HRT to remove >80% of 4 mg/L effluent. The sorption capacity is similar to other active media

including blast-furnace slag (Han et al., 2016), which has been studied extensively. The use of DRI has not been evaluated at field-scale treating municipal lagoon effluent.

The goal of this study is to develop a passive filter to polish municipal lagoon effluent consisting of an unsaturated media layer to remove BOD, TSS and NH_4^+ and a saturated media layer to remove P. The first objective of the study is to compare two coarse sand media utilised in the Ontario onsite wastewater industry to crushed recycled glass with similar D_{10} values for the polishing of COD, TSS and NH_4^+ . It is hypothesised that the recycled glass will have less clogging potential than the sand media due to lower biofilm development on smooth surfaces as well as fewer fines, however, with potentially lower treatment efficiencies. The second objective is to evaluate DRI media for total phosphorus removal under field conditions.

4.3 Material and Methods

4.3.1 Site description and operation

The pilot filters are located at the municipal lagoon in the Town of Alfred, Ontario, Canada, approximately 70 km east of Ottawa (approx. population 1350) (45°32'36" N, 74°51'32" W). The Town's wastewater is treated in a two-cell facultative controlled discharge lagoon that discharges once a year in the spring to a small stream, which flows into the Ottawa River. The lagoon cells were built in the early 1970s.

A pump dock was constructed to access the lagoon effluent (Fig. 4.2). A 0.5HP submersible sewage pump transferred effluent to a 200L plastic barrel where a 0.3HP effluent pump dosed the three filters through 1 inch PVC piping. Both pumps were controlled by a timer.

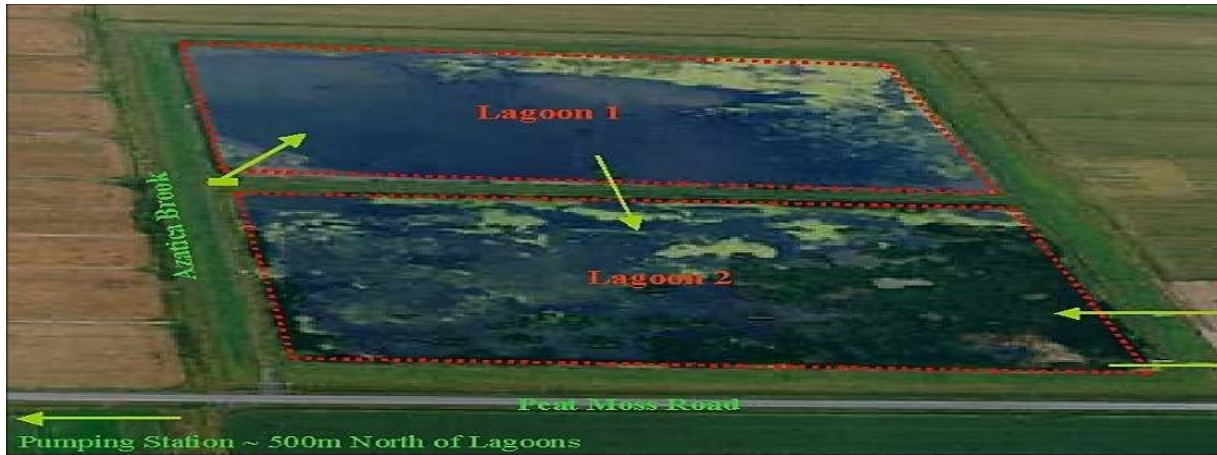


Figure 4.1 Aerial photograph of Alfred and Municipal Sewage Lagoon



Figure 4.2 Pump Dock and Pilot Filters at Alfred Municipal Lagoon

The three pilot filters were constructed in 1 m³ plastic totes and consist from top to bottom of:

- 1-L tipping bucket to evenly distribute the municipal lagoon effluent
- 10 cm (1.2 cm dia.) clean gravel distribution layer
- 45 cm unsaturated media layer (FM, EJ & RG)
- 5 cm (1.2 cm dia.) clean gravel transition layer
- 5, 10 or 15 cm of saturated media layer (1.25 cm dia. DRI)
- 10 cm (3.8 cm dia.) clean gravel drainage layer

Three ISF media were selected for this study. Two represent coarse sand specifications utilised for high-rate onsite wastewater treatment applications in Ontario (Filter Media Sand (FM) (OBC s. 8.7.5) (Ontario Ministry of Municipal Affairs and Housing, 2012) and Eljen Inc. specified sand (ES) (www.eljen.com). These were acquired from Brissenden Pit (Mountain, ON). The crushed recycled glass (RG) product was obtained from Enviro Grit-Abrasives (Abbotsford, BC). Particle size analysis of the ISF media was conducted following ASTM D422 and is presented in Table 4.1. The DRI media was acquired from ArcelorMittal’s direct reduction plant in Contrecoeur, Québec with a nominal diameter of 12.5 mm and presented in Table 4.2. Figure 4.3 depicts the porous characteristics of DRI, as observed through scanning electron microscopy imaging of the surface of DRI pellets (Qin, 2019).

Table 4.1 ISF Media Specifications

ISF Media	Effective size (D ₁₀) mm	U _c (D ₆₀ /D ₁₀)	% Fines (<0.075mm)
FM	0.43	2.6	4.5
EJ	0.18	5.8	2.1
RG	0.45	2.2	0.04

Table 4.2 DRI characteristics

Elemental Analysis (%)	Bed density (kg/m ³)	Density (g/cm ³)	Specific area (m ² /g) (Avg. ± SD)	Bed porosity (%)
Fe: 92.2 O: 2.6 C: 1.8	1653	2.93	0.27 ± 0.04	41.1

Source from: (Qin, 2019)

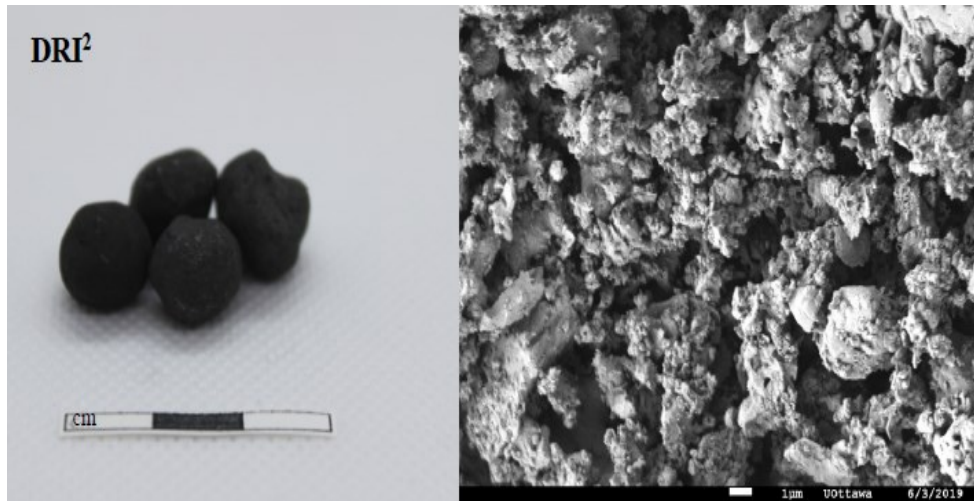


Figure 4.3 DRI media and SEM surface imaging (Qin, 2019)

The filters were time dosed with lagoon effluent into 1L/tip tipping buckets to distribute the effluent on the filter surfaces evenly. The hydraulic loading rate was 29 cm/day with a frequency of 48 doses per day (a dose every 30 minutes). This resulted in hydraulic retention times in the saturated DRI media of 1.9, 3.8 and 5.7 hrs for the 5, 10 and 15 cm DRI layers, respectively. Due to the low ammonium concentrations in the lagoon effluent, ammonium chloride was spiked into the influent water in a 200L pump chamber from July 20, 2022 to the end of the operating season. A peristaltic pump was used to dose concentrated ammonium chloride to achieve an influent NH_4^+ -N concentration of 15 mg/L.

The filters were constructed in the fall of 2021 with preliminary dosing occurring in the late fall of 2021. The filters were subsequently evaluated over a complete operating season from May to November 2022.

4.3.2 Sampling and analysis

Inlet and outlet water quality grab samples were collected weekly from May 11th until Nov 11th, 2022. All the samples were analyzed for total suspended solids (TSS), total phosphorus (TP), orthophosphate ($\text{PO}_4^{3-}\text{-P}$), ammonia ($\text{NH}_4^+\text{-N}$), and nitrate ($\text{NO}_3^-\text{-N}$) at the environmental

engineering laboratory at the University of Ottawa as per ‘Standard Methods for the Examination of Water and Wastewater’ (APHA, 2012). TP and PO₄³⁻-P were measured as per method 4500-P B & D (stannous chloride). NH₄⁺-N and NO₃⁻-N were measured according to methods 4500-NH₃ D and 4500- NO₃- D respectively. 5-day BOD (BOD₅) and Chemical oxygen demand (COD) were measured using the as per method 5210 B and HACH method 8000 respectively. Grab samples were *in-situ* analyzed for pH, dissolved oxygen, and temperature with a HACH-HQ40D multimeter (LDO101 probe for DO and PHC101 probe for pH).

4.3.3 Data Analysis

The data were divided into three phases to compare any effect of both start-up and season on the system performance: Preliminary start-up (Fall 2021), Late Spring & Summer (May -Aug 2022) and Fall 2022 (Sep – Nov 2022).

The filter performance was calculated in terms of concentration (%Removal) as:

$$\%R = \frac{C_{in} - C_{out}}{C_{out}} \times 100 \quad \text{Equation 3.2}$$

where C_{in} and C_{out} were the concentrations of a given contaminant inflow and outflow sample.

4.3.4 Statistical Analysis

A paired t-test was performed to examine significant differences in concentrations. Differences were considered to be significant at P<0.05, slightly significant at P<0.10 and not significant at P>0.10.

4.4 Results and Discussion

The system was initially operated from the last week of Oct 2021 until the last week of Nov 2021 (Preliminary start-up Period), when the municipal lagoon started freezing. The system was restarted in May 2022 and operated until Nov 2022 with weekly sampling.

4.4.1. Dissolved Oxygen and pH

The measurements of dissolved oxygen (DO) and pH were conducted for each sample. The average values for the entire study are presented in Table 4.3, as there were no notable changes detected over time for either parameter. The water column in the inlet (lagoon effluent) and filter outlets exhibited a consistently high level of dissolved oxygen, with concentrations ranging from 4.5 to 7.4 mg/L. Additionally, the pH of the water remained within a slightly basic range, with average pH varying from pH 8.4 to 8.5. The pH levels observed fell within the specified range of 6.5 to 9.0, which is necessary to comply with water discharge regulations (Kadlec & Wallace, 2008).

Table 4.3 DO and pH (Mean \pm STDEV) at Filter Inlet and Outlet

Location	DO mg/L	pH
Lagoon	5.4 \pm 2.1	8.4 \pm 1.0
FM	4.7 \pm 1.8	8.4 \pm 1.0
EJ	4.5 \pm 1.6	8.4 \pm 1.0
RG	5.3 \pm 1.4	8.5 \pm 0.9

The air and filter outlet temperatures are presented in Figure 4.4 and decline to a low of 6°C in November to a high of 29°C at the end of July.

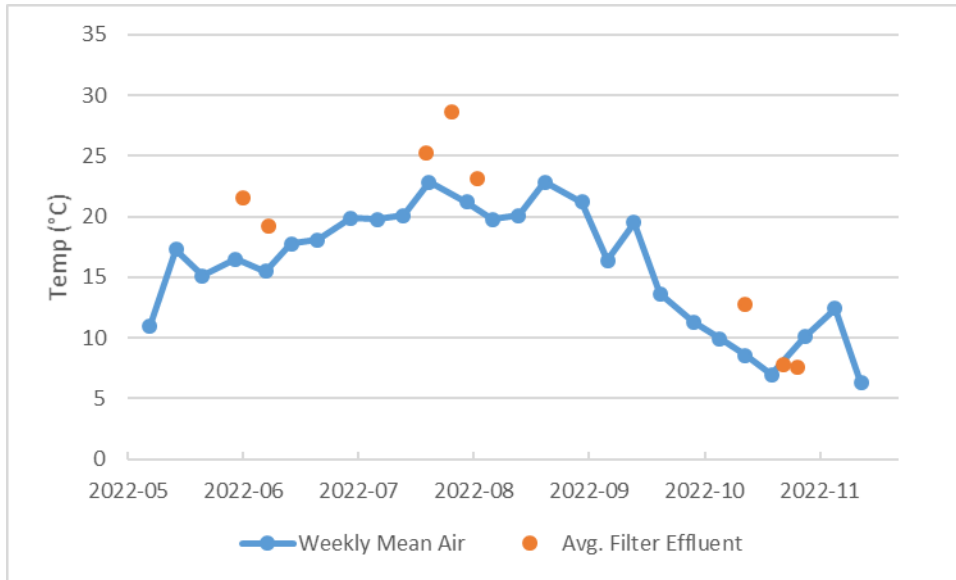


Figure 4.4 Filter Effluent and Average Weekly Air Temperature (Ottawa International Airport)

4.4.2 Total Suspended Solids (TSS)

Inlet average TSS concentrations over the study period varied between 7 to 16 mg/L, with higher concentrations observed during the preliminary phase (Late Fall 2021), while outlet concentrations in all three filters were significantly reduced to between 2-5 mg/L (Fig. 4.5) ($P < 0.05$). Time series data for the 2022 operating season (Fig 4.6) demonstrated average inlet concentrations of 7 ± 4 mg/L and outlet concentrations of 3 ± 3 mg/L for both FM and EJ and 5 ± 5 mg/L for RG, with slightly significant differences between FM and RG ($P = 0.05$) and between EJ and RG ($P = 0.10$). This suggests that FM and EJ, with higher % fines, and rough surfaces are somewhat more effective at filtering solids from lagoon effluent than RG, with no fines and smooth glass surfaces.

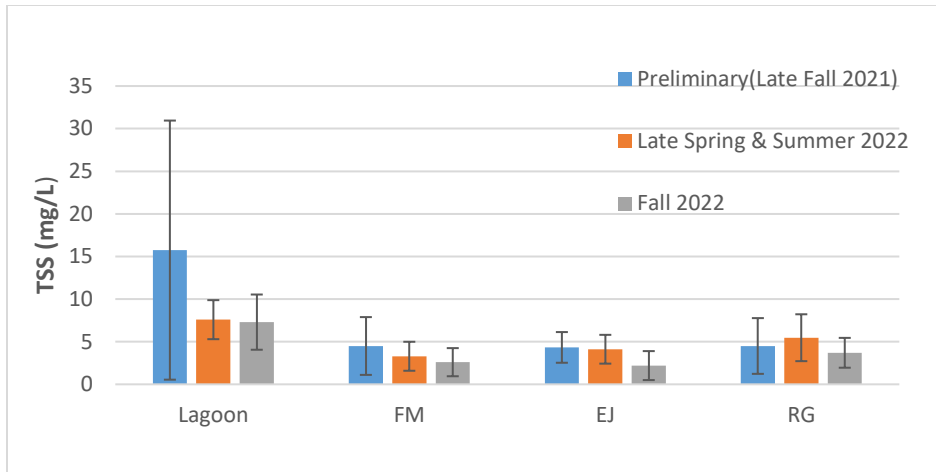


Figure 4.5 TSS Concentration (Avg ± SD) with Operating Period

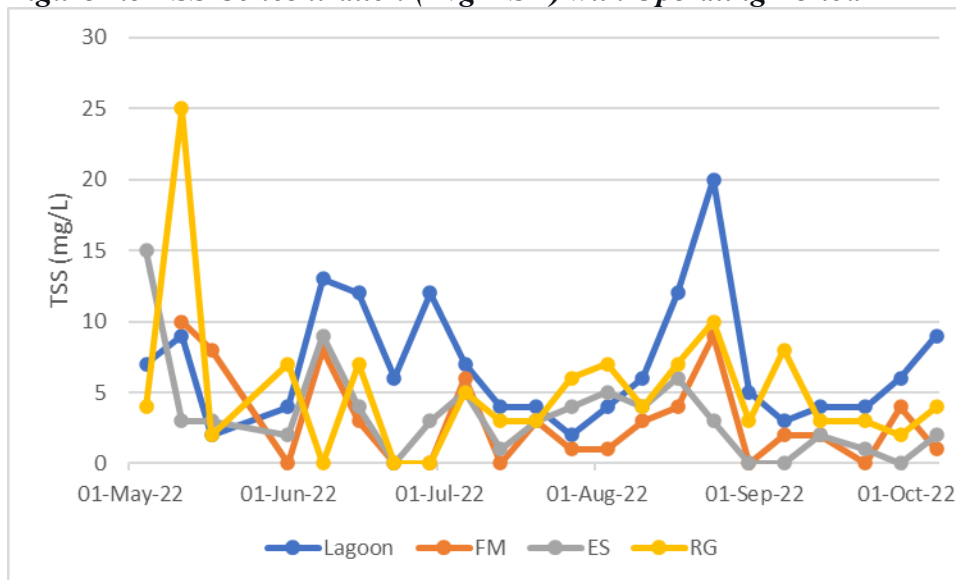


Figure 4.6 TSS Concentration with Time (2022 Operating Season)

4.4.3 Organic Matter

BOD₅ concentrations were measured several times throughout the season with lagoon BOD₅ = 4±3 mg/L. Therefore, the readily available organic carbon in the system is insignificant. COD was measured from the middle of July to the end of the operating season with time series data presented in Figure 4.7. Average removal efficiencies of 36, 41 and 24 % were observed for FM, EJ and RG, respectively, with both FM and EJ providing significantly lower outlet COD concentrations than RG (P<0.05). Furthermore, RG showed no significant difference to the lagoon influent water (P

>0.10), while both FM and EJ showed slightly significant differences to the lagoon influent water ($P < 0.10$). This suggests that the recycled glass is not as effective at reducing more recalcitrant organics as the two types of sand media. This could be due to a combination of the smooth surfaces on the recycled glass reducing biofilm attachment as well as the fines present in both FM and EJ playing a role in increasing liquid retention time within the unsaturated filters.

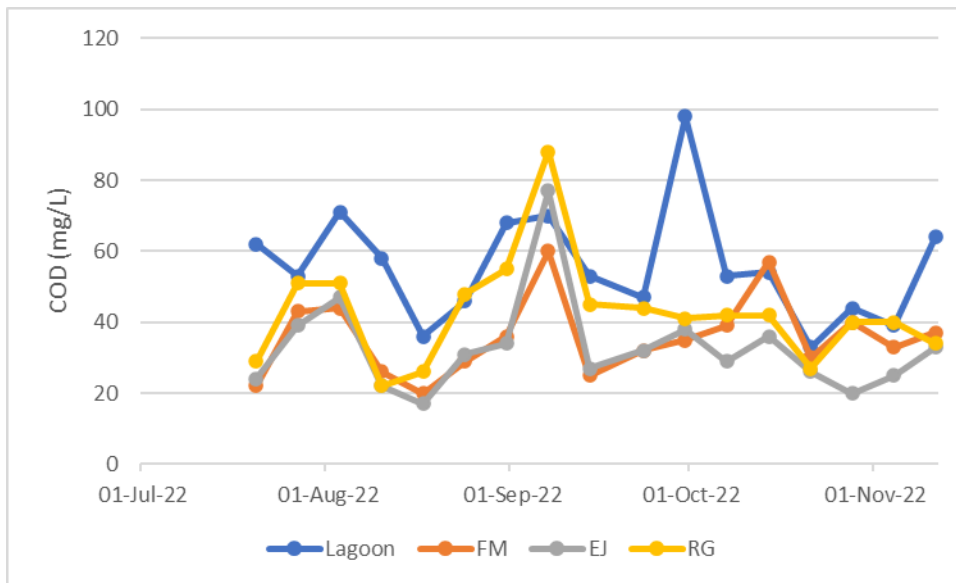


Figure 4.7 Pilot Filter COD with Time

4.4.4 Nitrogen

Due to the low ammonium concentrations in the lagoon effluent, ammonium chloride was spiked in the feed water from July 20th to the end of the operating season (Fig. 4.8). After ammonium spiking commenced, removal efficiencies were similar for both FM and EJ with 66 and 69%, respectively, while RG demonstrated a significantly lower removal efficiency of 42% ($P < 0.05$) (Table 4.4). No nitrate removal was observed with ammonium reduction commensurate with increased nitrate concentrations. Since the Effective size and Coefficient of Uniformity were similar between the FM and RG, these results suggest that sand media provided better surface

roughness for nitrifying biofilm attachment than the RG (flat glass surfaces), resulting in superior nitrification. Interestingly, the colder effluent temperatures at the end of the operating season (approx. 8-9°C) did not affect nitrification efficiency, while Torrens et al (2009), with a filter depth of 650 cm, reported a decline from an average of 93% to 65% during winter (wastewater T ~ 2°C) at a HLR of 40 cm/d. The present study suggests that it is feasible to maintain nitrification below 10°C, while further research is required to optimize design at colder temperatures.

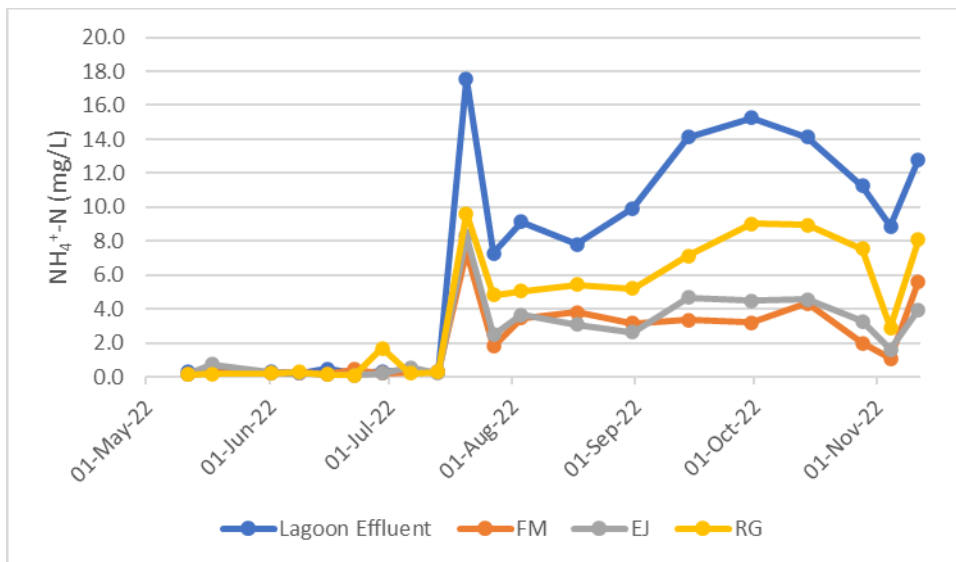


Figure 4.8 Ammonium Concentration with Time

Table 4.4 Inorganic Nitrogen Concentrations (Avg ±SD) (July 20 – Nov 11, 2022)

	Lagoon Effluent	Filter Outlet	Lagoon Effluent	Filter Outlet
	NH ₄ ⁺ -N (mg/L)		NO ₃ ⁻ -N (mg/L)	
FM	11.7±3.4	3.6±1.8	2.3±0.6	9.9±3.4
EJ		3.9±1.7		10.0±2.6
RG		6.7±2.1		4.9±2.9

4.4.5 Phosphorus

A seasonal effect on Lagoon Effluent concentrations of both TP and SRP was observed, with concentrations peaking in the middle of summer, and is likely related to algae production in the lagoon (Fig. 4.9 & 4.10 respectively).

All three filters were very effective at reducing phosphorus with average TP removal efficiency ranging from 76 to 85% and SRP removal efficiencies ranging from 89 to 94% (Table 4.5). Additionally, average TP concentrations were reduced to below 0.2 mg/L and average SRP concentration to below 0.04 mg/L. Comparing the three filters, no significant differences in either TP or SRP concentrations were observed between FM/5 cm DRI and EJ/10 cm DRI ($P>0.10$), while TP was significantly higher in RG/15 cm DRI than both FM/5 cm DRI and EJ/10cm DRI, and SRP was significantly higher in RG/15 cm DRI than EJ/10cm DRI ($P<0.10$). This strongly suggests that the overlying FM and EJ sand filters contributed to SRP reduction, likely through cation adsorption sites in the media. Crushed glass media, on the other hand, is unlikely to contribute to P adsorption, and thus provides a better measure of the DRI effectiveness. Therefore, the 15 cm depth (5.7 hr HRT) of DRI is conservatively recommended for design purposes. The grain size distributions and particularly the % fines in the sand media could also have played a role in improving the filtration of particulate phosphorus and polyphosphates compared to the crushed glass.

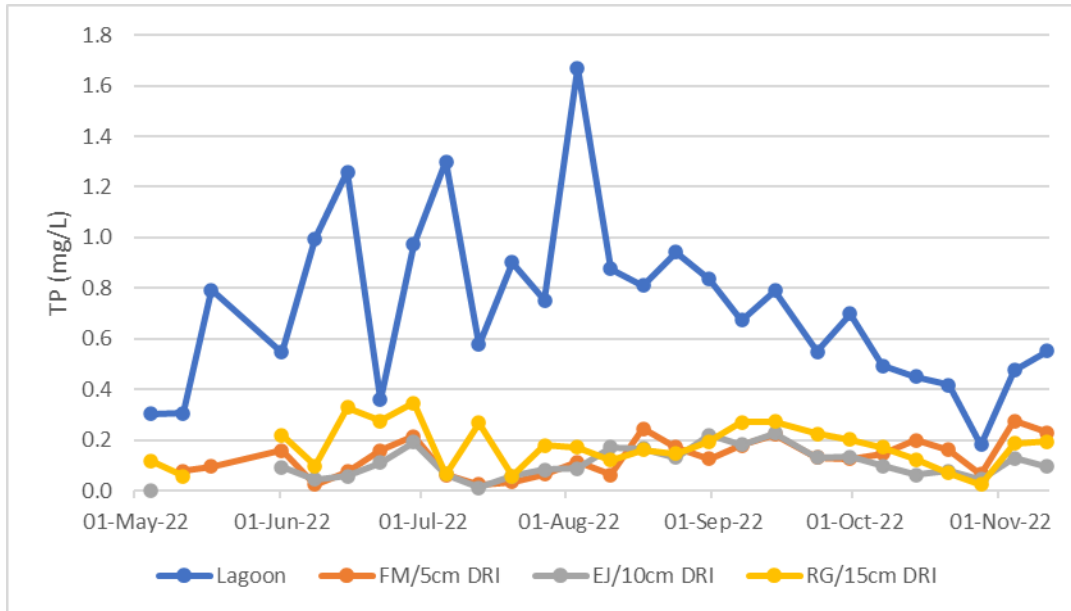


Figure 4.9 Pilot Filter TP with Time

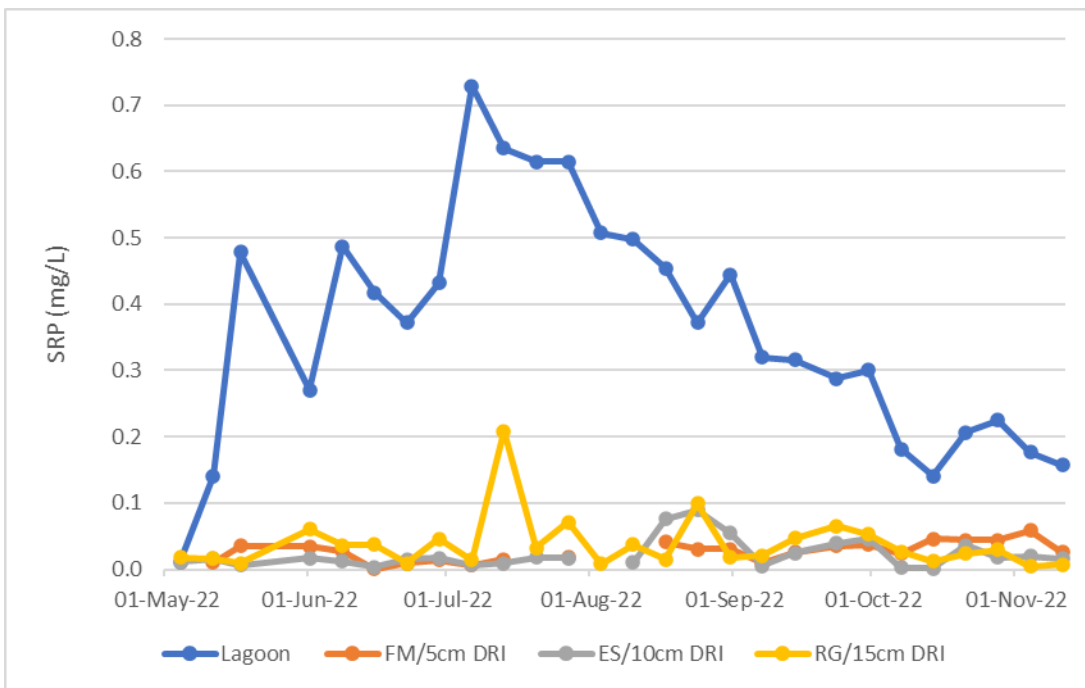


Figure 4.10 Pilot Filter SRP with Time

Table 4.5 Phosphorus (Average Conc. \pm Standard Deviation (mg/L))

	Lagoon Effluent	FM / 5 cm DRI	EJ / 10 cm DRI	RG / 15 cm DRI
TP	0.72 \pm 0.33	^b 0.13 \pm 0.07	^a 0.11 \pm 0.06	^{a,b} 0.17 \pm 0.09
SRP	0.36 \pm 0.17	0.027 \pm 0.015	^b 0.022 \pm 0.022	^b 0.038 \pm 0.040

^a Significant Difference (P<0.05)

^b Significant Difference (P<0.10)

4.5 Conclusions

A filter comprising 45 cm of unsaturated media (comparing 2 coarse sands and crushed glass) and 5-15 cm of saturated DRI media was successful at polishing a low carbon municipal lagoon effluent at 29 cm/d loading for 7 months with no signs of clogging.

The two coarse sand media performed better than similar crushed glass with similar D₁₀ in terms of TSS removal (57 vs 28%), COD removal (39 vs 24%) and NH₄⁺ removal (68 vs 42%). The smooth surfaces of the crushed glass media likely reduced biofilm development, negatively impacting nitrification and COD removal. Additionally, the greater %fines in the sand media likely increased filtration and liquid retention time compared with the crushed glass media.

Average TP concentrations were reduced to below 0.2 mg/L and average SRP concentration to below 0.04 mg/L with DRI depth ranging from 5-15 cm. As the sand media likely played a role in P reduction, a conservative design should utilize 15 cm of DRI with 5.7 hrs HRT. Under the conditions studied, two sand media (D₁₀=0.43mm, CU=2.6, 4.5%fines; D₁₀=0.18mm, CU=5.8 and 2.1%fines) performed significantly better than the crushed glass media (D₁₀=0.45mm, CU=2.2, 0.04%fines). A recommended design would be a 0.45 m unsaturated coarse sand layer over a 0.15 m saturated DRI layer (12.5 mm dia.) with a loading rate of 29 cm/d dosed intermittently.

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CHAPTER 5

5.0 Conclusions and Recommendations

A column study investigated the application of a passive filter comprising an unsaturated layer of coarse-grained material for organics and ammonium reduction over a saturated layer of DRI for SRP reduction to treat synthetic municipal lagoon effluent ($\text{cBOD}_5=39$ mg/L, $\text{NH}_4^+\text{-N}=21$ mg/L, $\text{SRP}=3.3$ mg/L). Two sources of coarse sand and a recycled crushed glass media were compared at 30-60 cm depths with 5-15 cm of DRI media. Continuous dosing was applied to the columns to represent conditions of gravity discharge where electricity is not available for time dosing at two hydraulic loading rates of 55 and 25 cm/d. The sand media ($D_{10} = 0.43$ mm, $\text{CU} = 2.6$, $\% \text{fines} = 4.5$; $D_{10} = 0.18$ mm, $\text{CU} = 5.8$, $\% \text{fines} = 2.1$) observed biofilm clogging at both loading rates, while the crushed glass ($D_{10} = 0.45$ mm, $\text{CU} = 2.2$, $\% \text{fines} = 0.04$) did not. This suggests that for conditions where intermittent dosing is not feasible, crushed glass can provide an appropriate filter media to polish lagoon effluent for BOD and NH_4^+ . The optimum crushed glass filter depth was found to be 45 cm at 25 cm/d loading rate, reducing cBOD_5 and $\text{NH}_4^+\text{-N}$ concentrations by 87 and 93%, respectively. With all unsaturated media types and depths, a 15 cm layer of saturated DRI was effective at reducing soluble phosphorus by 89%, with no apparent impact of biofouling on removal efficiency.

A field study compared three pilot filters with 45 cm of unsaturated media (2 coarse sands and crushed glass as above) and 5-15 cm of saturated DRI media to polish municipal lagoon effluent ($\text{COD}=56$ mg/L, $\text{TSS}=7\text{-}16$ mg/L, $\text{NH}_4^+\text{-N}=12$ mg/L, $\text{TP}=0.7$ mg/L, $\text{SRP}=0.4$ mg/L). All filters were effective at polishing the low carbon municipal lagoon effluent at 24 cm/d loading (with intermittent dosing) for 7 months with no signs of clogging. The two coarse sand media performed better than the crushed glass in terms of TSS removal (57 vs 28%), COD removal (39 vs 24%) and

NH_4^+ removal (68 vs 42%). The smooth surfaces of the crushed glass media likely reduced biofilm development, negatively impacting nitrification and COD removal. Additionally, the greater %fines in the sand media likely increased filtration and liquid retention time compared with the crushed glass media. The filters with 15 cm of DRI were effective at reducing TP and SRP by 76-85% and 89-93%, respectively.

The column study demonstrated the benefits of the crushed glass media in maintaining filter percolation under conditions of continuous loading while biofilm clogging was observed with the two types of sand media. Also, the column study showed that the hydraulic loading rate plays a more crucial role than the organic loading rate in the performance of the column. However, the field study, with a low-carbon and solids influent, clearly demonstrated superior BOD and NH_4^+ removal efficiencies with the two coarse sand media, while no signs of clogging were observed. In both studies, excellent removal of SRP was obtained at 15 cm of DRI (5.9 hr HRT) with no obvious impact of biofilm fouling on removal efficiencies. These results suggest that a passive filter comprised of 45 cm of unsaturated media and 15 cm of saturated 12.5 mm dia. DRI media at a loading rate of 25 cm/d can provide effective polishing of municipal lagoon effluent. Crushed glass can be considered as an alternative to coarse sand where intermittent dosing is not feasible.

Future Research

- Operate the DRI filters for long-term under real wastewater conditions to achieve P breakthrough and investigate media rejuvenation strategies.
- Run column/filters studies to saturation to determine ideal design capacity.
- Conduct further research on cold-temperature nitrification to determine appropriate loading rates and the impact of media characteristics/depth on removal efficiencies.

- Conduct a larger pilot evaluation at a continuous discharge lagoon to include winter operation/nitrification.