Evaluation of the effectiveness of pervious concrete in the treatment of greywater

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DECLARATION

I, Zanele Rose Mabaso, declare that all the work in this thesis is my own, with the guidance of my supervisor. This thesis provides my own views and the use of materials and information from other sources have been fully acknowledged. Moreover, no other university has received this thesis for credit towards a degree or examination.

Student: Zanele Rose Mabaso (201820285)

Signature:…………………. Date:……………………………..

Main supervisor: Dr A.N. Shabalala

Signature:…………………. Date:………………………………

DEDICATION

I passionately dedicate this thesis to my mom, Thembi Madonsela, for her immeasurable love, encouragement and support. My Sister, Philile Mabaso who has shown great support and always reminded me about the importance of pursuing this degree. I also like to dedicate this thesis to my brother, Sicelo Mabaso, who has been emotionally present and given me all the support I needed to finish this degree. This thesis is also dedicated to my best friend, Christopher Mziyako, for being there for me from the beginning of this course and for his support and encouragement. God, for giving me life and strength to keep on pushing no matter the circumstances.

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ABSTRACT

Freshwater shortage affects both developing and industrialized nations due to population growth, urbanization, high water consumption, and climate change. This situation requires interventions to reduce reliance on freshwater. Greywater, a low-strength wastewater with various reuse possibilities, can replace freshwater for non-portable tasks like crop irrigation. However, using untreated greywater can harm crops due to harmful substances, including salts and pollutants. Effective filtration of greywater impurities is essential, with pervious concrete proposed as a potential treatment solution for contaminated water sources. This study aimed to evaluate the effectiveness of pervious concrete in the treatment of greywater and its subsequent application for irrigation purposes. The research was divided into 3 tests (Batch reactor tests, Column tests, and the laboratory-scale greywater treatment system). Column tests were done to determine the long-term performance of the greywater treatment system. The efficiency of pervious concrete in eliminating pollutants from greywater was compared with that of moringa and activated carbon. Greywater was obtained from a student residence at the University of Mpumalanga. Pervious concrete and moringa seeds were used to conduct batch reactor tests with the greywater. The treated greywater's quality was evaluated using physical, chemical, and microbiological parameters. The electrical conductivity (EC) and total dissolved solids (TDS) in the pervious concrete-treated greywater increased from 45.5 mS/cm to 108.6 mS/cm and 252mg/l to 543 mg/L, respectively. The pH increased from 7.4 to 10.89. Values for pH, EC, and TDS fell within the acceptable ranges for irrigation and wastewater discharge into a water source. *E. coli*, Biochemical oxygen demand (BOD) and turbidity were also reduced following treatment with pervious concrete to levels below the permissible limits for irrigation use and release of wastewater into a body of water. The values of EC (75.8mS/cm-229.3mS/cm), TDS (379mg/l-1147mg/l), *E. coli* (1CFU/100ml), turbidity (40NTU-122NTU) and BOD (10mg/l-135mg/l) exceeded the maximum limit recommended when the greywater was treated with moringa. Following treatment with pervious concrete and activated carbon for column tests, the values of pH (10.01), EC (37.9 mS/cm), and TDS (190 mg/l) were in the applicable restrictions for the discharge of wastewater after treatment with pervious concrete. BOD (<11), Turbidity (1.1 NTU), and *E. coli* (<1 CFU) were reduced following treatment with pervious concrete. TDS and EC values exceeded the maximum limit recommended after treatment with activated carbon. Pervious concrete achieved a 90.9% Mg removal, 83% ortho phosphate removal and 79.1% Fe removal, while activated carbon achieved a 77% Ca removal and 90.9% Mg removal. Therefore, the results show that pervious concrete can be a simple and efficient method that can be adopted for treating greywater for use in agriculture and replenishing water resources.

Keywords: Activated carbon**,** greywater, irrigation, moringa, pervious concrete, reuse.

RESEARCH OUTPUTS

Presentations at conferences for research studies associated to this thesis were given as follows:

Mabaso, Z.R. (2022). Evaluation of the effectiveness of pervious concrete in the treatment of greywater. Water Institute of Southern Africa (WISA). Sandton, South Africa, 28-30 September 2022.

THESIS LAYOUT

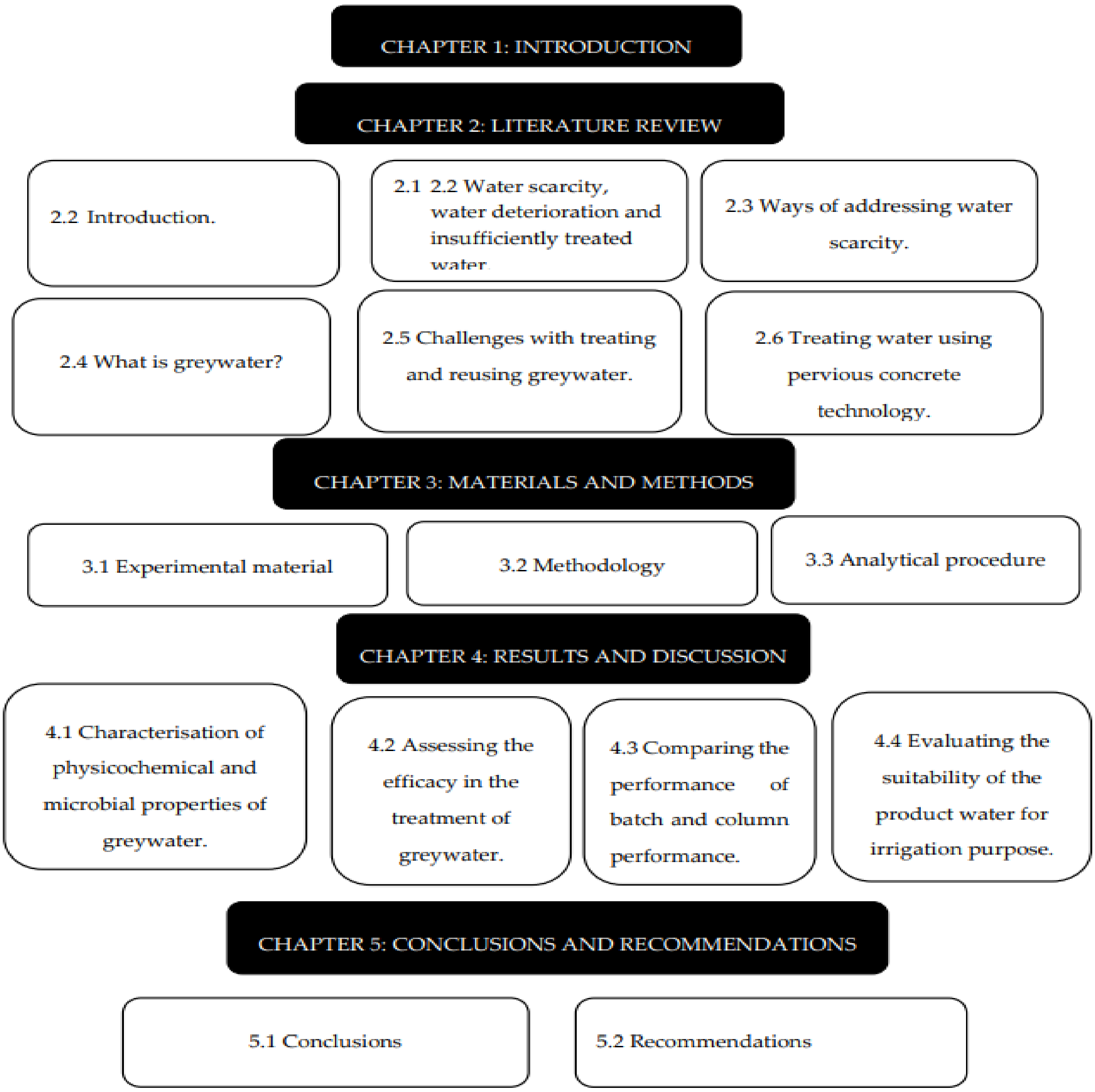

Figure 1-1: *Thesis Road Map*

Chapter 1: A concise explanation of the research theme and an outline of its supporting evidence are provided in this chapter. The aim, problem statement and objectives are all comprised within this chapter.

Chapter 2: This is the literature review where explanations are given, including the problem that needs to be addressed in this study, for example, water scarcity, water deterioration and insufficiently treated water. The known solutions, e.g. purification methods, recycling and reuse and current methods of treating greywater. This chapter explains the challenges with the current solutions and how the study is going to solve the current challenges. This chapter will also explain why pervious concrete was selected for this study.

Chapter 3: This chapter offers a thorough discussion of the research methods utilised to conduct the research, including the experimental materials, methodology and analytical procedures.

Chapter 4: This chapter displays and discusses the findings of the data collected.

Chapter 5: The Chapter provides a total summary of the objectives, aim and outcomes of the thesis, as well as the recommendations for future applications of the project.

References: This is the section where a comprehensive list of all the sources cited, and in-text references will be written.

Appendices: This is the attachment for any further study-related data.

LIST OF FIGURES

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ABBREVIATIONS

Abbreviation	Description
BOD	Biochemical Oxygen Demand
EC	Electrical Conductivity
FAO	Food and Agriculture Organization
GGBS	Ground Granulated Blast Furnace
GW	Greywater
KR	Kelly's ratio
PERVC	Pervious Concrete
pH	Potential Hydrogen
SAR	Sodium Adsorption Ratio
SSP	Soluble Sodium Percentage
TDS	Total Dissolved Solids
WHO	World Health Organization
WISA	Water Institute of Southern Africa

LIST OF SYMBOLS

Symbol	Explanation
°C	Degrees Celsius
cm	Centimetre
cm^3	Cubic centimetre
g	Gram
KG	Kilogram
ℓ	Litre
m	Metre
mg/L	Milligrams per litre
ml	Millilitre
mS/m	Millisiemens per meter

CHEMICAL FORMULA

Element/compound	Description
H_2O	Dihydrogen monoxide (water)
SO_4^{2-}	Sulphate
NaCl	Sodium Chloride (Salt)
Na^+	Sodium ion
Ca^{2+}	Calcium ion
Mg^{2+}	Magnesium ion
K^+	Potassium ion
PO_4^{3-}	Orthophosphate
NO_3^-	Nitrate

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CHAPTER 1

INTRODUCTION

1.1. Background of the research

The increase in pollution coupled with dwindling water resources constitutes a big problem in most parts of the world (Jain, 2019). The scarcity of freshwater is an issue that both developing and developed nations are particularly concerned about. According to Brown et al. (2019), these occurrences are commonly caused by increased urbanisation, population growth and climate change. These activities do not only deplete the existing water resources, but they result in production of high volumes of wastewater, of which greywater constitutes a larger share. The term "greywater" is used to define domestic wastewater that is produced from kitchens and bathrooms (including shower, bath, hand basin, and laundry water discharges). The wastewater generated from toilet usage is referred to as black water and is excluded from the definition of greywater (Brown et al., 2019). The amount of greywater generated by individual households can vary significantly based on a diversity of variables, comprising the household lifestyle and water supply, to name a few. According to Filali et al. (2022), the amount of greywater typically makes up 50% to 80% of residential home water use. The potential purpose of treated Greywater includes, irrigation of gardens, crops, and landscaping, flushing of toilets, cleaning pavements and public spaces, construction purposes like mixing concrete (Pandey and Jagnnath, 2022). The use of treated greywater will particularly benefit rural communities with limited access to reliable water supply, townships and informal settlements experiencing water shortages, agricultural communities requiring water for irrigation, schools, clinics, and public facilities to reduce operational water costs, urban households seeking sustainable and cost-saving water alternative (Madzaramba and Zanamwe, 2023).

Treatment and reuse of wastewater and greywater is becoming a key component of water demand management, encouraging the conservation of freshwater and lowering overall supply prices while also minimising environmental uncleanness (Van de Walle et al., 2023). Pervious concrete is one of the most environmentally friendly water treatment methods due to its use of the commercially existing concrete making materials. Purifying greywater using pervious concrete permits water to be reused safely and recycled for such functions as irrigation, toilet flushing, groundwater recharge, firefighting, and industrial reuse (Teymouri et al., 2023). Studies have shown that correctly constructed pervious concrete can effectively remediate polluted and acidic water by removing most ionic contaminants such as iron (Fe), sulphate (SO_4^{2-}), salt (NaCl), zinc (Zn), manganese (Mn), magnesium (Mg), as well as increase the pH level (Alimohammadi et al., 2021). Tortajada (2020) has observed that pervious concrete can also eliminate various bacteria and other microorganisms such as faecal coliforms and *Micrococcus luteus* that occur in polluted water systems from a variety of sources. Pervious concrete treatment also lessens the detrimental effects of water scarcity on people by enabling recycling of wastewater from various sources. This can conserve a substantial amount of fresh water.

Current water consumption and wastewater treatment patterns suggest that greywater recycling makes feasible water management solution for water scarce communities. However, this approach raises concerns about the quality of the recycled materials and the potential harm to public health in recipient communities (Tripathi et al., 2019). Byrne et al. (2020) reason that greywater reuse for irrigation, as well as other non-potable water uses, will considerably aid in the reconnection of urban ecosystems to the natural water cycle. This will result in more sustainable urban growth.

1.2. Problem Statement

Lack of water is a worldwide issue of dire concern that results from inadequate freshwater resources to satisfy the regular water demand. Treating greywater presents several challenges, including high levels of organic matter, detergents, oils, and pathogens that require proper filtration and disinfection before reuse. Conventional treatment systems can be costly, energy-intensive, and difficult to maintain, especially in rural or low-income communities (Filali et al., 2022). These challenges highlight the need for alternative, low-cost and sustainable treatment methods such as pervious concrete systems, which allow greywater to infiltrate through specially designed porous surfaces, promoting natural filtration and groundwater recharge while reducing surface runoff (Filali et a., 2022). In addition, South Africa is classified as a water-scarce country, with limited and unevenly distributed freshwater resources. Increasing demand from households, agriculture, and industry places further pressure on existing water supplies. This makes it essential to explore alternative water sources, such as treated greywater, particularly for irrigation purposes, to reduce dependence on potable water and improve long-term water security (du Plessis, 2023). Greywater that hasn't been properly treated can have a serious impact on both human and environmental health in that it impairs soil quality and makes plants poisonous through building up salts, surfactants, and boron.

According to Oh et al. (2018), greywater has several negative aspects, such as high turbidity and microbiological contamination by viruses, bacteria, and protozoa. Greywater has been found to have suspended particle concentrations between 149 and 162 mg/L, which is more than the minimal values permitted for surface dumping in several states. When greywater is not appropriately absorbed into the ground or drained away, dangerous contaminants such as viruses, fungi, bacteria and protists can build up because they stick to suspended particles in highly turbid water. Greywater has been found to have a high alkalinity (low acidity) because of soap and detergent residues, which might be harmful to plant growth (Rakesh et al., 2020). These problems are further worsened by accelerated water pollution and inadequate water treatment systems. This work seeks to redress water quality degradation due to greywater and the resultant harm to humans and the environment using a pervious concrete treatment system.

1.3. Motivation for the research study

The treatment of greywater will increase the amount of water available for irrigation and other non-potable purposes, which will substantially aid in sustainable urban development (Siddique, 2022).The treatment of greywater will also assist in tying urban ecosystems to the water cycle. Treating greywater allows cities to reconnect with the natural water cycle rather than remaining separate from it. Urban areas begin to operate more like natural ecosystems, where water is continuously reused and recycled instead of being discarded as waste (Meney and Pantelic, 2022). Greywater treatment and reuse can save costs by substituting less expensive applications for expensive drinking water, such as irrigation, laundry washing, industrial processes, and toilet flushing. This will reduce the production of wastewater in addition to freshwater utilisation.

Parts of the Middle East and Africa, which experience significant water scarcity can enhance their domestic water supply through greywater recycling (Mohamed et al., 2019). A higher agricultural production can be assured by ensuring a larger water supply for irrigation (McDermid et al., 2023). Greywater recycling has several benefits, including improved surface and groundwater quality, increased agricultural yield, reduced freshwater withdrawal from aquifers and rivers, less infrastructure impact from wastewater treatment plants, reduced energy use, and chemical contamination during treatment (Prakash et al., 2024).

1.4. Novelty and significance

Greywater remediation using pervious concrete is proposed as a feasible solution to address technical, aesthetic, and health concerns which arise from the occurrence of suspended solids, pathogens, and organic matter. Pervious Concrete is able to simultaneously treat and infiltrate water through its interconnected pore structure, which many conventional treatment systems cannot easily achieve. Unlike traditional treatment methods that require complex infrastructure, energy, and maintenance, pervious concrete filters contaminants while allowing water to percolate into the ground, promoting natural purification and groundwater recharge (Sha et al., 2024) This makes it a low-cost, passive, and sustainable treatment option, particularly suitable for stormwater and greywater management. Water reclamation from greywater is also suitable for broadening water reuse options given the recent spates of water shortage in South Africa that has forced consumers to substantially reduce water usage. An innovative and efficient treatment technique that could provide alternatives for greywater treatment is the pervious concrete reactive barrier system that has been shown to produce water of a standard that makes it usable for such activities as agricultural irrigation. Shabalala et al. (2017) demonstrated the environmental advantages of pervious concrete in enhancing water quality through the capturing of pollutants. With the correct design, pervious concrete may effectively purify acidic and pollutant-laden water by filtering out undesired pollutants, including sulphate, iron, zinc, magnesium, manganese, and salts. Additionally, according to Shabalala and Ekolu (2019), pervious concrete can be used to remediate mine water for applications such as irrigation.

1.5. Research aim and objectives

1.5.1. Aim

To evaluate the effectiveness of pervious concrete in the treatment of greywater and its subsequent application for irrigation purposes.

1.5.2. Specific objectives:

1. To characterise the physicochemical and microbial properties of greywater emanating from a student residence at the University of Mpumalanga.
2. To fabricate a tailor-made and purpose-driven permeable reactive barrier and assess its efficacy in the treatment of greywater emanating from a student residence at the University of Mpumalanga.
3. To compare the performance of a batch and column system in the treatment of greywater using a permeable reactive barrier.
4. To evaluate the suitability of the product water for irrigation purposes in line with the irrigation water guidelines, specifications, and standards.

1.6. Research questions

1. What are the physicochemical and microbial properties of greywater emanating from a student residence at the University of Mpumalanga?
2. How to fabricate a tailor-made and purpose-driven permeable reactive barrier and assess its efficacy in the treatment of greywater?
3. How is the performance of a batch and column system in the treatment of greywater using the permeable reactive barrier?
4. What is the suitability of the product water for irrigation purposes as compared to irrigation water guidelines, specifications, and standards?

1.7. Hypothesis

Pervious concrete can effectively treat greywater by reducing total dissolved solids (TDS), electrical conductivity (EC), *E. coli*, biochemical oxygen demand (BOD), turbidity, raising pH, and removing metals.

1.8. Delineation of the study

The pilot installation of the system was not included in the study.

1.9. Chapter summary

This chapter emphasizes the rationale and significance of conducting the study. The topic of the study, the problem statement, motivation, aim and objectives and justification have been unpacked. The next chapter offers a review of related literature along with an explanation of the selection of pervious concrete for this study.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

This chapter discusses water scarcity challenges that necessitate this study and further explores the factors that contribute to water scarcity such as water deterioration and insufficiently treated water. South Africa faces significant challenges related to declining water quality, largely driven by human caused activities such as mining, agricultural runoff, industrial discharge, and urban development. These activities introduce pollutants like heavy metals, nutrients, and chemicals into rivers and groundwater. Poorly treated wastewater effluent from overloaded or poorly maintained treatment plants further contaminates water sources, increasing risks to ecosystems and public health. These pressures highlight the urgent need for improved wastewater treatment systems and sustainable water management practices (Mishra, 2023).

2.2. Water scarcity, water deterioration and insufficiently treated water

According to Greve et al. (2018), a surge in water extraction over the past century has been the main cause of the world's catastrophic water shortage. The study further predicted that an increasing societal demand for water and climate change would worsen water scarcity in numerous parts of the world over the next few decades. Reduced water availability is expected to jeopardize gains in agricultural and productivity of grass and food security and may adversely disturb various regions of the world (Fitton et al., 2019). Water scarcity, water quality deterioration, and insufficiently treated water have serious implications for food security, particularly in water-scarce countries such as South Africa. These challenges affect agricultural production, food safety, and the source of revenue of communities that depend on farming (Linderhof et al., 2021). Water scarcity reduces the quantity of water accessible for irrigation, which limits crop production and livestock farming. When farmers do not have enough water, crop yields decrease and some crops may fail completely. This leads to reduced food availability, higher food prices, and increased vulnerability for rural and low-income households. Water quality deterioration, often caused by pollution from industries, agriculture, and poorly managed wastewater, also threatens food security (Khondoker et al., 2023). Contaminated water can damage crops, degrade soil quality, and introduce harmful substances into the food chain. This not only reduces agricultural productivity but also affects the nutritional quality and safety of food.

According to Mishra (2023), the deterioration of water quality in rivers, lakes, and groundwater has progressively grown to be a worry on a global scale. The demand for the already limited water resources is increased by urbanization, population growth, industrialization, and a surge in agricultural activities (Mativenga and Marnewick, 2018). With the increased demand for water there is inherently an extreme difficulty in preventing the transfer of toxins from moving from one body of water to another. According to McDaniel et al. (2017), farming or agriculture consumes more water, with irrigation of croplands accounting for 70% of water extractions from aquifers and surface water bodies. Even though 95% of agricultural land is rain-fed, decreasing surface and ground water availability coupled with rising water scarcity might reduce the productivity of pastures and crops (Hadebe et al., 2017).

According to Pamla et al. (2021), the problem of water scarcity has already had a significant impact on South Africa's economic development and general well-being. In addition to having a severe drought, South Africa also has a bad track record of water conservation and obsolete, inadequate water treatment facilities. These factors feed the existing fears about the deteriorating quality of the already scarce amount of accessible water (Pamla et al., 2021). It was predicted in 2019 that several African regions will experience high rainfall variability and lengthy drought by 2025 (Dosio et al., 2019). As a result, sourcing water for domestic use and agriculture is expected to become more problematic.

According to the United Nations' Children Fund (UNICEF) and the World Health Organization (WHO), over 2.2 billion people around the world have no access to safe and clean drinking water (WHO, 2019). These effects of declining water supply and quality extend to industries, towns, farms, recreational use facilities, and natural ecosystems as well (Tariq and Mushtaq, 2023). In addition to requiring major capital investments to lower water consumption or improve water supplies, water shortages result in lost income and business interruption. The problem of water scarcity is severe and has been worsening with each passing year. The pollution of the oceans, rivers, lakes, and streams has put stress on many of the water systems that support thriving ecosystems and provide for an increasing human population.

Climate change could have a substantial influence on water availability in the future due to variable precipitation, rising temperatures and increased water consumption over time due to growing urbanisation (Arfanuzzaman and Rahman, 2017). In industrialised countries, rapid urbanisation may exacerbate the gap between water demand and supply and increase the likelihood of a water crisis (Brown et al., 2019). Further urbanisation may be hampered by the problems of a growing water shortage and scarce water supplies. Millions of poor people are facing more difficulties because of climate change, including issues with food, water, livelihood security, infrastructure, transportation, energy, cultural identity loss, forced relocation, and health effects. The Social factors that lead to water scarcity, such as urbanisation, deforestation, industry, the destruction of wetlands, mining, agriculture, and unintentional water contamination, are also impacted by climate change in both direct and indirect ways, in addition to its effects on the hydrological cycle (Leal Filho et al., 2022).

2.3. Ways of addressing water scarcity

2.3.1. Current methods of treating greywater

Before being used for a variety of reasons, greywater needs to be treated to lower pollution levels related to organic load, nutrients, and pathogenic microorganisms (Rakesh et al., 2020). To handle, manage, and treat greywater, several industrialized nations have used simple to sophisticated techniques while a few of these countries reuse the greywater for non-potable and potable purposes (Rakesh et al., 2020). Greywater treatment technologies have been utilised to lower the degree of pollution prior to reuse or disposal. Each is administered in the order specified by the specific contaminant and follows the standard protocol for treating wastewater (pre-treatment, the primary, secondary, and the tertiary treatment). Every one of such systems uses a biological or physicochemical approach to remedy water pollution (Rai, 2024). Filtration is one of the physical and/or chemical treatment techniques used in physicochemical procedures.

Filtration is the process of eliminating solid particles from a liquid or gaseous fluid by using a filter substance through which the fluid can flow but the solid particles are retained. Both the filtrate and the retained solid particles may be the desired products for different uses (Rezai and Allahkarami, 2021). Filtration was used, as demonstrated by a study by Shegokar et al. (2015), which examined the filtration stage and performance evaluation for the removal of load contaminants in greywater at each filter bed. According to the study findings, a nylon rope filter media outperformed dual media filters (a blend of activated carbon and *Zea mays* feedstock) in the filtration stage. For the usage of biochar-based column filtration systems (BCFS) for the greywater treatment, Quispe et al. (2022) developed three filter column conformations: a single biochar filter, a multilayer filter and a polishing step in the treatment cable. Between 50 and 99% of pollutants were removed by BCFS.

According to Kataki et al. (2020), a constructed wetland (CW) is an artificial wetland that mimics the environmental characteristics of a natural wetland by applying ecological technologies. The technique uses unique soil, microbes, and the flora and fauna to eliminate important pollutants. According to Ramdabu et al. (2020), wetlands are the most popular treatment option and are thought to be the least expensive restoration technique when employed in their entirety. Anaerobic and aerobic wetland systems are the two primary varieties of wetland treatment systems that are available. Shallow water bodies are defined as aerobic wetlands (less than 30 cm in depth), according to Benny and Chakraborty (2024). While anaerobic digestion wetlands use rich organic substrates, sulphate reducing bacteria (SRB) inoculum, and limestone to improve acidic metalliferous waters, aerobic digestion targets alkaline waters. Wetlands are categorised as surface flow (SF), hybrid systems, and subsurface flow (SSF) hydrological systems. Hybrid wetlands are designed to remove pollutants more effectively, particularly nitrogen-based pollutants. The effectiveness of the contaminant removal procedure depends on the addition of substrates.

Rotating biological contactors (RBCs) are horizontal shaft-mounted fixed-bed reactors with revolving disks. During wastewater flow, they rotate while partially submerged. The microorganisms in charge of the treatment undergoes periodic exposure to the air to encourage the aeration, absorption, and decomposition of nutrients and dissolved organic contaminants. In Pakistan, Abdelkader (2021) investigated the effectiveness of a single-stage RBC on greywater. The RBC was made using textured plastic disks and plastic sheets and the revolving discs were immersed in the greywater for up to 40% of the time the greywater was kept within the system. The efficiency of an RBC is measured by the removal of indicator microorganisms (faecal coliforms, heterotrophic bacteria) and certain pathogens (*Pseudomonas aeruginosa sp., Staphylococcus aureus sp.),* according to research done in 2024 by Yan and Pei. The RBC by Abdelkader (2021) removed 88.5–99.9% of all four types of bacteria.

Wastewater is also treated using an active sludge technique called a sequencing batch reactor (SBR) where the whole treatment process is carried out in batches in the reactor tank. Every batch goes through a time-controlled sequence of treatment procedures, such as equalisation, biological treatment, and secondary clarifying, all in a single tank (Li et al., 2021.

A membrane bioreactor (MBR), which combines a biological process with a perm-selective technique, is used to treat greywater. To finish the treatment, it combines biological, microfiltration, and ultrafiltration equipment. Its compact size makes it a practical choice for cleaning and recycling greywater in densely populated areas where space is highly prized. Atanasova et al. (2017) examined how well an MBR handled greywater in a Spanish hotel. When the chemical oxygen demand (COD) content in the wastewater was less than the measurement limit of 30 mg/L as per the Spanish water reuse regulations, the removal effectiveness for COD was in the range 80 to 95%. The average elimination of total nitrogen (TN) and ammonia was 85.1% and 80.5, respectively, at a high initial concentration. Cecconet et al. (2019) also investigated the efficacy of an MBR consisting of an ultrafiltration membrane in treating greywater from a Moroccan sports facility.

Mainardis et al. (2020) state that for a variety of wastewater streams, the up-flow anaerobic sludge blanket (UASB) remains among the most often used methods for treating wastewater due to its anaerobic process, which keeps a high concentration of active floating biomass and produces better settleable sludge than other methods.

2.3.2. Recycling and reuse of greywater

Reusing water is encouraged worldwide because it helps replenish freshwater supplies, offers reliable water services in isolated or ecologically delicate areas, lessens the quantity of sewage dumped into water bodies, and lowers the growing expenses of complying with drinking water treatment and wastewater discharge regulations. Greywater reuse is growing in popularity in South Africa because it can supplement limited freshwater resources in the face of increasing aridity and demand (Nel et al., 2022). As such greywater reuse is encouraged as a method for addressing freshwater shortage.

Reusing greywater is a practical way to augment household water use, especially for outdoor irrigation and it has been a long-standing practice in various water-scarce nations and regions all over the world (Gómez-Monsalve et al., 2022). To lessen the need for freshwater and address the global water shortage, treated greywater may be utilised for non-potable end uses instead of freshwater (Ghaly et al., 2021). Reusing greywater for toilet flushing and garden watering can save between 30 and 50% of potable water (Ghaly et al., 2021). The permissible concentration of organic contaminants in greywater is strictly regulated worldwide. Other than the actual concentration of the organics, total suspended solids (TSS), turbidity and electrical conductivity are the key indicators of greywater pollutant load. Therefore, monitoring TSS and turbidity is essential for maintaining the aesthetic quality of treated greywater, and most nations apply severe turbidity and TSS control regulations. According to Oh et al. (2018), the most shared guidelines for treated greywater are 10 NTU for turbidity and 30 mg/L for TSS. To ensure human safety, The majority of regulation require that the amount of hazardous bacteria in treated greywater be as low as possible.

Greywater reuse can help sustainably managed ecosystems provide more clean water, food, and habitat for wildlife (Gomez et al., 2022). These systems integrate their human occupants into biological cycles while recovering important "waste" products, manure, home compost, and greywater.

In nations and regions with limited freshwater supplies, recycling wastewater allows the substitution of freshwater for recovered water in uses that don't require drinking water. Potential water reuse applications include irrigation for agriculture, landscaping, industrial reuse, groundwater replenishment, urban uses like street cleaning and firefighting, as well as recreational and ecological uses (Manikandan et al., 2022). Agricultural runoff and return flows, stormwater, cooling water and industrial process, municipal wastewater, and produced water from natural resource extraction activities are some of the sources of reusable water.

2.4. What is greywater?

Greywater is defined as wastewater generated from bathroom sinks, showers, kitchen sinks, or baths and laundry outputs (Mainardis et al.,2020). It does not include toilet inputs and can be used to replace freshwater for applications like irrigation and toilet flushing.

2.4.1 Studies done on greywater treatment

Table 2-1 shows different greywater treatment methods used in various studies between 2015 and 2023, highlighting their performance, advantages, and limitations. The studies show that several technologies, such as rotating biological contactors, membrane bioreactors, filtration systems, biochar filtration, electrocoagulation, activated carbon, and constructed wetlands are capable of eliminating significant amounts of pollutants like BOD, COD, turbidity, nutrients, and pathogens. Many of these systems achieve high pollutant removal efficiencies (often above 80–95%), improving water quality for reuse applications such as toilet flushing and irrigation. However, most methods also have drawbacks, including high energy consumption, expensive operation and maintenance, or clogging problems, which highlight the need for more cost-effective and sustainable treatment alternatives. Summary of Studies done on greywater treatment are listed in **Table 2-1** below.

Table 2-1*: Shows studies done on greywater treatment*

Study	Year	Treatment method	Findings	Location	Advantages	Disadvantages	Ref
1	2021	Rotating biological contactors	Faecal coliforms, heterotrophic bacteria and certain pathogens were eliminated by RBC	Pakistan	High treatment effectiveness	Excessive energy use	Abdelkader (2021)
2	2022	Membrane Bioreactor and Biological Aerated Filter	Both MBR and BAF-treated greywater satisfied the requirement for reusing water for flushing toilets.	Done in the Laboratory	Superior effluent quality is provided by MBR systems. Compact designs and great treatment effectiveness are provided by BAF systems	MBR- High maintenance and operating expenses BAF- Problems with clogging	Ren et al. (2022)
3	2015	Filtration	When compared to dual media filters, nylon rope filter media performs better during the filtration stage. (Activated carbon and *Zea mays* fodder combination).	India	Enhanced quality of water	Clogging	Shegokar et al. (2015)

4	2017	Membrane bioreactor	The COD removal efficacy was between 80 and 95%. The average elimination of TN and ammonia was 85.1% and 80.5, respectively, at a high level.	Spain	Elevated quality of effluent.	High operating costs and capital	Atanasova et al. (2017)
5	2022	Biochar-based column filtration.	Between 50 and 99% of pollutants were removed by BCFS.	UK	Efficient elimination of pollutants.	Possible leakage of contaminants.	Quispe et al. (2022)
6	2022	Electrocoagulation treatment process.	At ideal operating conditions, 70% COD removal, 87.5% BOD removal, 82.7% nitrate removal, and 84.7% phosphate removal were accomplished.	Mumbai, India	Minimal costs for upkeep and operation	High energy consumption.	Patel et al. (2022)
7	2023	Electrocoagulation-electrooxidation process	Removal rates of 96.1%, 97.5%, 90.9%, and 98% for COD, colour, turbidity, and TOC, respectively.	Qazvin, Iran.	High effectiveness of removal.	High energy cost.	Mousazadeh et al. (2023)

8	2021	Granular Activated Carbon.	Broad range of contaminants from aqueous solutions were absorbed.	Canada	Absorbs a variety of contaminants.	Costly.	Sharaf et al. (2021)
9	2021	Rotating biological contactors.	BOD removal was ranged between 84.0% and 95.0% for all concentrations of influent greywater.	Turkey	Cost effective.	Needs regular inspection and maintenance	Mizyed (2021)
10	2020	Constructed wetlands.	Achieved 92% turbidity removal, 85% TSS removal, 89% COD removal and 88% BOD removal.	Italy	Improves water quality.	Clogging	Collivignarelli et al. (2020)

2.5. Challenges with treating and reusing greywater

According to Oh et al. (2018), greywater has several negative aspects, such as high turbidity and microbiological contamination by viruses, bacteria, and protozoa. Greywater has been found to have suspended particle concentrations between 149 and 162 mg/L, which is more than the minimal values permitted for surface dumping in several states. When greywater is not appropriately absorbed into the ground or drained away, dangerous contaminants such as viruses, fungi, bacteria and protists can build up because they stick to suspended particles in highly turbid water. Greywater has been found to have a high alkalinity (low acidity) because of soap and detergent residues, which might be harmful to plant growth (Rakesh et al., 2020).

Sodium compounds are typically used as "filler" ingredients in powdered detergents and soaps. This makes laundry detergents, softeners, and soaps with high salt, potassium, or calcium content unsuitable for use when greywater is intended for irrigation. This is because these substances have an alkaline pH, which increases the soil's alkalinity when it is applied to the surface. Human contact might also result in the microbial contamination of greywater. When sick persons take a shower, wash their hands, or do their laundry, pathogens can be released into the greywater (Nagarkar et al., 2021). Faeces with *E. coli* can enter greywater through the bathtub and underwear rinsed in the washing. Over the course of a year, researchers from the University of Arizona studied the composition of greywater from ten residences and further analysed how it affected the soil that they irrigated. The results demonstrated that there were more faecal coliforms than they had anticipated in the greywater. The potential of disease transmission is among the most important issues with greywater reuse. This makes it necessary that greywater indicator organism concentrations should be known to decide what safety measures should be implemented to protect public health.

The digestive system of warm-blooded animals is rich in faecal coliform bacteria (Nagarkar et al., 2021). Due to their regular occurrence in the faeces of warm-blooded animals and ease of detection, these organisms are utilised as markers of the existence of harmful bacteria or the level of disinfection. A potential presence or concentration of harmful bacteria is indicated by elevated levels of faecal coliform bacteria. Greywater might include chemical and organic substances that endanger human health and contaminate the environment. Greywater contains a variety of elements, with detergents as its main source, including salts, pathogens, home medications, personal care products, organics, and nutrients.

When compared to the rest of residential wastewater, greywater has lower quantities of organics, sediments, nutrients, and pathogen contamination (Nagarkar et al., 2021). Pathogen concentrations in greywater have been found in several investigations to be higher than the legal limits for recovered wastewater and drinking water. It is common practice to interpret the presence of indicator organisms as evidence of faecal pollution and, consequently, of infections and diseases that are dangerous to human health. To reduce exposure to pathogens, greywater should be handled carefully and reused. Greywater that has not been properly handled can modify the properties of the soil and increase plant toxicity by collecting salts, surfactants, and boron in the water and soil (Nagarkar et al., 2021).

2.6. Treating water using pervious concrete technology.

According to Chandrappa and Biligiri (2016), pervious concrete is constructed from a single size of Portland cement, coarse aggregate, water, and a negligibly small amount of sand. At a time where the reuse of wastewater has raised worries about public health dangers, pervious concrete has been shown to have water treatment qualities on its own (Alimohammadi et al., 2021). Pervious concrete has been used extensively in stormwater management. Due to the large surface area that runoff must traverse as it infiltrates, pervious pavements themselves offer a porous medium on which contaminants such as metals may be immobilised. According to Ahmed and Hoque (2020), pervious concrete can infiltrate at a rate of 5-45 m/h and often contains 20% voids. In addition to improving the pH level, experiments by Alimohammadi et al., (2021) have revealed that correctly constructed pervious concrete may efficiently treat pollutant-laden, acidic water by removing most unwanted contaminants such as sulphate (SO_4^{2-}), iron (Fe), zinc (Zn), salt (NaCl), magnesium (Mg), manganese (Mn), and a host of other metals. Petroleum compounds (polycyclic aromatic hydrocarbons) and oil and grease are decreased in the water effluent that is drained through pervious concrete in practical applications of pervious concrete in pavements (Alimohammadi et al., 2021).

Shabalala et al. (2017) demonstrated the environmental advantages of pervious concrete in enhancing water quality through the capturing pollutants. With the correct design, pervious concrete may effectively purify acidic and pollutant-laden water by filtering out undesired pollutants, including sulphate, iron, zinc, magnesium, manganese, and salts. Additionally, according to Shabalala and Ekolu (2019), pervious concrete can be used to remediate mine water for applications such as irrigation.

This technique is classically used to drain stormwater runoff from sidewalks, parking lots, roads, and other surfaces. According to Chandrappa et al. (2016), porous pavements in metropolitan areas are known to lessen surface run-off and rainfall buildup during rain events. Pervious concrete can also operate as a pollutant sink for runoff because of its ability to retain particles through filtration. Due to the high porosity of pervious concrete, air and water penetration are both effectively filtered and exchanged (Ekolu et al., 2014). Since permeability is one of the most crucial performance factors for pervious concrete, understanding the amount, kind, and size of sediments that could impede flow in permeable pavements and gradually reduce permeability is essential to the long-term usage of these materials. It is acknowledged that one dependable stormwater control solution is pervious concrete. When used in paving structures, the pervious concrete's design permits water to permeate through the pavement and into the underlying soils (Agrawal et al, 2017; Dash et al, 2018).

2.7. Wastewater treatment using *Moringa oleifera* seeds.

The drumstick tree, *Moringa oleifera*, is a fast-growing perennial shrub that is indigenous to the tropics and subtropics, particularly the Himalayas (Devkota and Bhusal, 2020). Since ancient times, *Moringa oleifera* has been utilised to treat and prevent various illnesses including heart disease and diabetes (Thanki and Singh, 2021). Due to its capacity to lessen turbidity and microbiological presence in water, *Moringa oleifera* seed powder is used. According to Devkota and Bhusal (2020), *Moringa oleifera* extract is safe for the environment, non-toxic, biodegradable, and does not change the conductivity or pH of the treated effluent.

Given the high turbidity levels in greywater, it is impossible to understate the potential of moringa extracts in the treatment process (Ntibrey et al., 2020). Al-Gheethi et al. (2017) observed that a dosage of 120 mg/L of *Moringa oleifera* seeds effectively removed 83.63% of the turbidity from wastewater via adsorption and coagulation. The study further demonstrated that when employed as a coagulation agent, moringa seed extract produces less sludge than alum. Brar (2022) also observed that the application of moringa seed extract resulted in bacterial elimination in untreated water of 90-99.99%. Laboratory scale research has demonstrated that *Moringa oleifera* seeds are safe for both humans and animal consumption and have efficient coagulative characteristics. According to Brar (2022), activated carbons prepared from the husks covering moringa seeds proved efficient in water treatment by adsorption.

2.8. Treating wastewater using activated carbon

One innovative way to meet different water quality criteria is to use activated carbon, an adsorption medium. Activated carbon adsorptive treatment is a long-established technology that has been used for thousands of years to improve drinking water quality (Perrich, 2018). It has been utilised worldwide in a variety of forms (powdered and granular) for multi-objective purposes, including the removal of heterogeneous compounds that, following disinfection, produce colour and precursors to pollutants, trace organic and inorganic contaminants, and chemicals that give surfaces flavour and odour.

Additionally, activated carbon can be used with flexibility in both biological and adsorption modes (Perrich, 2018). In the latter, it offers a big surface area for the adsorption of organisms and breaks down organic pollutants. According to Shukla et al. (2020), water treatment utilities may use activated carbon for a variety of reasons such as: i) regulatory compliance with existing legislation, ii) pre-emptive compliance to anticipated regulations, iii) protecting public health and fostering customer confidence, and iv) sustainability considerations.

Applications for activated carbon include power plant and landfill gas emissions, precious metal recovery, ground and municipal water treatment and drinking water purification for both industrial and domestic use (Sajid, 2023). Activated carbons have demonstrated efficacy in eliminating a range of contaminants from aqueous solutions such as dyebath wastewater, pharmaceuticals, personal care products (PPCPs) and heavy metals (Sultana et al., 2022). The material's adsorption capacity with the increase in the pores that are formed during the processes that transform raw materials to activated carbon during. These pores are involved in the process of water treatment in that the pollutants' molecules lodge themselves into the pores resulting in mass transfer from the liquid to the pollutant surface. The removal of the pollutants results in colour and smell eliminateion (Alves et al., 2021).

2.9. Benefits of greywater reuse

Treated greywater can be used for domestic chores such as washing clothes, flushing toilets and irrigation of lawns, ornamental plants gardens, and food crops. Reusing greywater for irrigation and other non-potable water uses aids in re-establishing the natural water cycle in urban ecosystems, which considerably advances the cause of sustainable urban growth (Mohamed et al., 2019). Reusing greywater conserving the already scarce drinking water by replacing it in domesic chores that do not require ultrapure water. Such activities include irrigation, industrial processes, toilet flushing, and laundry washing. This results in lower freshwater usage in addition to generating less wastewater. Greywater recycling has the potential to significantly increase national water reserves in areas of the world where water is limited, including the Middle East and Africa (Mohamed et al., 2019). The availability of water for irrigation can be increased, resulting in higher agricultural output.

Greywater recycling has several benefits, including reducing freshwater withdrawal from rivers and aquifers, reducing the impact of wastewater treatment plants on infrastructure, nitrifying soil, reducing energy consumption and chemical pollution from treatment, replenishing groundwater, improving agricultural productivity, nutrient reclamation, and improving surface and groundwater quality (Baykal, 2019). According to Boano et al. (2020), recycled water is perfectly safe and, in some cases, even contains essential elements that might promote plant growth.

2.10. Chapter summary

This chapter has given an overview of available sources (literature review) relevant to the treatment of greywater, the different treatment methods used, and their effectiveness in removing the toxins and impurities in greywater. Several methods that have been proven by previous studies to be effective in the treatment of greywater, including filtration methods, rotating biological contactors (RBCs), constructed wetlands, up-flow anaerobic sludge blanket (UASB), sequencing batch reactor (SBR), and membrane bioreactor (MBR) have been discussed. Additionally, challenges with treating and reuse of greywater have been reviewed. The following chapter gives a detailed description of the methods used to analyse the results of this study.

CHAPTER 3

METHODOLOGY

3.1. Introduction

This chapter explains the materials and methods used to determine the pervious concrete permeable barrier as a potential remedial technology for the treatment of greywater. Pervious concrete allows water to seep into its structure through a network of interconnected spaces since it is naturally permeable. Methods used include batch reactor tests, column tests, and a laboratory-scale greywater treatment system. Proper planning, compacting, and maintenance of pervious concrete can yield numerous sustainability benefits. The greywater treatment experiments, collection, and pervious concrete characterisation (experimental, sample preparation, and material analysis) is explained in this chapter.

3.2. Description of the study area

The study was conducted at the University of Mpumalanga, Mbombela campus (25, 4365˚ S, 30, 9818˚E), under laboratory conditions. The University of Mpumalanga is found in Mbombela (Nelspruit), South Africa, as shown in **Figure 3-1**. It was established in 2014 when it initially accommodated a small number of students. Nelspruit serves as the capital of the Mpumalanga province and is situated in the Lowveld region. With warm subtropical temperatures and heavy summer rains, the Lowveld has a tropical environment. Analyses of greywater samples were done at the Water-lab in Pretoria, South Africa.

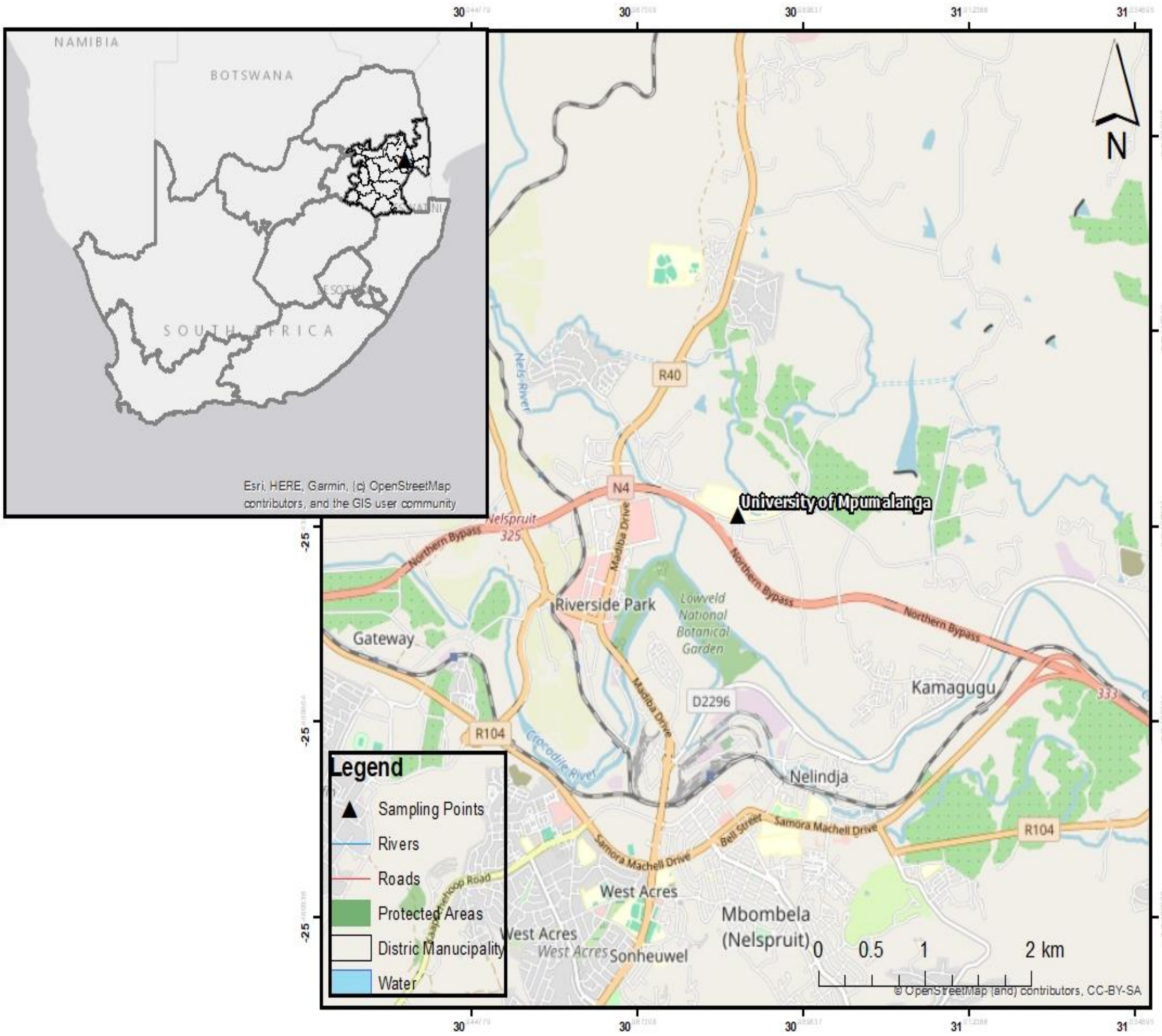

Figure 3-1: Map of study area

3.3. Collection of Greywater

Greywater was collected from a student residence at the University of Mpumalanga as shown by the sequence of pictures in **Figure 3-2** and was brought into the laboratory to be used for further experimental investigations. Greywater was collected in the drainage using the bucket method, and was stored in the laboratory and covered with a black plastic bag before being used for conducting experiments. The physical parameters pH, biochemical oxygen demand (BOD), electrical conductivity (EC), total dissolved solids (TDS), turbidity, E. coli, Macro elements (Na, Ca, Mg, K, P, and

Nitrate) and micro elements (iron (Fe) and Manganese (Mn)) were analysed. pH was analysed using Hanna HI98107 pH Tester, country of production is Romania, also manufactured by Hanna Instruments. Electrical Conductivity (EC) was analysed using Hach HQ14d Conductivity Meter, country of production is United States. Total Dissolved Solids (TDS) was analysed using HM Digital TDS-3 Meter, country of production is South Korea. Turbidity was analysed using Hach 2100Q Turbidimeter, country of production is United States. Biochemical Oxygen Demand (BOD) was analysed using OxiTop IS 6 BOD System, country of production is Germany. *E. Coli* was analysed using IDEXX Colilert-18 Quanti-Tray System, country of production is United States.

***Figure 3-2**: Collection of greywaters from the University of Mpumalanga student residences, drainage system.*

3.4. Materials and sample preparation

Activated carbon was purchased from H_2O/BWT International, Nelspruit while *Moringa oleifera* seeds were purchased from takealot.com. Portland cement and 50 kg of ground-granulated blast furnace slag (GGBS) were supplied by AfriSam Ltd. and Pretoria Portland Cement Company, respectively. Granite, water, and superplasticiser for concrete were acquired from local suppliers.

3.4.1. Casting of pervious concrete

The concrete was made up of a mixture of 33 kg Portland cement 52.5R, 189 kg of a single-size aggregate of granite in the size ranges 6-7 and 8-10-mm, 14 kg Ground Granulated Blast-furnace Slag (GGBS), 800 ml concrete super plasticizer (Chryso Fluid premia 310) and 13 Litres of water. These were all poured into a fuel-operated concrete mixer and allowed to mix for approximately five (5) minutes and then scooped into 30×18×12mm and 19×15×9 mm rectangular plastic containers and compacted to create a tightly connected course permeable matrix with permeability values in the range 20 - 30% blocks of concrete. These blocks were air cured for seven (7) days and then water cured for 30 days at room temperature as can be seen on **Figure 3-3**.

Figure 3-3*: Casting of pervious concrete used in the experiments. a) A mixture of 33 kg Portland cement 52.5R, 189 kg of a single-size aggregate of granite in the size ranges 6-7 and 8-10-mm, 14 kg Ground Granulated Blast-furnace Slag (GGBS), 800 ml concrete super plasticizer (Chryso Fluid premia 310) and 13 Litres of water were all poured into a fuel-operated concrete mixer and allowed to mix for approximately five (5) minutes. b) The mixture was poured down on the black plastic to be filled in the plastic containers. c) The mixture was then scooped into 30×18×12mm and 19×15×9 mm rectangular plastic containers. d) The blocks were air cured for seven (7) days. e) The blocks were water cured for 30 days at room temperature. f) The final product (pervious concrete blocks).*

3.5. Experimental procedure

3.5.1. Batch reactor tests experiment

Pervious concrete, which was prepared from a mixture of Portland cement 52.5R, granite, slag/GGBS, water and concrete super plasticizer, was mixed with powdered *Moringa oleifera* seeds as shown in **Figure 3-4**. The blocks were used to conduct batch reactor tests for the treatment of greywater as shown in **Figure 3-5**. The batch experiments where 1 L of reactive material was mixed with 3 L of greywater, were monitored for a period of 30 days. Containers were closed firmly to prevent evaporation. During the first 7 days, 200 mL of aqueous samples were collected once a day and afterward the frequency of sampling was then reduced to three times a week. A batch reactor experiment was carried out to assess the water quality that pervious concrete produced. Comparisons regarding greywater's treatability were then made using pervious concrete versus using moringa as an adsorbent.

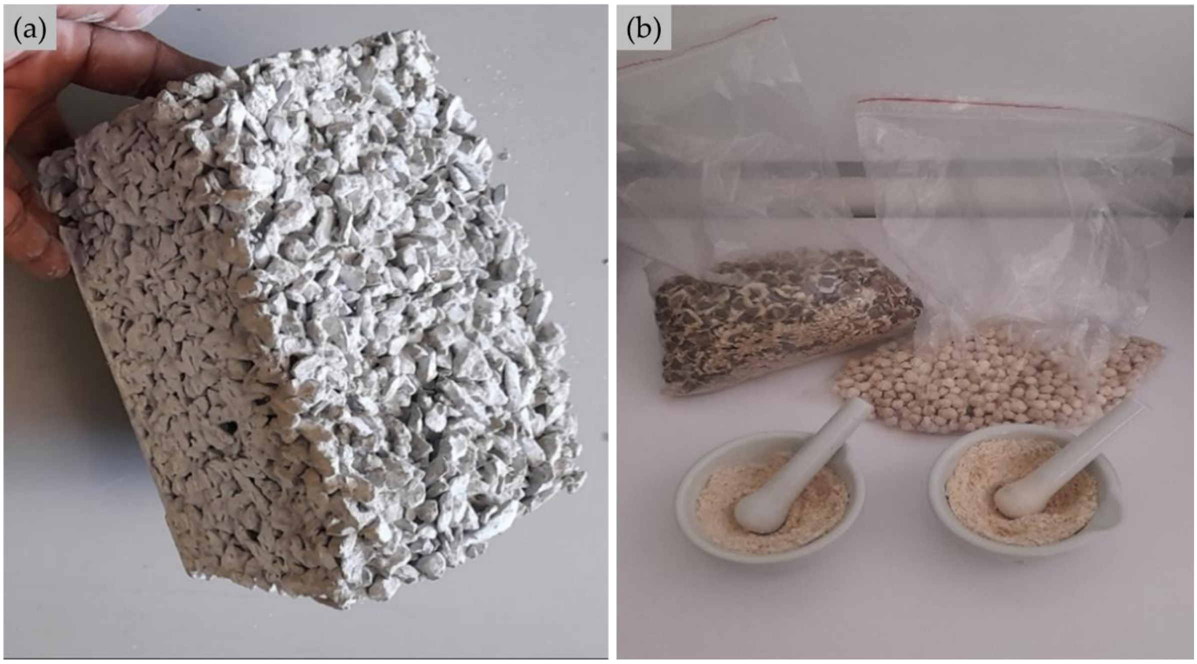

Figure 3-4: *(a) Pervious concrete and (b) moringa seeds*

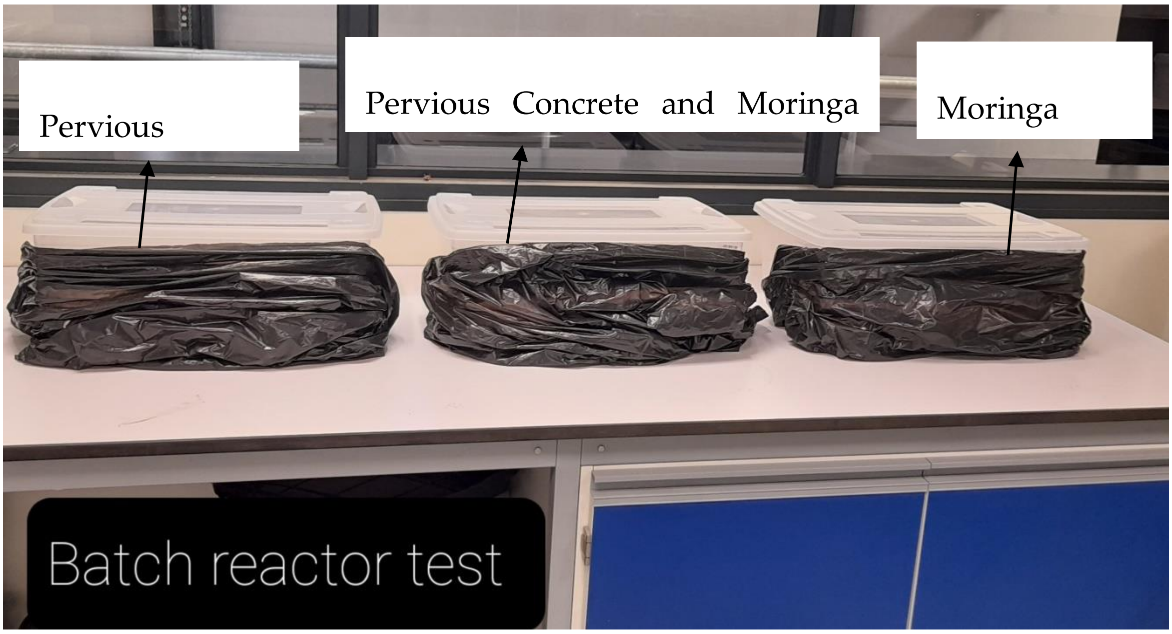

Figure 3-5: *Batch reactor tests (Experimental setup)*

3.5.2. Column tests experiment

Three pervious concrete cubes together with activated carbon were placed inside a column to conduct column test experiments as shown in **Figure 3-6**. The performance of pervious concrete was both compared to that of activated carbon and evaluated in combination with activated carbon. The comparison was conducted to assess the individual treatment efficiencies of each material, while the combined application was investigated to determine whether their integration would enhance overall treatment performance. This approach allowed for a comprehensive assessment of their effectiveness both independently and synergistically. Greywater was pumped from an elevated reservoir to the bottom of the column. During the first week, samples were collected once a day. Thereafter, the frequency of sampling was reduced to twice a week as the significance of temporal fluctuations in metal concentrations diminished. The experiment ran for a period of 5 months. Column tests were done to determine the long-term performance of the greywater treatment system.

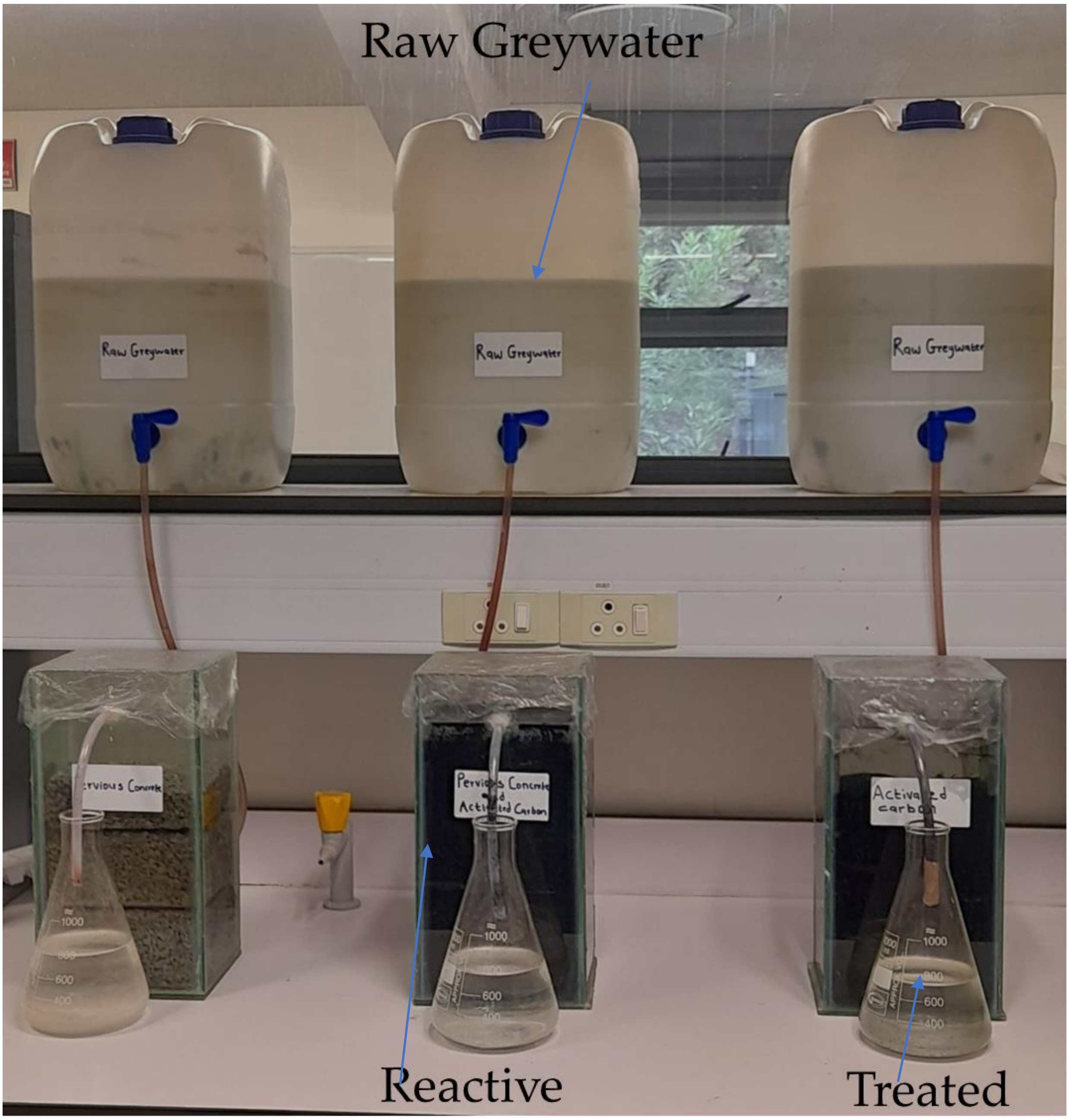

Figure 3-6*: Column tests experimental setup where the columns from left to right consist of pervious concrete, pervious concrete/activated carbon and activated carbon.*

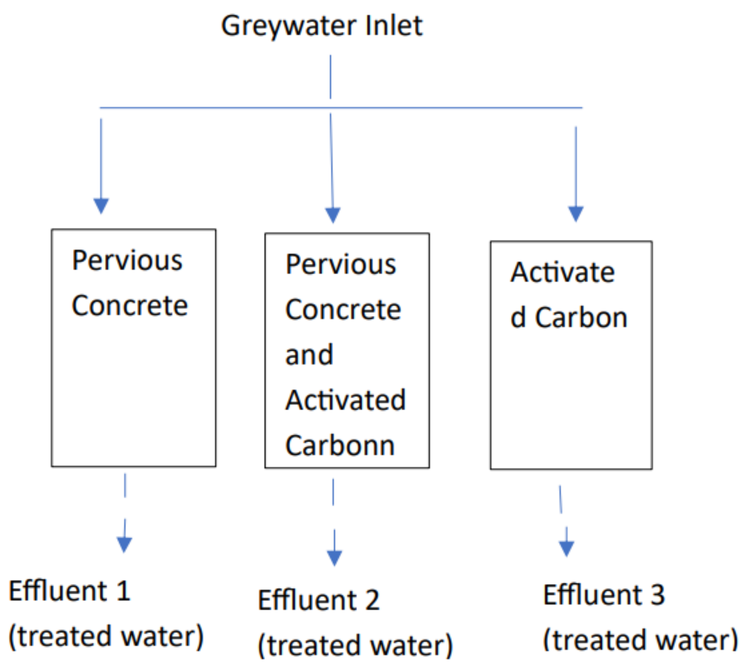

Figure 3-6 (a): *Schematic diagram (Column tests)*

3.5.3. Laboratory-scale greywater treatment system

The greywater treatment system consisted of multiple stages of physical operation, including a raw greywater unit, sedimentation unit, sand and gravel filtration unit, pervious concrete unit, and the storing unit for treated greywater as can be seen in **Figure 3-7**. A sedimentation unit was used to filter the greywater. The purpose of the sedimentation unit was to keep the water flowing steadily. Lighter pollutants float at the liquid's surface, whereas heavier particles settle at the tank's bottom. Clear water passed from the sedimentation unit to the sand and gravel filtration unit (Tusiime et al., 2022). A net weigh of 5 kg materials consisting of sand and gravel were used as filter media in the filtration unit. A mass of 5 kg of pervious concrete was used as reactive media in the pervious concrete unit. Water flow was accomplished by gravitational flow from the raw greywater unit to the storage unit for treated greywater. The flow rate was adjusted to 40 mL/h. Samples were collected from the raw greywater and the storage unit (treated greywater) for analysis.

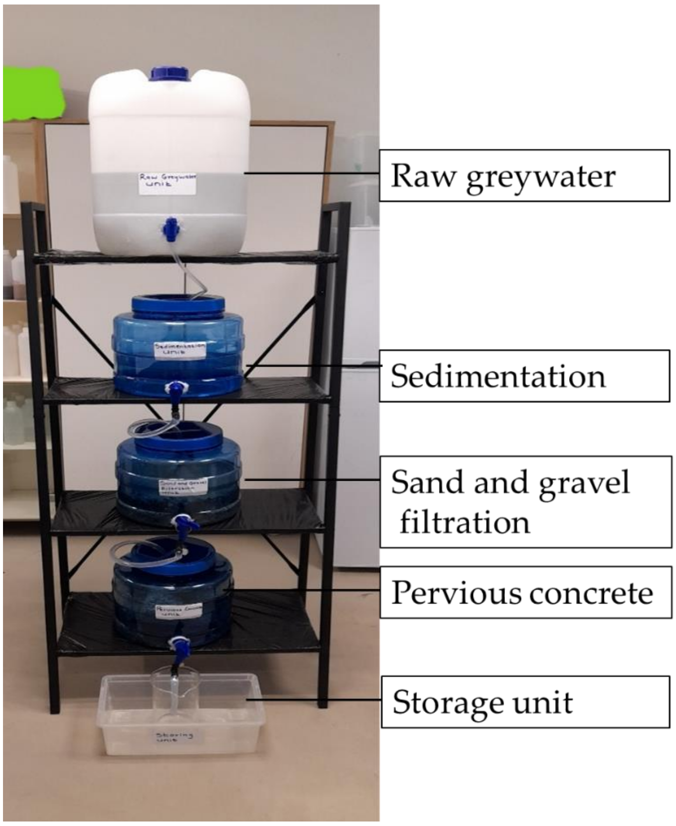

Figure 3-7: *Laboratory-scale greywater treatment system experimental setup.*

3.6. Analyses of samples

3.6.1. Physico-chemical characteristics of treated and untreated greywater

Raw and treated greywater samples were taken to a laboratory for the determination of the physical parameters pH, biochemical oxygen demand (BOD), electrical conductivity (EC), total dissolved solids (TDS), turbidity, *E. coli*, Macro elements (Na, Ca, Mg, K, P, and Nitrate) and micro elements (iron (Fe) and Manganese (Mn)).

HANNAH instruments (Combo HI98129 and Multiparameter HI98194) were used in determining parameters such as EC, pH, TDS, and Temperature. ***Table 5-3*** (Appendix) shows methods/instruments used in analysing the other parameters (BOD, *E. coli*, turbidity, Na, Fe, Mn, P, Nitrate, Ammonia). pH was analysed using Hanna HI98107 pH Tester, country of production is Romania, also manufactured by Hanna Instruments. Electrical Conductivity (EC) was analysed using Hach HQ14d

Conductivity Meter, country of production is United States. Total Dissolved Solids (TDS) was analysed using HM Digital TDS-3 Meter, country of production is South Korea. Turbidity was analysed using Hach 2100Q Turbidimeter, country of production is United States. Biochemical Oxygen Demand (BOD) was analysed using OxiTop IS 6 BOD System, country of production is Germany. E. Coli was analysed using IDEXX Colilert-18 Quanti-Tray System, country of production is United States.

3.6.2. Irrigation water indices

After treatment, the water's suitability for irrigation was assessed. Water quality indices such as Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP) and Kelly's ratio (KR) were determined and compared against standard water quality requirements for irrigation.

3.6.2.1. Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) which is given by ***Equation 3-1*** is an irrigation water quality parameter used to manage sodium-impacted soils. According to Asadi et al. (2019), the amount of earth-alkaline and primary alkaline cations in the water indicates whether it is suitable for use in agricultural irrigation. It is a typical diagnostic metric for a soil's sodicity risk, as assessed by an examination of pore water drawn from the soil. Sodium adsorption ratio (SAR) is calculated using the formula:

$$SAR = \frac{[Na^{+}]}{\sqrt{\frac{[Ca^{2+}+Mg^{2+}]}{2}}}$$ *Equation 3-1*

SAR enables the evaluation of a soil's flocculation or dispersion of clay particles. Clay particles' dispersion is aided by sodium and potassium ions, whereas their flocculation is aided by calcium and magnesium ions (El Bilali et al., 2021). The behaviour of clay aggregates affects the permeability of the soil, which directly affects the rate of water infiltration, as well as the soil structure. SAR is a calculation of how much Na^{+} soil can hold. High quantities of sodium in the soil can accumulate over time because of irrigation water with high SAR levels, which can slow down soil infiltration and percolation. According to Asadi et al. (2019), the presence of high Na^+ concentrations in the soil may cause Ca^{2+} and Mg^{2+} ions to be replaced by Na^+ ions. This could damage the soil's structure and cause waterlogging and poor plant growth. Sandy soils experience fewer issues, while fine-textured soils experience serious issues if SAR is higher than 9. There won't be a problem if SAR is less than 3.

3.6.2.2. Soluble Sodium Percentage (SSP)

Irrigation water is categorised based on its soluble Na^+ content and it is calculated as a percentage of Na^+ to the sum total of the Ca^{2+}, M^{2+} and K^+ as shown in ***Equation 3-2***. Water with an SSP of less than 60% is of good quality and is acceptable for irrigation, whereas water with an SSP of 60% or more is of low quality and is not suited for irrigation (Singh et al., 2020). The formula for calculating SSP is:

$$SAR = \frac{[Na^{+}]\times 100}{[Ca^{2+} + Mg^{2+} + K^{+}]} \qquad \textit{Equation 3-2}$$

3.6.2.3. Kelly's ratio (KR)

The Kelly's Ratio (KR), one of the key index factors used to evaluate irrigation water. It is the ratio of sodium to calcium and magnesium as depicted by ***Equation 3-3*** (Balamurugan et al., 2020). If the KR value is higher than 1.0, the water has too much Na^+ in it and is, therefore, unfit for irrigation. A KR number between 1.0 and 2.0 denotes marginal appropriateness, whereas a value under 1.0 denotes irrigation water of high quality. The formula for calculating Kelly's ratio is:

$$KR = \frac{[Na^{+}]}{[Ca^{2+} + Mg^{2+}]} \qquad \textit{Equation 3-3}$$

3.6.3. X-Ray Diffraction (XRD)

A non-destructive method for describing crystalline materials is X-ray diffraction (XRD). It gives information about critical features such as crystal structure, phases, preferred crystal orientation, crystallite size and strain. The X-rays diffract through the crystal and enter a detector when a crystalline sample is in the path of the beam. The planes of the crystals match the angles at which the beam is diffracted into the detector. To determine the material in the solid samples, the diffraction data are compared to the standard database kept up to date by the International Centre for Diffraction Data (Ali et al., 2022). Mineral analysis of reactive materials was carried out using X-Ray Diffraction (XRD) operated at a scan rate of 0.02◦, 2-theta per minute using a Pan Analytical X-ray X'pert PRO diffractometer, manufactured by PANalytical in Netherlands. A copper X-ray tube and a PW3830 X-ray generator running at 40 kV and 40 mA made up the XRD instrument, and the Pan Analytical X'pert High Score Plus software was used to identify the mineral phases.

3.7. Chapter summary

This chapter explained the research methods used in the research project. Pervious concrete materials were mixed and prepared to be used for experiments in the laboratory and greywater was collected using the bucket method from the student residence at the University of Mpumalanga. It also explained how the materials used in the project were characterised. The results and discussion will be provided in depth in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Introduction

In this chapter, the findings of the study are presented, emphasising the key trends and differences identified in the data. The results are analysed and discussed in relation to the research objectives, with comparisons drawn to existing literature where relevant.

4.2. Batch reactor tests

Table 4-1*: Analyses of greywater samples before and after treatment with pervious concrete, moringa seeds and a mixture of pervious concrete with moringa seeds*

	Day	Code	pH	EC (ms/m)	TDS (ppm)	BOD	*E. coli*	Turbidity (N.T.U)
Standard (General limit) Ayers and Westcot, 1989			6.5-8.0	70	500	5	10^{-6}-10^{-9}	5
Raw greywater	0	RGW	7.4	45.5	252	30	690	15
Pervious concrete	1	D1-P2	7.11	69.8	349	10	3	4.6
	7	D7-P2	10.12	50.7	254	10	1	4.7
	21	D2W3-P2	11.01	85.3	427	10	1	1.4
	30	D3W4-P2	10.89	108.6	543	10	N/A	1.4
Moringa	1	D1-M60	7.06	75.8	379	10	1	40
	7	D7-M60	6.75	80.9	405	210	250	111
	21	D2W3-M60	7.03	198.4	992	92	600	96
	30	D3W4-M60	7.31	229.3	1147	135	N/A	122
Pervious concrete & moringa	1	D1-PM48A	7.27	83.7	418	24	3	58
	7	D7-PM48A	8.41	120.1	601	20	4900	36
	21	D2W3-PM48A	9.38	185.1	926	180	1	20
	30	D3W4-PM48A	10.18	179.5	898	159	N/A	14

The data presented in ***Table 5-1*** shows analysis of greywater samples before and after treatment with pervious concrete, moringa seeds and a mixture of pervious concrete with moringa seeds. The physico-chemical characteristics of the treated and untreated greywater are detailed in ***Table 5-1***. The water parameters were contrasted with the Food and Agriculture Organization, FAO's guidelines for irrigation water quality

(Ayers and Westcot 1989). The parameters measured include pH, TDS, EC, BOD, Turbidity and *E. coli* concentration.

Pervious concrete and moringa seeds were used to conduct batch reactor tests with the greywater. The chemical, physical and microbiological characteristics of the treated greywater were assessed.

The pH value of non-treated greywater was 7.4, as shown in **Figure 4-1a**. After treatment with pervious concrete, pH increased from 7.4 to 10.89; the dissolution of portlandite from the cementitious matrix, which contributes alkalinity to the system, is the cause of the high pH values seen in greywater treated with pervious concrete (Chandrappa and Biligiri, 2016). The pervious concrete was pre-conditioned by permeation with deionised water to remove residual fines and stabilise the pore structure before exposure to greywater. Moringa seeds kept pH neutral in the range 7.06 to 7.31. The electrical conductivity (EC) and total dissolved Solids (TDS) of non-treated greywater were 45.5mS/cm and 252 mg/l, following treatment with pervious concrete, the values increased from 45,5 to 108.6 mS/cmand 252 to 543 mg/l respectively (**Figure 4-1b, c**). However, the Moringa seeds system also showed an increase in EC and TDS from 75.8mS/cm day 1 to 229.3 mS/cm on day 30, which was above the limit (70 mS/cm) and 379 to 1147mg/l, which was above the limit (500 mg/l), respectively. The pervious concrete primarily functions as a physical filtration and adsorption medium, making it more suitable for influent with higher suspended solids and particulate matter (Khankhaje et al., 2024). In contrast, the Moringa seed powder relies on coagulation–flocculation and antimicrobial mechanisms, which are more effective when the influent has lower turbidity and a more stable chemical composition. EC and TDS values of greywater treated with pervious concrete were within the acceptable limits for discharge of wastewater into a water resource and for irrigation from day 0 to day 21. The mixture of pervious concrete with moringa kept EC and TDS values above the limit at values in the range 83.7 on day 1 to 179.5 mS/cm by day 30 for EC and 418 on day 1 to 898 mg/l on day 30 for TDS. The increase in EC in water treated with moringa and pervious concrete is mainly due to the release of soluble ions and organic compounds from the moringa seeds into the water (Oluwasanya et al., 2024). Moringa seeds contain water-soluble proteins, salts (e.g. Na^+, K^+, Ca^{2+}, Mg^{2+}), and organic matter, which dissolve during contact with water, increasing the concentration of dissolved charged species. This raises electrical conductivity (EC) and consequently total dissolved solids (TDS) over time.

E. coli, BOD and turbidity were reduced from 690 CFU/100ml to <1 CFU/100ml, 30 mg/l to <10 mg/l and 15 NTU to 1.4 NTU following treatment with pervious concrete (**Figure 4-1d-f**). The reduction in turbidity from 15 NTU to 1.4 NTU cannot be attributed to sedimentation alone and is indicative of effective treatment processes, likely involving filtration and particle retention mechanisms within the treatment medium (Pinto da Silva et al., 2024). According to Sandoval et al. (2022), Pervious concrete is widely regarded as a viable approach for reducing turbidity and other water pollutants. The values of TDS, *E. coli*, turbidity and BOD exceeded the maximum limit recommended when the greywater was treated with moringa. The presence of organic debris, oils, detergents, and surfactants, typically found in greywater, could impede the coagulation process of moringa seeds. These compounds may restrict the effectiveness of seed proteins in their capacity to bind with bacteria or suspended particles (Kozyatnyk and Njenga, 2023). Therefore, the results of the batch reactor tests show that pervious concrete can be an effective and simple method that can be suitable for the treatment of greywater for agriculture and for recharging water resources.

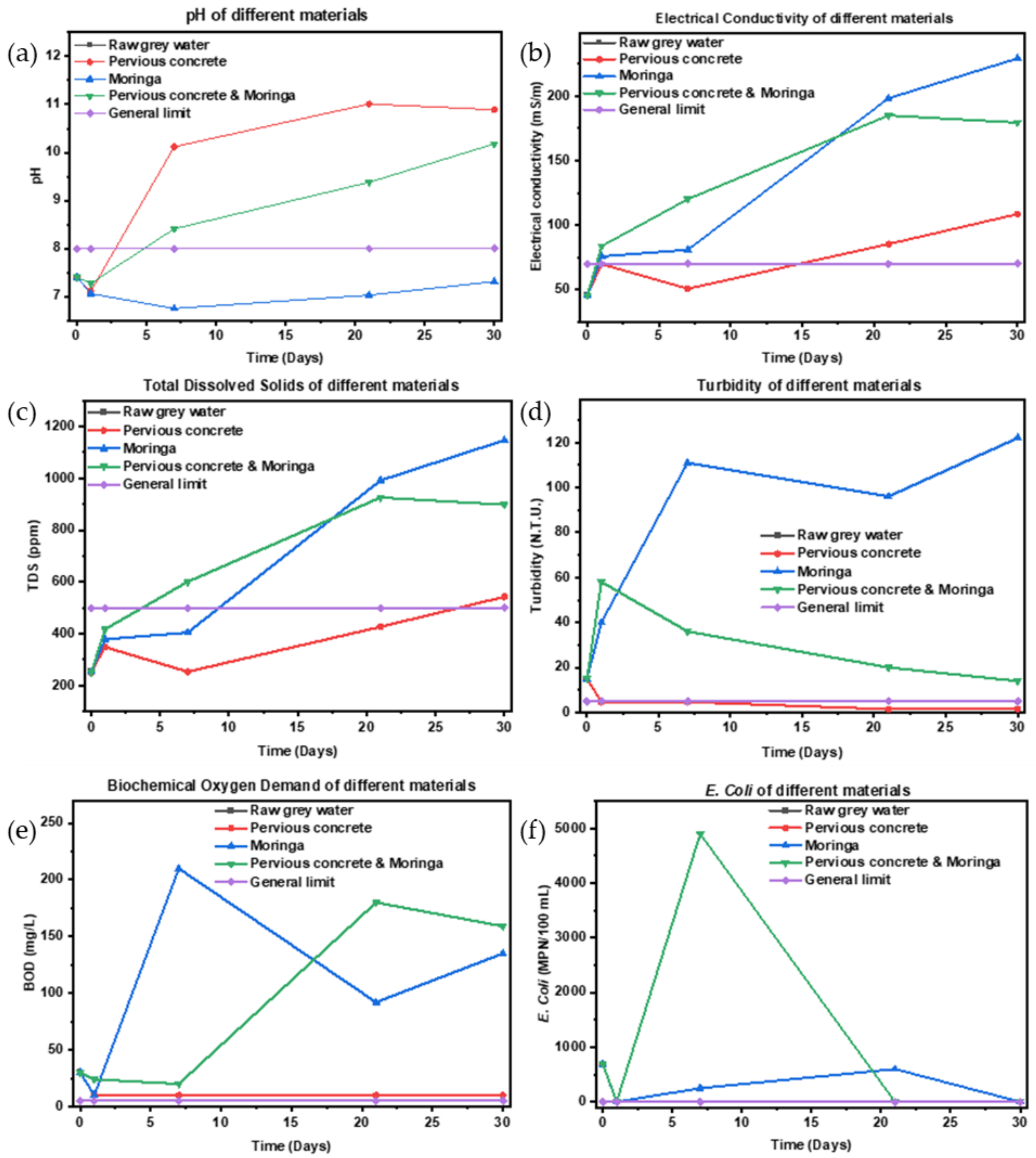

Figure 4-1: *Graphs of different parameters over time*

4.3. Column tests

***Table* 5-2** (Appendix) shows analysis of greywater samples before and after treatment with pervious concrete, activated carbon and a mixture of pervious concrete with activated carbon. Key water quality parameters include pH, electrical conductivity

(EC), turbidity, TDS, BOD, and *E. coli*. The water parameters were contrasted with the FAO guidelines for irrigation water quality (Ayers and Westcot 1989). Due to the poor performance of moringa seeds (exceeding maximum limit for EC, TDS, BOD, *E. coli* and Turbidity) in the treatment of greywater from the Batch reactor tests experiment, activated carbon was used together with pervious concrete to conduct the column tests.

4.3.1. pH

The pH of raw greywater at day 0 was 7.4, respectively. The results attained following treatment with pervious concrete gave a pH value of 9.88 to 10.01, as shown in **Figure 4-2**. The pH level exceeds the maximum permitted range of 6.5 to 8.0 for irrigation water quality (Ayers and Westcot, 1989). Following treatment with activated carbon, the pH was reduced from 9.74 to 9.25. Treatment with the mixture of pervious concrete and activated carbon increased pH from 10.21 on day 1 to 10.69 by day 54 and afterwards it decreased to 9.78 on day 119. This increase in pH is due to the alkaline nature of the pervious concrete, especially calcium-based compounds in the concrete. According to Shabalala and Ekolu (2019), high pH values have the capacity to negatively impact nutrient availability, which in turn affects crop development and productivity.

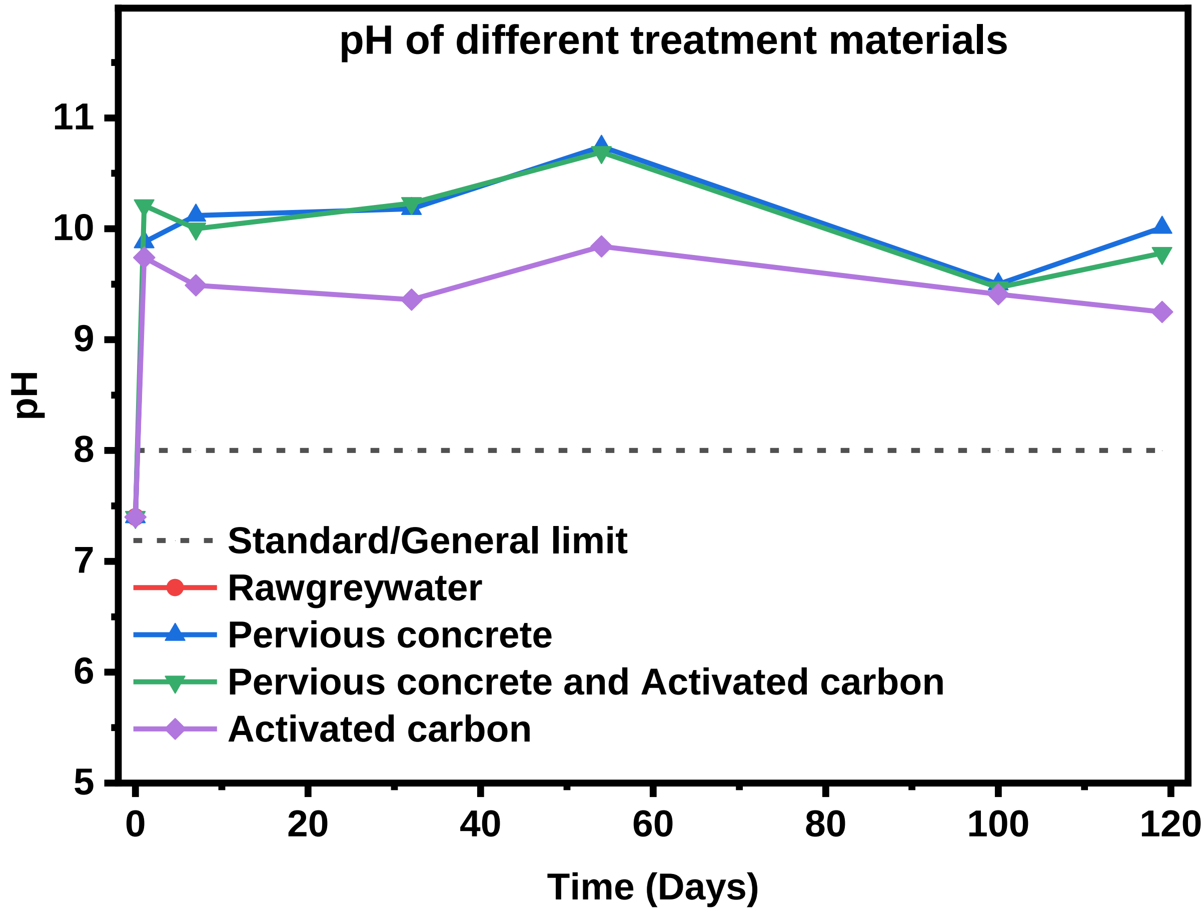

Figure 4-2: pH of various treatments over time

4.3.2. Electrical conductivity (EC)

The electrical conductivity of water is a crucial characteristic that is commonly used as a gauge of the level of mineralisation (total ion concentration) of water. It gives an evaluation of the total concentration of dissolved ions in water. (Taheri et al., 2024). The results show that the initial EC value for raw greywater at day 0 was 45.5 mS/cm, as shown in **Figure 4-3**. The EC is reduced following treatment with pervious concrete from 56.4 mS/cm on day 1 to 37.9 mS/cm on day 119, which was below the standard (70mS/cm). Activated carbon and a mixture of pervious concrete with activated carbon significantly increase EC values initially (up to 320.3 mS/cm for activated carbon and 266.7 mS/cm for the mixture on day 1), but these values decrease over time. Activated carbon can increase electrical conductivity (EC) mainly because it can release dissolved ions and minerals into the water, especially when it's new or not pre-washed (Manoleva et al., 2024). activated carbon can initially leach ions, leading to higher TDS and therefore higher electrical conductivity. The ion exchange and salt leaching from the treatment materials, particularly activated carbon, may be the cause of the initial increase in EC (Moosavi et al., 2020).

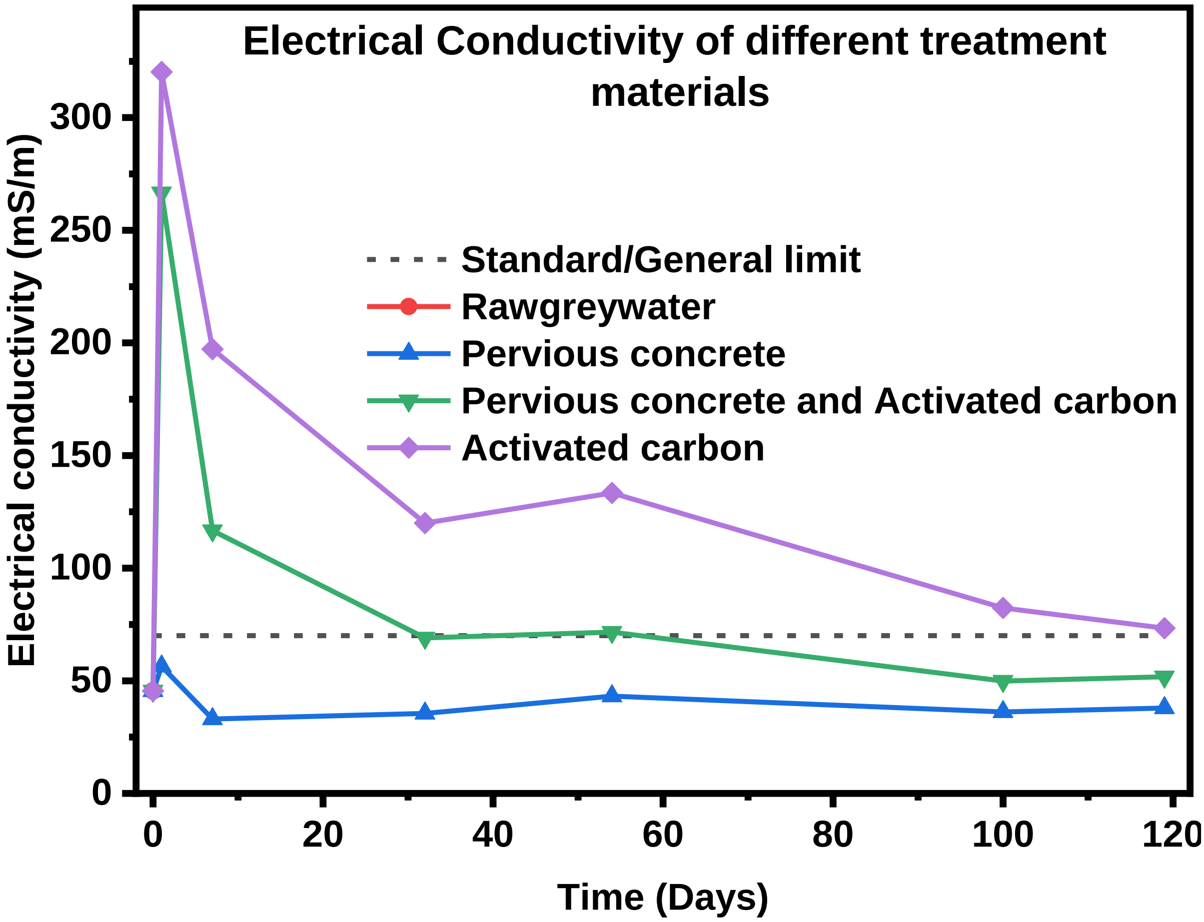

Figure 4-3*: Electrical conductivity of various treatments over time*

4.3.3. Total Dissolved Solids (TDS)

The overall concentration of dissolved compounds in water is known as total dissolved solids (Adjovu et al., 2023). The maximum permissible TDS concentrations for irrigation water quality are 500 mg/l (***Table 5-2***). **Figure 4-4** gives the changes in TDS of the treated greywater over the period of the experiment. TDS for non-treated greywater was 252 mg/l. Following treatment with pervious concrete, TDS decreased from 282 mg/l on day 1 to 190 mg/l on day 119, which was below the standard of 500 mg/l. Activated carbon increased TDS up to 1605 mg/l on day 1, and the values decreased over time. Due to dissolved ions from treatment materials, a rise in TDS is correlated with a greater EC (Barroso et al., 2023). The gradual decrease suggests efficient absorption and stability.

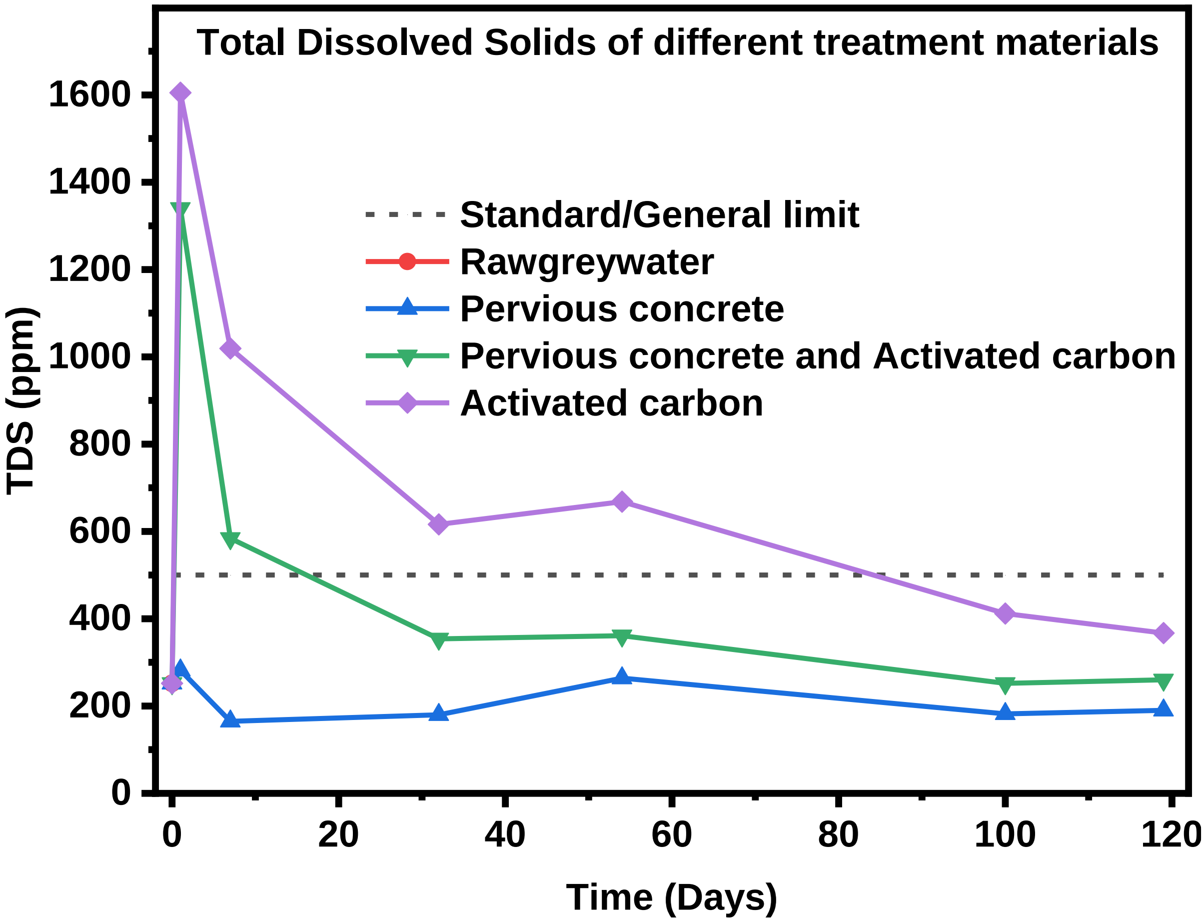

***Figure 4-4**: Reduction in total dissolved solids of various treatments over time*

4.3.4. Turbidity

The turbidity for raw greywater at day 0 was 15 NTU. The results show that all treatments substantially reduced turbidity as shown in **Figure 4-5**, from 4.0 to 1.1 NTU (pervious concrete), 2.8 to 0.4 NTU (Mixture of pervious concrete with activated carbon), 3.7 to 0.4 NTU (Activated carbon). Turbidity was reduced and within the standard for irrigation use and discharge of wastewater into a water resource by all three treatment methods.

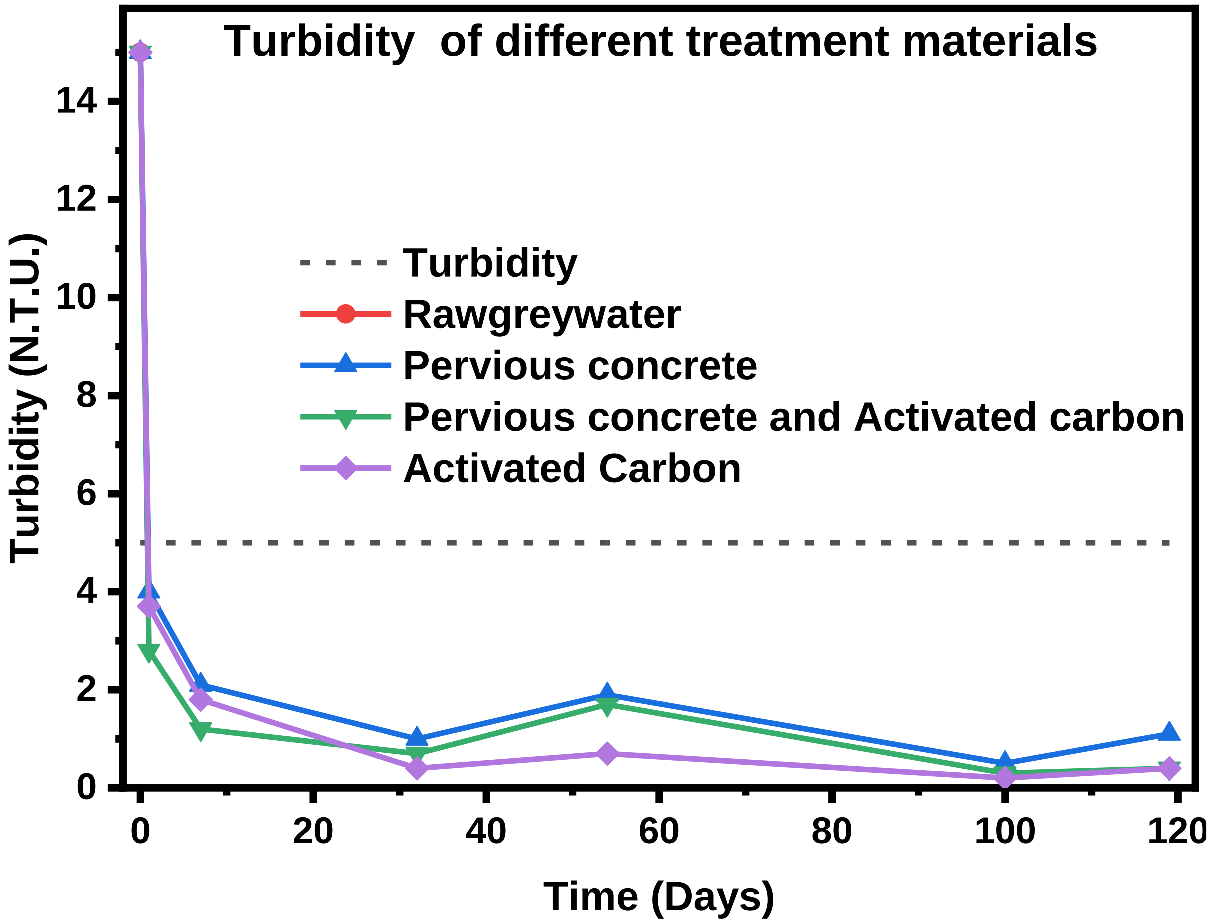

Figure 4-5: Turbidity of various treatments over time

4.4. Removal of organics-Biochemical Oxygen Demand

The BOD of raw greywater at day 0 was 30 mg/L as can be seen in **Figure 4-6**. Pervious concrete treatment steadily decreased BOD from 16 mg/l to <11 mg/l. Both activated carbon and the mixture of pervious concrete with activated carbon achieved <10 mg/l, maintaining this level throughout the experiment. Lower BOD indicates better treatment efficiency in reducing organic pollutants (Lokman et al., 2021). Adsorption and microbial activity help in degrading organic matter in greywater.

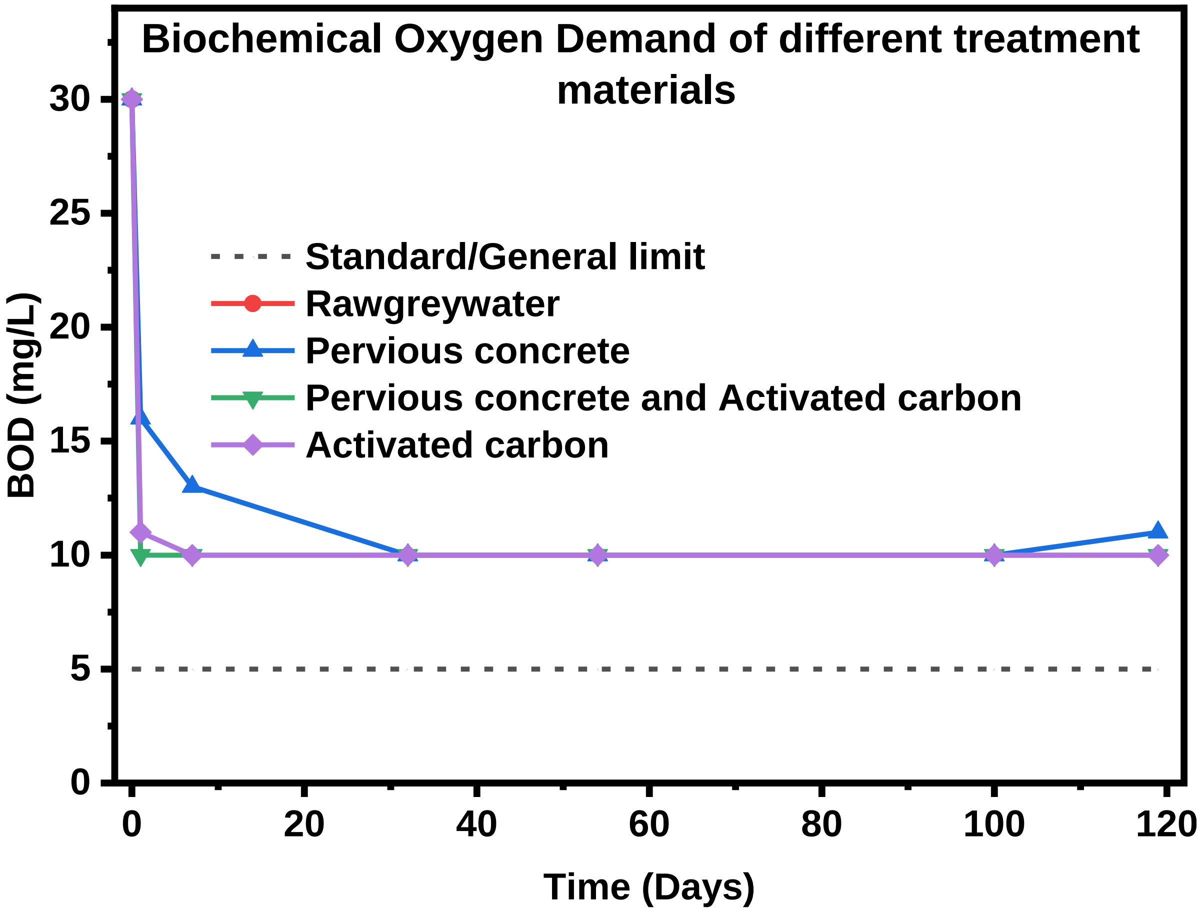

***Figure 4-6**: Biochemical oxygen demand of various treatments over time*

4.5. Microbial reduction-*E. Coli*

The *E. coli* of non-treated greywater was 690 CFU/100ml, as shown in **Figure 4-7**. Pervious concrete and a mixture of pervious concrete with activated carbon reduced *E. coli* levels to 1 CFU by day 1 and maintained this level. Activated carbon shows a minor lag, taking longer to stabilise but eventually achieving 1 CFU. The antimicrobial qualities of the treatment medium, which physically filter and chemically inactivate pathogens, are likely the reason all treatment materials are so successful in lowering bacterial contamination and making the water safer for reuse (Koul et al., 2022).

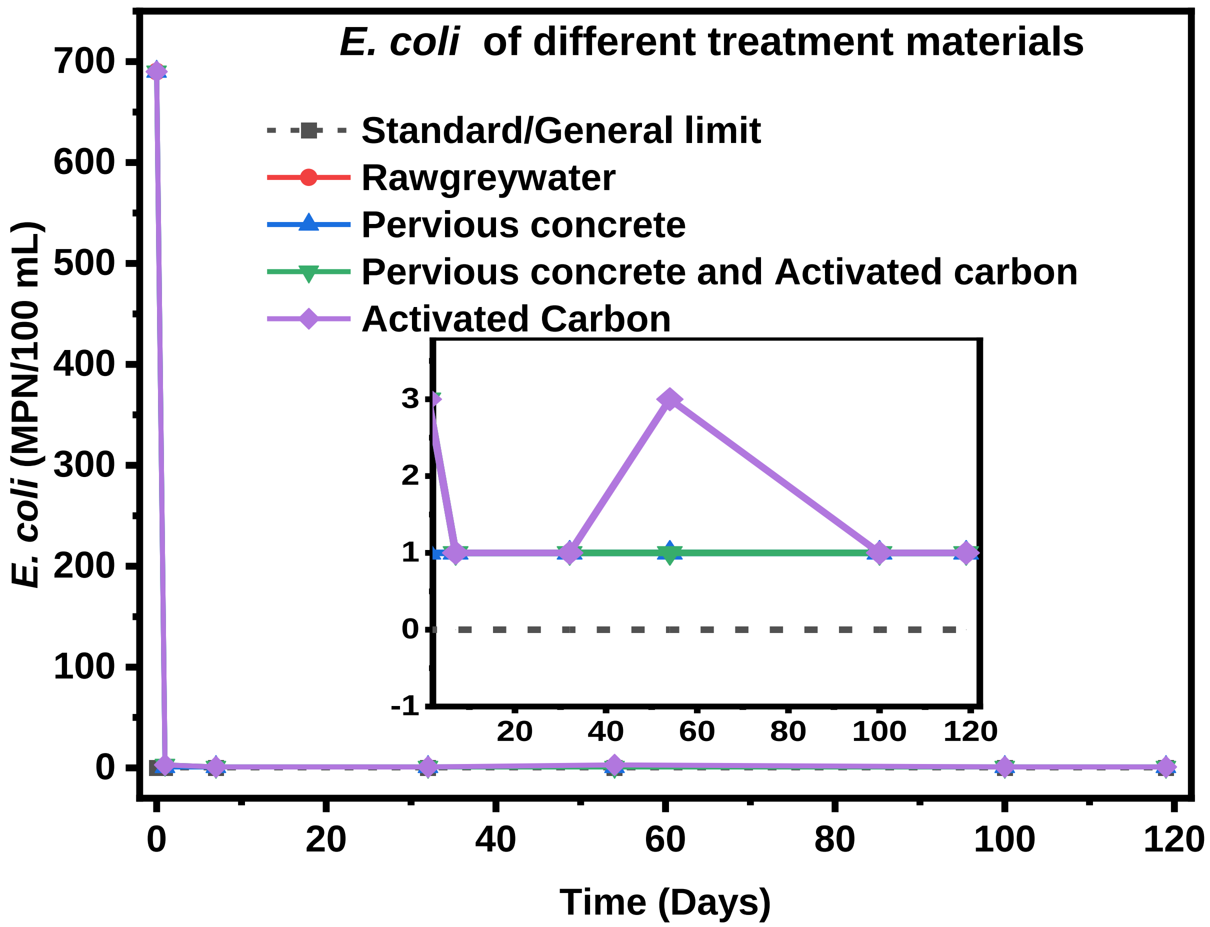

Figure 4-7: E. coli of various treatments over time

4.6. Water irrigation indices

Indicators of irrigation water quality for various materials, pervious concrete, a mixture of pervious concrete with activated carbon, and activated carbon alone are shown in **Table 4-2**. The main indices are discussed in the subsections.

Table 4-2: Irrigation water quality indicators

	Equation	Raw Greywater	Pervious Concrete	Pervious concrete and Activated carbon	Activated carbon	Limits
SAR	SAR= $\frac{[Na^{+}]}{\sqrt{\frac{[Ca^{2+}+Mg^{2+}]}{2}}}$	2.39	2.91	5.66	5.66	<10
KR	KR= $\frac{[Na^{+}]}{[Ca^{2+}+Mg^{2+}]}$	1.19	2.08	6.96	6.96	<1

SSP	SSP = $\frac{Na^{+}\times100}{[Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}]}$	50.95	60.5	38.39	38.39	<40

4.6.1. Sodium Adsorption Ratio (SAR)

One of the quality indicators for irrigation water is the sodium adsorption ratio (SAR), which quantifies the proportion of sodium (Na^{+}) to calcium (Ca^{2+}) and magnesium (Mg^{2+}) in water. High SAR values suggest that sodium may predominate in the soil, influencing permeability and soil structure. Excessive concentrations of Na^{+} may cause the soil Ca^{2+} and Mg^{2+} ions to be replaced by Na^{+} ions, which can harm the soil structure, resulting in waterlogging and subsequent poor plant growth (Khapra and Singh, 2024). The results show that pervious concrete has an SAR of 2.91, suggesting that using pervious concrete slightly raises the sodium adsorption hazard **Figure 4-8**. Treatment with activated carbon and a mixture of pervious concrete with activated carbon results in an SAR of 5.66, which is significantly higher; thus, indicating a greater sodium hazard compared to pervious concrete treatment. The permissible level for SAR is <10, and the results shows that pervious concrete and the mixture were within the permissible level for irrigation.

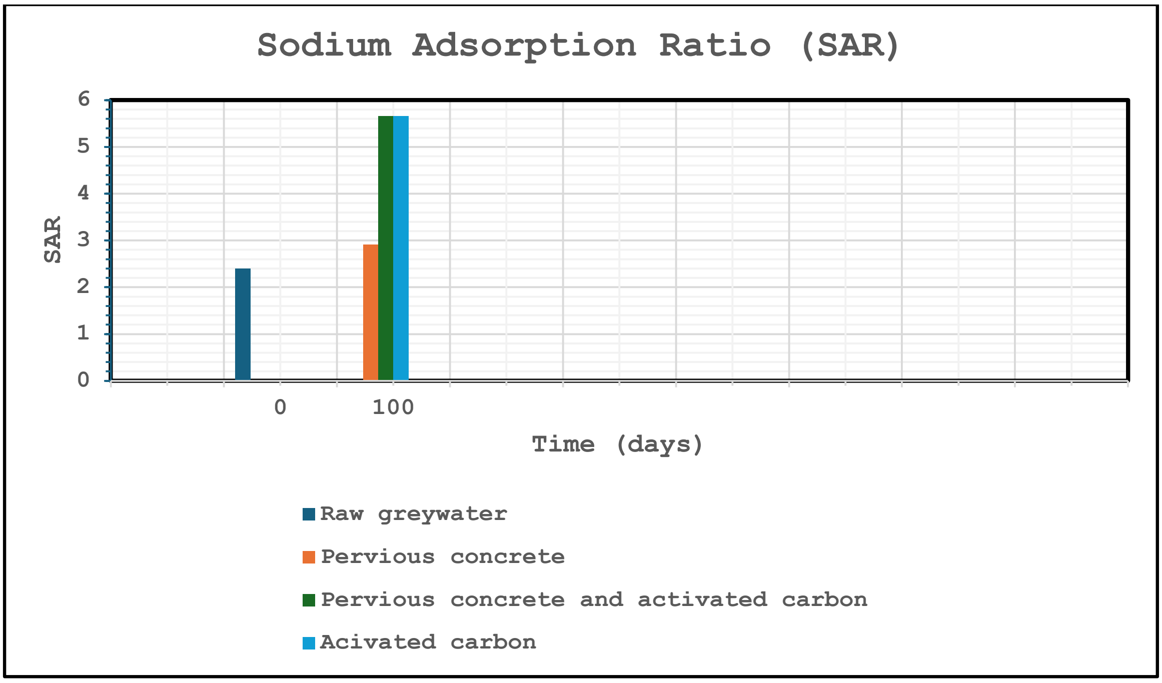

Figure 4-8: SAR of various treatments over time

4.6.2. Kelly's Ratio (KR)

Kelly's Ratio is another vital indicator of the effect of sodium on the soil and it specifically compares sodium to calcium and magnesium, another index parameter that is utilised to evaluate irrigation water (Satyanarayana et al. 2016). Low KR values are preferable as high values suggest poor water quality, which could affect soil health. The results in **Figure 4-9** show that KR is 2.08 for pervious concrete and 6.96 for activated carbon, which means that the KR value is higher than 1.0 for all treatment materials. Therefore, the water has excessive Na^+ and is, therefore, unfit for irrigation.

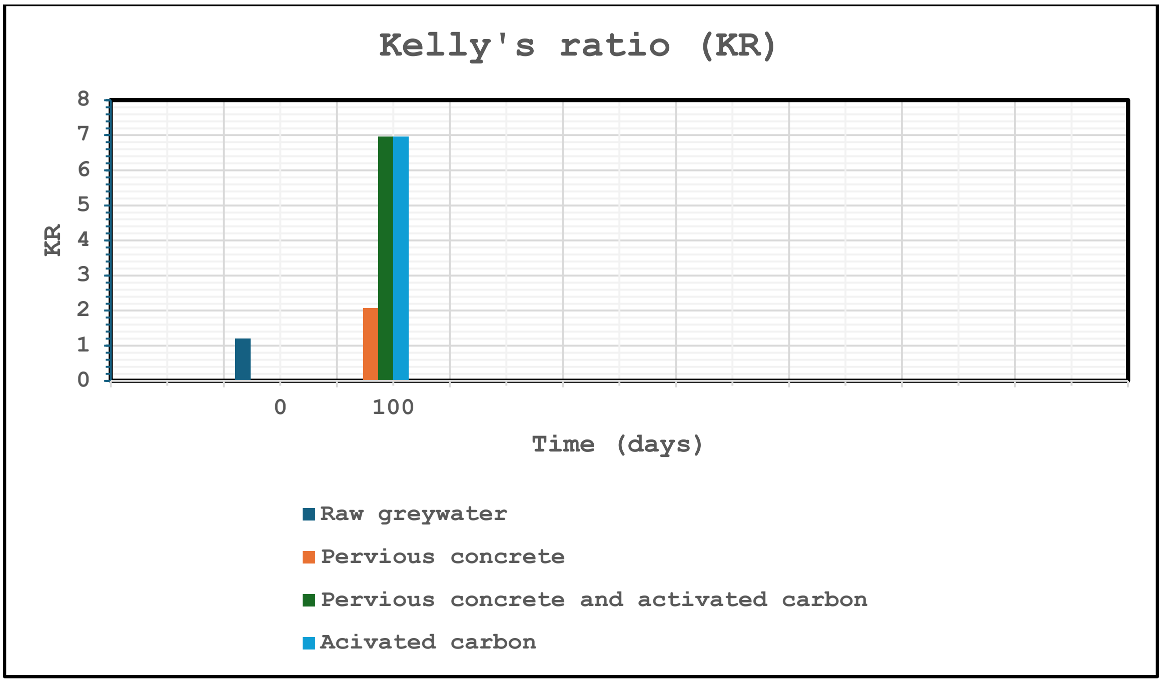

Figure 4-9: *Kelly's ratio of various treatments over time*

4.6.3. Soluble sodium percentage (SSP)

The percentage of sodium in water compared to other soluble ions is provided by SSP. Lower SSP values indicate better water quality, as high SSP can contributes to soil salinity. The acceptable SSP value is <40, For pervious concrete treatment, SSP is slightly high at 60.5%, while it decreases to 38.39% for activated carbon and the mixture of pervious concrete with activated carbon as shown in **Figure 4-10**. This reduction indicates that activated carbon can greatly mitigate the soluble sodium percentage, which could be beneficial in managing soil salinity.

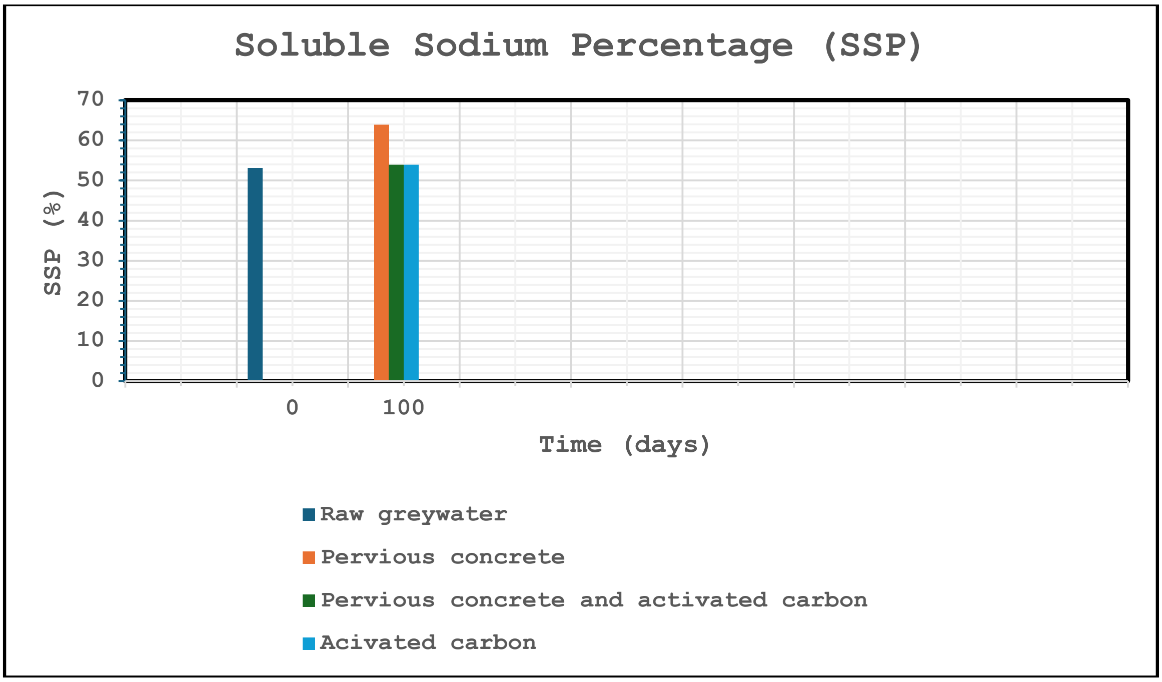

Figure 4-10: *SSP of various treatments over time*

4.7. Removal efficiency of micro and macro elements

The percentage removal efficiency refers to the proportion of a substance eliminated from a system. The effectiveness of removal was determined using ***Equation 4-1***:

$$RE(\%) = \frac{C_0 - C_e}{C_0} \times 100 \qquad \textit{Equation 4-1}$$

where C_0 and C_e represent the initial and equilibrium concentrations (mg/L) of the contaminants, respectively, before and after greywater treatment. **Figure 4-11** and ***Error! Reference source not found.*** show the percentage removal of various elements (Na, K, Ca, Mg, Fe, and Mn) from raw greywater when treated using three different methods: pervious concrete, pervious concrete with activated carbon, and activated carbon alone.

Table 4-3: % removal

Parameters	Raw greywater	Pervious Concrete	% removal	Pervious concrete and Activated carbon	% removal	Activated carbon	% removal
Sodium as Na	55	47	14.5	53	3.6	53	3.6
Potassium as K	5.7	6.7	17.5	64	0	64	0
Calcium as Ca	22	18	18	5	77	5	77
Magnesium as Mg	11	1	90.9	1	90.9	1	90.9
Iron as Fe (Dissolved)	<0.047	<0.025	46.8	<0.025	46.8	<0.025	46.8
Manganese as Mn (Dissolved)	<0.025	<0.025	0	<0.025	0	<0.025	0

Pervious concrete treatment achieved a low 14.5% removal for sodium, and even lower (3.6%) removal when the water was treated using activated carbon. Clearly, these treatments were ineffective in removing sodium from the greywater. Pervious concrete also achieved a low (17.5%) removal of potassium, while activated carbon achieved 0% removal of potassium. Activated carbon achieved a slightly higher removal percentage of (77%) for calcium, while pervious concrete achieved a lower (18%) removal efficiency for calcium, meaning activated carbon was effective in removing calcium in the water. All treatments achieved a high removal for magnesium (90.9%), which suggests that pervious concrete and activated carbon contribute similarly to magnesium removal. All treatments achieved a moderate removal for iron (46%), which means it was ineffective in removing iron. Pervious concrete and activated carbon were ineffective in removing manganese because there was 0% removal observed for manganese using any of the methods. As seen in **Figure 4-11**, magnesium was successfully removed by all treatments, and activated carbon slightly removed calcium in the water.

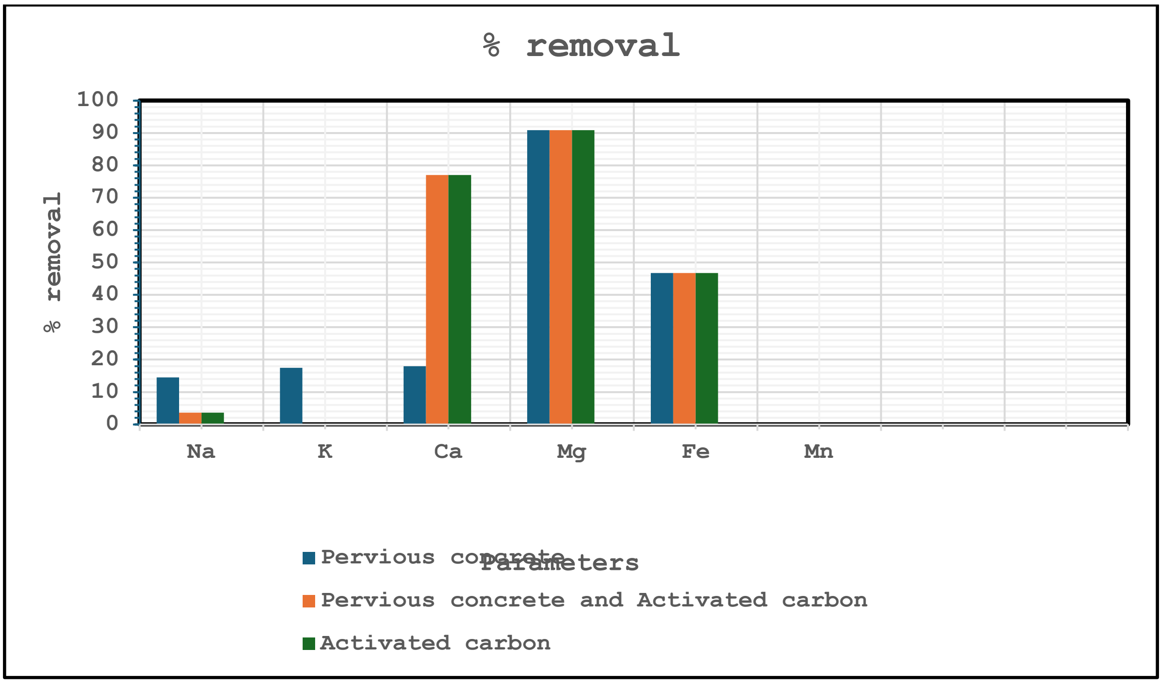

Figure 4-11: % removal

4.8. Laboratory-scale greywater treatment system

The experimental set-up was performed using low-cost materials such as sand, gravel and pervious concrete reactive medium. Sand and gravel were used in the filtration unit. A sedimentation tank was used to filter the greywater. The purpose of the sedimentation tank was to keep the water flowing steadily. Lighter pollutants float at the liquid's surface, whereas heavier particles settle at the tank's bottom. Clear water passed from the sedimentation unit to the sand and gravel filtration unit. Water samples were obtained from the raw greywater and pervious concrete unit for analysis, not from each stage. The parameters analysed include pH, EC, TDS, turbidity, BOD, and *E. coli* concentration, as well as Iron, Nitrate, Ortho Phosphate and Free and saline Ammonia. The water parameters were contrasted with the FAO guidelines for irrigation water quality (Ayers and Westcot 1989). The experiment was done 3 times (***Table 5-5***, Appendix) and the data were recorded as Mean (***Table 5-6***, Appendix). The concentrations of several selected parameters are shown in ***Table 4-4***.

The laboratory-scale experiment's findings indicate that the raw greywater's starting value on day 0 was 7.45, respectively, as shown in ***Table 4-4***. Pervious concrete treatment increased pH from 10.01 to 10.8. The use of soap and detergents makes greywater classically alkaline (Shegokar et al., 2015). The values of EC and TDS were reduced following treatment with pervious concrete from 70.6 mS/cm to 64.7 mS/cm and 352 mg/l to 325 mg/l and were within the acceptable limits (70 mS/cm and 500 mg/l). Turbidity was reduced after treatment with pervious concrete from 3.7 NTU to 2.2 NTU. The BOD exceeded the maximum limit after treatment from 24.3 mg/l to 25.6 mg/l. *E. coli* was reduced from 130.6 CFU to 1CFU. The laboratory scale greywater treatment system results show that pervious concrete was effective in reducing EC, TDS, Turbidity, and *E. coli* concentration.

Table 4-4: *Concentration of various parameters before and after treatment with pervious concrete.*

	Days	**pH**	**EC (mS/m)**	**TDS (ppm)**	**Turbidity (N.T.U)**	**BOD**	***E. coli***
Standard (General limit) Ayers and Westcot, 1989		6.5-8.0	70	500	5	5	10^{-6}-10^{-9}
Raw greywater	0	7.45	59.4	296	12	48	980
Pervious concrete treatment	1	10.1	70.6	352	3.7	24.3	130.6
	3	10.4	72.2	362	4.2	27.6	1.3
	7	10.5	60	303	3.2	28.6	1

10	10.8	64.7	325	2.2	25.6	1

4.9. Percentage (%) removal of nitrate, ortho phosphate, ammonia and iron

Figure 4-12 shows the percentage removal of various parameters (nitrate, ortho phosphate, ammonia and iron) over time. The results show that pervious concrete treatment achieved a low (46,6%) removal on day 1 and day 3, and a lower (20% and 26%) on day 7 and day 10, meaning that pervious concrete was less effective in removing nitrate in the water. A total of 83% of ortho phosphate was removed by pervious concrete from day 1, day 3 and day 10, and 78.3% was removed on day 7- meaning pervious concrete was successful in removing ortho phosphate. Pervious concrete was ineffective in removing free and saline ammonia since it achieved a lower (15%) on day 1, 10% on day 3, 30% on day 7 and 28.1% on day 10. Pervious concrete treatment achieved 79.1% removal of iron on day 1 and day 3, a low removal (58%) on day 7 and 75% removal on day 10. Therefore, the results of the laboratory scale greywater treatment system show that pervious concrete was only successful in removing ortho phosphate and iron, but ineffective in removing nitrate and ammonia.

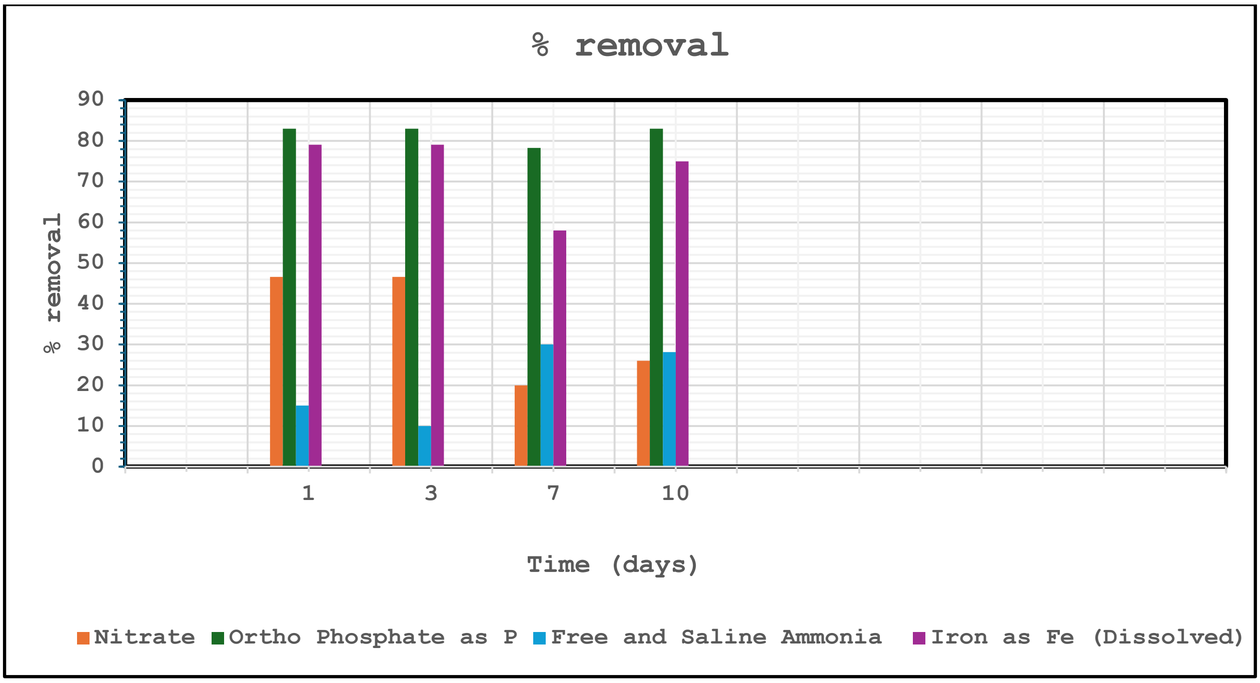

Figure 4-12: *percentage removal efficiency*

4.10. Microscopic Observations

Scanning Electron Microscopy (SEM) analysis revealed a porous and heterogeneous matrix in pervious concrete, with interconnected voids and crystalline deposits that enhanced physical filtration and chemical precipitation (**Figure 4-13**). These structural features explained the observed increases in alkalinity and reductions in turbidity, BOD, and *E. coli*. In contrast, activated carbon exhibited a fine pore structure with high adsorption capacity, though evidence of pore clogging and salt deposition aligned with the initial EC and TDS increases observed during column tests. Together, the microstructural analyses confirmed that material properties strongly influenced treatment performance.

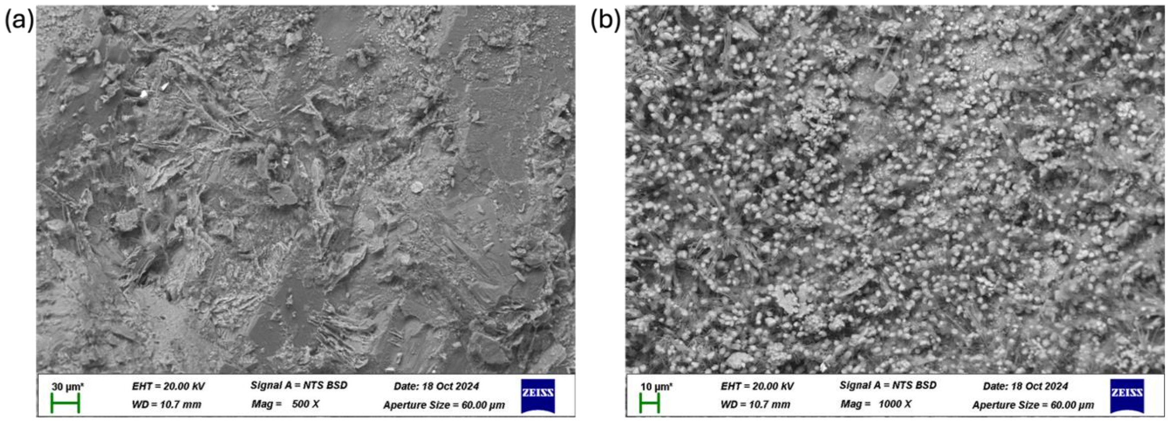

Figure 4-13: *SEM images of (a) raw pervious concrete and (b) pervious concrete after being used for treatment of greywater.*

4.11. Microscopic evidence and treatment mechanisms

SEM observations provided valuable insights into the mechanisms driving greywater purification. The interconnected voids and crystalline deposits in pervious concrete facilitated both filtration and chemical precipitation, while the high alkalinity enhanced microbial inactivation. Comparable structural effects of pervious concrete on contaminant removal have been reported in acid mine drainage and stormwater studies (Shabalala & Ekolu, 2019; Sandoval et al., 2022). Pervious concrete can produce comparable structural and treatment effects when used for the removal of contaminants in both acid mine drainage (AMD) and stormwater runoff. Pervious concrete is designed with a high percentage of interconnected voids, which allows water to pass through the material while simultaneously promoting physical, chemical, and biological treatment processes. Activated carbon's microporous structure enabled effective adsorption of organics but suffered from pore blockage and salt accumulation, explaining the unstable EC and TDS patterns. These mechanistic insights demonstrate how the physical and chemical properties of the treatment media directly influenced their performance.

4.12. Chapter summary

This chapter presented data in tables and graphs and discussed the outcomes obtained before and after treatment using a variety of techniques. Pervious concrete treatment shows better performance in reducing parameters such as EC, TDS, *E. coli*, turbidity, BOD and reduced some of the metals. Based on the findings presented in this chapter, conclusions and recommendations are provided in the next chapter. Pervious concrete treatment increased pH from 7.4 to 10.89. E. coli, BOD and turbidity were reduced from 690 to <1 CFU, 30 to <10 mg/l and 15 to 1.4 NTU following treatment with pervious concrete. EC and TDS values of greywater treated with pervious concrete were within the acceptable limits for discharge of wastewater into a water resource and for irrigation from day 0 to day 21. This result shows that pervious concrete performed better than the other 2 treatment methods.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

5.1. Conclusion

This study evaluated the effectiveness of pervious concrete, moringa seeds, and activated carbon in treating greywater collected from the University of Mpumalanga student residence. The results demonstrated that the preparation and use of these materials provided valuable insights into their suitability for greywater treatment. The preparation of pervious concrete proved to be practical and effective for improving several water quality parameters, indicating that it can function as a viable filtration medium for greywater treatment systems.

The results showed that pervious concrete significantly improved the quality of greywater by reducing electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD), turbidity, and E. coli more effectively than moringa seeds and activated carbon. However, the treatment process resulted in an increase in pH levels, which suggests that additional pH control may be required before reuse. The system also showed varying efficiency in removing certain metals, demonstrating that while pervious concrete is effective for some contaminants, it may require complementary treatment methods for complete removal of specific ions.

The irrigation water quality indices (SAR, SSP, and KR) further indicated that most parameters were within acceptable ranges after treatment with pervious concrete, supporting its suitability for irrigation purposes. These findings are generally consistent with literature that identifies pervious concrete as a promising low-priced and maintainable treatment medium due to its filtration capacity and porous structure.

Overall, the hypothesis that pervious concrete can effectively treat greywater for irrigation purposes was largely supported. While it may not remove all contaminants completely, it demonstrated better overall performance compared to moringa seeds and activated carbon in this study. Therefore, pervious concrete can be considered a promising and sustainable option for greywater treatment, particularly in water-scarce regions where alternative water sources for irrigation are needed.

5.2. Recommendations

The subsequent recommendations are made based on the study findings:

- More research on the use of pervious concrete is required to improve pervious concrete treatment system and to improve the removal efficacy of pervious concrete for some metals.
- Larger-scale treatment system should be done for a more effective treatment of greywater.
- Long-term effectiveness of the system needs to be investigated.
- Greywater must be further treated and examined for the likelihood of human consumption, not only for irrigation purposes.
- More research on the treatment of greywater is required to improve the suitability of the water for irrigation.
- Analyses of surfactants and oils will be considered in future work to complement the current findings.

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APPENDICES

***Table 5-1**: Analyses of greywater samples before and after treatment with pervious concrete, moringa seeds and a mixture of pervious concrete with moringa seeds*

	Day	Code	pH	EC (ms/m)	TDS (ppm)	BOD	*E. coli*	Turbidity (N.T.U)
Standard (General limit) Ayers and Westcot, 1989			6.5-8.0	70	500	5	10^{-6}-10^{-9}	5
Raw greywater	0	RGW	7.4	45.5	252	30	690	15
Pervious concrete	1	D1-P2	7.11	69.8	349	10	3	4.6
	7	D7-P2	10.12	50.7	254	10	1	4.7
	21	D2W3-P2	11.01	85.3	427	10	1	1.4
	30	D3W4-P2	10.89	108.6	543	10	N/A	1.4
Moringa	1	D1-M60	7.06	75.8	379	10	1	40
	7	D7-M60	6.75	80.9	405	210	250	111
	21	D2W3-M60	7.03	198.4	992	92	600	96
	30	D3W4-M60	7.31	229.3	1147	135	N/A	122
Pervious concrete & moringa	1	D1-PM48A	7.27	83.7	418	24	3	58
	7	D7-PM48A	8.41	120.1	601	20	4900	36
	21	D2W3-PM48A	9.38	185.1	926	180	1	20
	30	D3W4-PM48A	10.18	179.5	898	159	N/A	14

Table 5-2: Analyses of greywater samples before and after treatment with pervious concrete, activated carbon and a mixture of pervious concrete with activated carbon.

	Days	**Sample code**	**pH**	**EC (ms/m)**	**TDS (ppm)**	**Turbidity (N.T.U)**	**BOD**	***E. coli***
Standard (General limit) Ayers and Westcot, 1989			6.5-8.0	70	500	5	5	10^{-6}-10^{-9}
Raw greywater	0	RGW	7.4	45.5	252	15	30	690
Pervious Concrete	1	CP01	9.88	56.4	282	4.0	16	1
	7	CP07	10.12	33	165	2.1	13	1
	32	CP14	10.18	35.5	180	1.0	10	1
	54	CP20	10.74	43.2	264	1.9	10	1
	100	CP30	9.50	36.2	182	0.5	10	1
	119	CP35	10.01	37.9	190	1.1	11	1
Mixture of pervious concrete and activated carbon	1	CPA01	10.21	266.7	1340	2.8	10	3
	7	CPA07	10.00	116.7	584	1.2	10	1
	32	CPA14	10.23	69	354	0.7	10	1
	54	CPA20	10.69	71.6	361	1.7	10	1
	100	CPA30	9.47	49.9	252	0.3	10	1
	119	CPA35	9.78	51.8	260	0.4	10	1
Activated Carbon	1	CA01	9.74	320.3	1605	3.7	11	3
	7	CA07	9.49	197.2	1019	1.8	10	1
	32	CA14	9.36	120	616	0.4	10	1
	54	CA20	9.84	133.4	668	0.7	10	3
	100	CA30	9.41	82.3	412	0.2	10	1
	119	CA35	9.25	73.3	367	0.4	10	1

Table 5-3: Instruments used for analyses of water.

WATERLAB (Pty)Ltd			
Method Name	**Method Number**	**Method Type**	**Original Method**
pH	WLAB/001/pH/ Method	Potentiometric	4500-H^+ pH Value: *Standard Methods for Examination ofWater and Wastewater; 20th Edition,* Instrument manual
Electrical Conductivity	WLAB/002/E.C./ Method	Onductometric	2510 Conductivity: *Standard Methods for Examination ofWater and Wastewater; 20th Edition,* Instrument manual
Total Dissolved Solids	WLAB/003/T.D.S ./Method	Gravimetric	2540 Solids; Total Dissolved Solids Dried at 180°C:*Standard Methods for Examination of Water and Wastewater; 20th Edition*
Turbidity	WLAB/005/Turbi dity/Method	Colorimetric / Spectrophotometri c	2130 Turbidity; Nephelometric Method: *Standard Methodsfor Examination of Water and Wastewater; 20th Edition*, Instrument manual
Biochemic al Oxygen Demand	WLAB/020/B.O. D./Method	Titrimetric	Biochemical Oxygen Demand; Determination of the BOD5 with dilution of the water sample; Merck
Microbiology analysis	WLAB/055/*E. coli* /Method	Collilert - 18	Instrument manual
Ammonia	WLAB/046/Discr ete analyser/Method	Colorimetric / Spectrophotometri c	Instrument manual

Nitrates	WLAB/046/Discrete analyser/Method	Colorimetric / Spectrophotometric	Instrument manual
Ortho Phosphate	WLAB/046/Discrete analyser/Method	Colorimetric / Spectrophotometric	Instrument manual
Sodium Absorption Ratio	WLAB/052/SAR/ Method	Calculation	----

Table 5-4: % removal

Parameters	Raw greywater	Pervious Concrete	% removal	Pervious concrete and Activated carbon	% removal	Activated carbon	% removal
Sodium as Na	55	47	14.5	53	3.6	53	3.6
Potassium as K	5.7	6.7	17.5	64	0	64	0
Calcium as Ca	22	18	18	5	77	5	77
Magnesium as Mg	11	1	90.9	1	90.9	1	90.9
Iron as Fe (Dissolved)	<0.047	<0.025	46.8	<0.025	46.8	<0.025	46.8
Manganese as Mn (Dissolved)	<0.025	<0.025	0	<0.025	0	<0.025	0

Table 5-5: Concentration of various parameters during the 3 weeks period

WEEK 1

Day	Sample Description	Sample code	PH	EC (mS/m)	TDS (ppm)	Turbidity (N.T.U)	BOD	E. Coli
0	Raw Greywater	RW	7,45	59,4	296	12	48	980
1	Pervious concrete	LP01	9,55	56,1	280	4,4	19	390
3	Pervious concrete	LP03	9,69	51,4	259	5,7	22	2
7	Pervious concrete	LP07	10,28	48,2	242	3,2	20	1
10	Pervious concrete	LP10	10,66	50,9	255	2,8	22	1

WEEK 2

Day	Sample Description	Sample code	PH	EC (mS/m)	TDS (ppm)	Turbidity (N.T.U)	BOD	E. Coli
1	Pervious concrete	MN01	10,14	63,7	320	4,1	36	1
3	Pervious concrete	MN03	10,96	76,1	378	4,2	42	1
7	Pervious concrete	MN07	10,64	60	302	5	53	1
10	Pervious concrete	MN10	11,15	70,5	354	2,6	44	1

WEEK 3

Day	Sample Description	Sample code	PH	EC (mS/m)	TDS (ppm)	Turbidity (N.T.U)	BOD	E. Coli
1	Pervious concrete	NR01	10,62	92	456	2,7	18	1
3	Pervious concrete	NR03	10,59	89,2	449	2,8	19	1
7	Pervious concrete	NRO7	10,67	72	365	1,5	13	1
10	Pervious concrete	NR10	10,76	72,8	366	1,3	11	1

WEEK 1

Day	Sample Description	Sample code	Nitrate as N	Ortho Phosphate as P	Free and Saline Ammonia as N	Iron as Fe (Dissolved)
0	Raw Greywater	RW	1,5	0,6	4,6	0,12
1	Pervious concrete	LP01	1,5	0,1	3,9	<0,025
3	Pervious concrete	LP03	1,6	<0,1	4,1	<0,025
7	Pervious concrete	LP07	1,6	<0,1	4,1	0,043
10	Pervious concrete	LP10	1,6	<0,1	2	0,063

WEEK 2

Day	Sample Description	Sample code	Nitrate as N	Ortho Phosphate as P	Free and Saline Ammonia as N	Iron as Fe (Dissolved)
1	Pervious concrete	MN01	0,9	<0,1	3,8	<0,025
3	Pervious concrete	MN03	0,9	<0,1	3,9	<0,025
7	Pervious concrete	MN07	0,9	0,2	2	0,095
10	Pervious concrete	MN10	0,8	<0,1	3,8	0,03

WEEK 3

Day	Sample Description	Sample code	Nitrate as N	Ortho Phosphate as P	Free and Saline Ammonia as N	Iron as Fe (Dissolved)
1	Pervious concrete	NR01	<0,1	<0,1	4,2	<0,025
3	Pervious concrete	NR03	0,1	<0,1	4,4	<0,025
7	Pervious concrete	NR07	1,2	<0,1	3,5	<0,025
10	Pervious concrete	NR10	1,1	<0,1	2,6	<0,025

Table 5-6: *Mean of various parameters over time*

Parameter	Day 1	Day 3	Day 7	Day 10
pH	30.31/3=10.1	31.24/3=10.4	31.59/3=10.5	32.57/3=10.8
EC	211.8/3=70.6	216.7/3=72.2	180.2/3=60	194.2/3=64.7
TDS	1056/3=352	1086/3=362	909/3=303	975/3=325
Turbidity	11.2/3=3.7	12.7/3=4.2	9.7/3=3.2	6.7/3=2.2
BOD	73/3=24.3	83/3=27.6	86/3=28.6	77/3=25.6
E. coli	392/3=130.6	4/3=1.3	3/3=1	3/3=1
Nitrate	2.5/3=0.8	2.6/3=0.8	3.7/3=1.2	3.5/3=1.1
Ortho phosphate	0.3/3=.01	0.3/3=.01	0.4/3=0.13	0.3/3=0.1
Ammonia	11.9/3=3.9	12.4/3=4.1	9.6/3=3.2	8.4/3=2.8
Iron	0.075/3=0.025	0.075/3=0.025	0.163/3=0.05	0.118/3=0.03

Table 5-7: *Percentage removal efficiency*

Parameters	Raw greywater	Day 1	% removal	Day 3	% removal	Day 7	% removal	Day 10	% removal
Nitrate as N	1.5	0.8	46.6	0.8	46.6	1.2	20	1.1	26
Ortho Phosphate as P	0.6	0.1	83	0.1	83	0.13	78.3	0.1	83
Free and Saline Ammonia as N	4.6	3.9	15	4.1	10	3.2	30	2.8	28.1
Iron as Fe (Dissolved)	0.12	0.025	79.1	0.025	79.1	0.05	58	0.03	75