THE EFFECT OF DOMESTIC GREYWATER ON SOIL QUALITY OF URBAN SOILS FROM THE CAPE TOWN AND STELLENBOSCH AREAS

by

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DECLARATION

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SUMMARY

During a recent drought and water scarcity in the Western Cape, the reuse of greywater for garden irrigation was encouraged. Greywater, although considered less polluted than same other wastewaters, can be environmental hazardous due to the pathogens, salts, alkalinity and micropollutants it contains. Some greywater streams are easier to capture and reuse than others, and types of detergent can have a significant effect on greywater quality. In previous research the role of soil properties in soil susceptibility to greywater degradation has received little or no attention. Therefore, this study investigated the effect of irrigation with different domestic greywater streams on soil quality of a variety of representative urban soils from the Greater Cape Town area. Six domestic greywater streams were characterised in terms of water quality parameters. Two of better (shower and liquid laundry detergent) and two of poorer quality greywater streams (dishwasher and powdered laundry detergent) were selected for use in subsequent soil application experiments. Twenty soil samples, representing the five major soil groups from the Cape Town and Stellenbosch areas, were collected and characterised. These groups consisted of aeolian coastal sands (avg. 5% clay), alluvial soils (avg. 10% clay), granite-derived soils (avg. 11% clay), shale-derived soils (avg. 20% clay) and Fe-rich chromic soils (avg. 23% clay).

In the first experiment, a laboratory soil column infiltration experiment was used to investigate the vulnerability of the five soil groups to degradation (pore sealing and dissolved organic carbon removal) by liquid laundry detergent (LLD) and powdered laundry detergent (PLD) greywaters in comparison to tap water (TW). Application of 200 mm PLD greywater had significantly more detrimental effects on soil permeability, clay dispersion and dissolved organic carbon (DOC) removal compared to 200 mm LLD or TW. This was attributed to PLD's high pH (*ca*. 9.95) and SAR (*ca*. 147). The saturated hydraulic conductivity (K_{sat}) of the LLD greywater was 1.3 - 2.3 times lower than that of TW, while PLD K_{sat} was 2.2 - 8.4 times lower. Granite and shale soils were more inclined to K_{sat} reduction (*ca*. -81% and -82%, respectively) while the chromic soils were the least susceptible (*ca*. -47%). PLD greywater resulted in greatest extent of DOC removal, with aeolian sands being most susceptible to DOC stripping (*ca.* 7.5% C lost) while the chromic soils were the least susceptible (*ca.* 1.5% C lost).

In the second leaching column experiment, the effect of the shower (SH) and dishwasher (DW) greywaters on soil degradation was compared to that of the laundry greywaters and TW on a smaller selection of (11) soils. Application of 200 mm of SH and DW reduced soil infiltration by *ca.* 50% compared to TW, although it was not statistically significant. Shower and dishwasher greywaters did not significantly remove DOC from the soils as compared to TW.

In the third experiment, a column experiment was conducted to simulate the effect of repeated summer greywater irrigation, followed by winter rainfall, on soil properties. The effect of repeated application (370 mm applied over 10 weeks) of the four greywater streams on soil quality of a representative dispersive (granite – SP1) and stable (chromic – BD1) soil types was determined. This was followed by repeated application of 370 mm of rainwater to see whether the soils could be rehabilitated. As expected, the PLD and DW had the most harmful effects on soil quality, resulting in the formation of alkaline and saline-sodic soils. Powdered laundry detergent greywater and DW also significantly increased plant available P. All the treatments lowered soil bacterial diversity, while no significant change was observed on the fungal community. Subsequent application of rainwater showed that no water was able to infiltrate into the dispersive granite soil after treatment with PLD or DW. This indicated that it would be very difficult to remediate this soil type after irrigation with these types of greywaters. Application of all four greywaters significantly decreased rainwater infiltration in the chromic (*ca.* -42% to -93%) and granitic (*ca.* -25% to -100%) soils. Application of rainwater was, however, able to decrease the exchangeable sodium percentage of the DW and PLD irrigated soils to around *ca.* 13%, but the pH values remained high. Total C content of the PLD treated chromic soil was significantly decreased (*ca.* -22% of total C) due to DOC stripping.

The results of this study demonstrate that soils vary in their susceptibility to degradation due to greywater application, depending mainly on texture and clay mineralogy. It is concluded that PLD and DW greywater should not be used for soil irrigation, whereas LLD and SH greywater should be used cautiously, especially on dispersive granite and shale-derived soils. The results of this study should be incorporated into the establishment of greywater irrigation guidelines.

OPSOMMING

Gedurende ‘n onlangse droogte en waterskaarste in die Wes-Kaap, was die hergebruik van gryswater vir tuinbesproeiing aangemoedig. In vergelyking met sommige ander afvalwaterbronne, kan gryswater kan as minder besoedelend beskou word, alhoewel dit steeds 'n omgewingsgevaar kan inhou as gevolg van potensiële patogene, soute, alkaliniteit en mikro-besoedelingstowwe wat dit bevat. Sommige gryswaterbronne is makliker herwinbaar as ander, en verskillende soorte skoonmaakmiddels kan 'n beduidende effek op die kwaliteit van die gryswater hê. In vorige navorsing was daar min klem gelê op die rol wat grondeienskappe op die vatbaarheid vir degeradering weens gryswater toediening het. Dus was die fokus van hierdie studie op die effek van besproeiing met huishoudelike gryswaterbronne op die grondkwaliteit van 'n verskeidenheid verteenwoordigende stedelike gronde uit die Groter Kaapstad area. Ses huishoudelike gryswaterstrome is gekaraktiseer in terme van waterkwaliteitparameters. Twee beter (stort- en vloeibare wasgoedmiddel) en twee slegter gehalte (skottelgoedwassermiddel en wasgoedpoeier) gryswaterbronne was gekies vir gebruik in opvolgende eksperimente vir grondtoediening. Twintig grondmonsters, wat die vyf belangrikste grondgroepe uit die Kaapstad en Stellenbosch gebiede verteenwoordig, is versamel en gekarakteriseer. Hierdie groepe het bestaan uit eoliese sand (gemiddeld 5% klei), alluviale grond (gemiddeld 10% klei), graniet afkomstige gronde (gemiddeld 11% klei), skalie-afkomstige gronde (gemiddeld 20% klei) en Fe-ryke chromiese gronde (gemiddeld 23% klei).

In die eerste eksperiment, was 'n laboratorium grondkolominfiltrasie eksperiment gebruik om die kwesbaarheid van die vyf grondgroepe vir degredasie (porie-verseëling en verwydering van opgeloste organiese koolstof) deur vloeibare wasgoedmiddel (LLD) en wasgoedpoeier (PLD) te ondersoek, in vergelyking met kraan water (TW). Die toediening van 200 mm PLD gryswater het aansienlik meer nadelige uitwerking op gronddeurlaatbaarheid, klei deflokkulasie en verwydering van opgeloste organiese koolstof (DOC) gehad in vergelyking met 200 mm LLD of TW toegedien. Dit word toegeskryf aan PLD se hoë pH (*ca.* 9.95) en NAV (*ca.* 147). Die versadigde hidroliese geleidingsvermoë (K_{sat}) van die LLD-gryswater was 1.3 - 2.3 keer laer as dié van TW, terwyl PLD K_{sat} 2.2 - 8.4 keer laer. Graniet- en skaliegrond was meer geneig tot K_{sat}-vermindering (*ca.* -81% en -82%, onderskeidelik), terwyl die chromiese gronde die minste vatbaar was (*ca.* -47%). PLD-gryswater het die grootste mate van verwydering van DOC tot gevolg gehad, met eoliese sand was die mees vatbaarste vir stroping van DOC was (verlies van 7.5% C), terwyl die chromiese gronde die minste vatbaar was (verlies van *ca.* 1.5% C).

In die tweede uitlogingskolom eksperiment is die effek van gryswater afkomstig van stort (SH) en skottelgoedwasser (DW) op die degredasie van grond vergelyk met wasmasjien gryswaters en TW op 'n kleiner verskeidenheid (11) gronde. Toediening van 200 mm SH en DW het die grondinfiltrasie met *ca.* 50% verminder in vergelyking met TW, hoewel dit nie statisties beduidend was nie. SH- en DW-gryswaters het nie meer opgeloste organiese koolstof van die grond as TW nie.

In die derde eksperiment is 'n kolomeksperiment uitgevoer om die effek van herhaaldelike somer gryswater besproeiing, gevolg deur winter reënval, op grondeienskappe te simuleer. Die effek van die herhaaldelike toediening (370 mm toegedien oor 10 weke) van vier gryswaterbronne op die grondkwaliteit is op twee verteenwoordigende disperse (graniet - SP1) en stabiele (chromiese - BD1) grondsoorte bepaal. Dit was gevolg deur die herhaaldelike toediening van 370 mm reënwater om te bepaal of die grond gerehabiliteer kon word. Soos verwag, het die PLD en DW die mees nadeligste gevolge vir die grondkwaliteit gehad, wat gelei het tot die vorming van alkaliese en natriumbrak gronde. Waspoeier gryswater en DW het ook die plantbeskikbare P aansienlik verhoog. Al die behandelings het die bakteriële diversiteit van die grond verlaag, terwyl daar geen noemenswaardige verandering in die swamgemeenskap waargeneem is nie. Die daaropvolgende toediening van reënwater het getoon dat geen water na die behandeling met PLD of DW in die disperse granietiesegrond kon infiltreer nie. Dit het aangedui dat rehabilitasie van hierdie grond na die besproeiing van hierdie tipe gryswaters uiters moeilik sal wees. Toediening van al vier gryswaters het die reënwaterinfiltrasie in die BD1 (*ca.* -42% tot -93%) en SP1 (*ca.* -25% tot -100%) gronde beduidend verminder. Die toediening van reënwater kon die uitruilbare Natrium persentasie van die besproeide grond DW en PLD egter met ongeveer 13% verlaag, maar die pH-waardes was steeds hoog. Die totale C-inhoud van die PLD-behandelde chromiese grond het beduidend afgeneem (*ca.* -22% van die totale C) as gevolg van die strooping van opgeloste organiese koolstof.

Die resultate van hierdie studie demonstreer dat gronde varieer in hul vatbaarheid vir degredasie a.g.v. gryswater toedining, hoofsaaklik as gevolg van tekstuur en kleimineralogie verskille. Daar kan tot die gevolgtrekking gekom word dat gryswater van PLD en DW nie vir besproeiing gebruik moet word nie, terwyl LLD en SH gryswater oordeelkundig gebruik moet word, veral op skalie- en graniet verweerde gronde. Die resultate van hierdie studie kan gebruik word in die opstel van riglyne vir gryswaterbesproeiing.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

GENERAL INTRODUCTION AND RATIONALE

The Western Cape Province has experienced serious drought from 2015-2018. In order to preserve water resources, the Cities of Cape Town and Stellenbosch have prohibited residents from using municipal treated water for irrigating gardens in 2017 and 2018 (City of Cape Town Level 6B Water Restrictions, 2017). This has resulted in inhabitants using alternative water sources such as boreholes, rainwater and greywater. Boreholes are very expensive to install and are thus limited to a minor proportion of the population. Rainwater harvesting tanks are more affordable, but still require substantial capital to install. Thus, the majority of residents rely on re-using greywater, which is also strongly encouraged by the municipalities on their websites. There are currently no Western Cape municipal guidelines on which types of domestic greywater are acceptable for irrigating garden soils. Furthermore, there are no published studies which show the effect of domestic greywater on soil quality (chemical, physical and microbiological properties) in the Western Cape. Some of the main concerns with reuse of greywater include health risks from pathogens and environmental risks due to alkalinity, salts and micropollutants contained in detergents (Eriksson *et al.*, 2002; Ghaitidak and Yadav, 2013; Lubbe *et al*., 2016; Maimon and Gross, 2018).

Given that there is very little research on the effect of irrigation of various greywater streams on soils with varying properties, the main aim of this study is to investigate the effects of the major streams of domestic greywater irrigation on a representative range of urban soils found in the Cape Town and Stellenbosch urban areas, and to establish which soil types are more susceptible to degradation by application of greywater. It is hoped that this information will inform Western Cape residents as to how to avoid degrading local soils and make informed choices when re-using greywater.

Therefore, the objectives of the study are as follows:

1. To characterise major streams of domestic greywater in terms of the water quality parameters in comparison to tap water and select a representative example of each major type of greywater for use in the subsequent soil application experiments.
2. To describe the selection and characterise representative soil samples from the major soil groups occurring in the Cape Town and Stellenbosch urban areas

3. To determine the effect of representative greywater streams in comparison to tap water, on soil hydraulic conductivity, dissolved organic carbon (DOC) removal and clay dispersion of a wide variety of typical garden soils from the Cape Town and Stellenbosch urban areas in order to determine which soil types are most susceptible to greywater degradation.
4. To determine the effect of repeated application of greywater streams on soil quality (chemical, physical and microbiological quality parameters) on two contrasting soils, and to determine whether the subsequent application of rainwater can reclaim the soils.

This thesis consists of seven chapters. The first chapter contains the General Introduction and covers the rationale and objectives of the study, while the second chapter (**Chapter 2**) is a literature review of greywaters and their effects on soils. The third chapter (**Chapter 3**) addresses the first objective of the study, which is the characterisation and subsequent selection of domestic greywater streams to be used in the soil application experiments (**Chapters 5** and **6**). The fourth chapter (**Chapter 4**) describes the selection of representative soil samples from the major forms occurring in the Cape Town and Stellenbosch urban areas and their physicochemical properties. The fifth chapter addresses the second objective of the study; investigating the effect of four selected greywater streams on soil degradation (hydraulic conductivity, DOC and fine particle removal) on the major urban soil groups and ascertains the role of soil properties in susceptibility to greywater degradation (**Chapter 5**). Two contrasting soils were selected for the detailed soil quality analysis **(Chapter 6)**, where the effect of repeated application of tap water and four greywater streams on soil quality (physical, chemical and microbiological quality parameters) were assessed. Furthermore, the effect of rainfall application on the soils exposed to multiple greywater irrigations was determined, in order to assess whether the soils can be remediated to their original condition (**Chapter 6**). The final chapter (**Chapter 7**) contains the General Conclusions and Recommendations.

CHAPTER TWO

LITERATURE REVIEW: GREYWATER CHARACTERISTICS AND EFFECT ON SOILS

2.1 INTRODUCTION

Water insufficiency has significantly increased worldwide due to population growth and erratic climate patterns (WHO, 2006; Sawadogo *et al.*, 2014). Therefore, re-use of wastewaters has been encouraged for irrigation purposes. The most preferred potential source of saving water is the use of greywater (Bubenheim *et al.*, 1997; Kanawade, 2015). Greywater is mainly wastewater produced from household activities such as water from the kitchen sink, dishwasher, showers, laundry and bathroom sinks except water resulting from flushing of toilets (Jeppesen, 1996; Eriksson *et al.*, 2002; Kanawade, 2015). Some authors also include water generated from floor cleaning (Jamrah *et al.*, 2008).

In many arid and semi-arid countries, greywater has been mainly recycled for irrigation. Greywater generally contains soap, shampoos, detergents, grease and oils. Some pollutants found in greywater include lint, solid particles, nutrients, alkaline salts and other salts, hypochlorite and heavy metals (Eriksson *et al.*, 2002). The composition of greywater is known to vary widely depending on lifestyle and number of household members and also the source from which it is produced from (Holgate *et al.*, 2011). Due to its composition, it has been proven to have both positive and negative impact on either soil or crops planted. Positive greywater characteristics is that it contains essential plant nutrients such as N, P, K, Ca and Mg (WHO, 2006), however, it can also have a negative impact on soil quality due to its alkalinity, salinity and sodicity (Pinto *et al.*, 2009).

Plant nutrients contained in greywater promote plant biomass and root nodule growth (Negahban-Azar *et al.*, 2013; Saeed *et al.*, 2015). Nevertheless, high Na contained in greywater has been proven to promote disaggregation of soil structure (Maxey and Meehan, 2009) and the use of surfactants in laundry greywater yield water- repellent soils (Wiel-Shafran *et al.*, 2006; Maimon *et al*, 2017). Additionally, greywater reuse for irrigation adds salts to the soil. Therefore, greywater reuse requires good practise that will take into consideration its effect on the soil, plant and environment (Sawadogo *et a*l., 2014). Certain treatments have been used to alleviate contaminants in greywater (Gilboa and Friedler, 2008; Holgate *et al*., 2011).

This review will focus on assessing greywater sources and their characteristics and the effect of greywater on soil physical, chemical and microbiological properties. The international and local guidelines regarding greywater reuse will also be discussed.

2.2 GREYWATER SOURCES

Greywater is usually obtained from three water sources, i.e., bathroom, laundry and kitchen (WHO, 2006). Nevertheless, some authors tend to exclude water from the kitchen as part of greywater due to its high contamination status (Al-Jayyousi, 2003). Wastewater from these three sources is referred to as greywater because of their cloudy and milky appearances (Maxey and Meehan, 2009) and is neither freshwater nor heavily polluted water.

2.2.1 Bathroom greywater

Bathroom greywater is basically wastewater from the showers, bathtubs and hand basins (Eriksson and Donner, 2009). It contains a wide variety of chemical detergents such as solid soaps, shampoos, toothpaste, hair conditioners, body washes (Morel and Diener, 2006; Maxey and Meehan, 2009) and sometimes might contain body waste which include skin, hair, body fats, and traces of blood, urine and faeces (Morel and Diener, 2006). Bathroom greywater containing solid soap contains high Na and has a higher pH value as compared to water containing shampoos, conditioners and body washes (Maxey and Meehan, 2009).

2.2.2 Laundry greywater

Laundry greywater refers to the wastewater produced from washing machines and laundry hand wash basins (Eriksson *et al.*, 2002; Newcomer *et al.*, 2017). It normally contains fabric detergents, bleaches, suspended solids, non-decomposable fibre from clothing, body oils, paints and solvents (Morel and Diener, 2006). In addition to this, laundry greywater also contains high levels of chemical oxygen demand (COD) and contains bacteria, coliforms, hence may contain faecal pathogens (Morel and Diener, 2006). Furthermore, laundry detergents can be generated from either the use of liquid or powdered laundry detergents. Mohamed *et al.* (2018) reported that liquid laundry detergents are chemically less contaminated compared to powdered laundry detergents. Therefore, the type of chemical used, can affect the composition of laundry greywater (Zavala and Estrada, 2016).

2.2.3 Kitchen greywater

Kitchen greywater refers to wastewater obtained from washing dishes, either from kitchen sinks or dishwashers (Rose *et al.*, 1991). It usually contains food particles, high amounts of oil and fats from cooking, dish washing detergents, grease and drain cleaning chemicals

(Christova-boala *et al.*, 1996; Al-jayyousi, 2003; Rodda *et al*., 2010). It is also known to contain high nutrient contents, suspended solid and bacteria which are basically from washing raw food (Morel and Diener, 2006). Additionally, Morel and Diener (2006) argued that greywater from the dishwasher usually contain high pH, high concentration of suspended solids and salts.

2.3 GREYWATER CHARACTERISTICS AND DIVISION

When considering greywater for irrigation, its characteristics are very important. Greywater can be characterised according to its quantity and quality. Greywater quantity is defined as the amount of greywater produced (Noutsopoulos *et al.*, 2017) while greywater quality refers to its chemical composition (Morel and Diener, 2006). Greywater quantity is known to influence its quality.

2.3.1 Greywater quantity

The amount of greywater produced in a household differs with respect to the greywater sources (see **Figure 2.1**), *viz.* washbasin, bathroom, shower, laundry, washing machine, kitchen sink and dishwasher (Ghaitidak and Yadav, 2013). This variation is mainly influenced by several factors such as the number of household members, age distribution and lifestyle characteristics (Rose *et al.*, 1991). Bathroom greywater contributes to the highest greywater production (Friedler *et al*, 2013; Noutsopoulos *et al.*, 2017), followed by laundry and kitchen greywater (Ghaitidak and Yadav, 2013). In addition to this, Ghaitidak and Yadav (2013) reasoned that water consumption in low income countries is generally lower than that of high income countries and the amount of water consumed can influence greywater quality. For example, less water used contributes to higher levels of pollutants, while high consumption produces larger volumes of greywater that are less polluted (Morel and Diener, 2006; Halalsheh *et al.*, 2008; Ghaitidak and Yadav, 2013). Al-Hamaiedeh and Bino (2010) observed high levels of biological oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solid (TSS) in treated greywater due to low water consumption. Thus, under drought, and water restricted conditions, greywater quality will be lower.

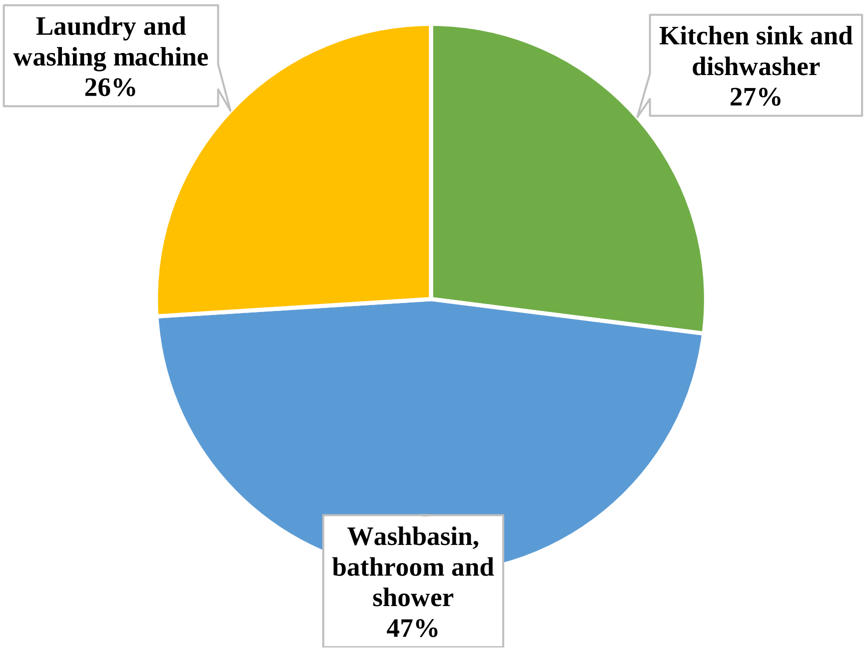


Figure 2.1: The amount of greywater produced from different sources (Adapted from Ghaitidak and Yadav, 2013).

2.3.2 Greywater quality

The quality of greywater sources differs and some of the physical, chemical and biological parameters used to determine greywater quality include the pH, electrical conductivity (EC), total suspended solids (TSS), chemical oxygen demand (COD), turbidity, heavy metals, pathogens, as well as macro and micro nutrients (refer to **Table 2.1**). Prathapar *et al.* (2005) and Sawadogo *et al.* (2014) reported that greywater is characterised by low levels of microbial pollution and high levels of boron, salts, oil, and surfactants.

Results from Birks and Hills (2007) stipulated that high levels of human bacteria found in bathroom greywater usually comes from bacteria on the skin, yet the pathogens in kitchen greywater originate from common species associated with food poisoning from partially cooked meat.

Table 2.1: Physical, chemical and biological characteristics of greywaters from different sources (compiled from DWAF, 1996; Eriksson *et al.*, 2002; Morel and Diener, 2006; Wiel-Shafran *et al.*, 2006; Travis *et al.*, 2010).

Greywater characteristics	**Parameters**	**Description**
Physical properties	Temperature	Kitchen greywater normally exhibits high temperatures, usually from the discharge of cooking water. High water temperatures favour microbial growth while decreasing calcium carbonate ($CaCO_3$) solubility which results in precipitation in storage tanks.
	Suspended solids	These include food, oils, soil particles, fibres from clothes, hair and residues from powdered detergents and can lead to high suspended solid contents in greywater. High suspended solids are usually found in laundry and kitchen greywater.
	Turbidity	Turbidity refers to the clarity of water. Measurement of turbidity and total suspended solids indicate the content of particles and colloids that can induce blockage. Kitchen greywater has shown to be the most turbid due to the presence of food particles, followed by laundry greywater due to detergent residues.
Chemical properties	pH and alkalinity	The pH range for irrigation water is 6.5 - 8.4 to avoid negative effect on the soil. Laundry water pH is typically between 9.4 - 10.0 (due to high concentration of detergents) which is above the maximum allowable pH for irrigation water. High pH values have also been reported for dishwasher greywater. The pH of most bathroom products ranges from 4.0 - 6.5 with exception of solid soaps which ranged from 7.2 - 9.8.
	Electrical conductivity and SAR	All greywater sources contain salts. Common sources of salt in soap and detergents include Na, Ca, K, Mg

		and Cl, which are major contributor ions to soil salinity. Due to the use of heavy detergents, laundry and kitchen greywater tend to have more salts.
	Biological oxygen demand (BOD), chemical oxygen demand (COD) and total organic carbon (TOC).	Organics in greywater are measured by the BOD, COD and TOC. These parameters indicate the risk of oxygen depletion due to degradation of organic matter, biofilm formulation, aesthetic problems and negative effects on plants and soils. BOD represents organic matter in water that can be readily metabolised by microorganisms, while COD is a fraction that can be chemically oxidised. The COD/BOD ratio indicates greywater biodegradability. Organics in greywater are easily biodegradable if the COD/BOD ratio is between 2.9 - 3.6.
	Element composition	High concentrations of chemicals such as sodium (Na), phosphorus (P), nitrogen (N), boron (B) and surfactants are normally found in laundry detergents, and are thus also high in laundry greywater. Chlorine is used in bleaches.
	Lipids (Oil and grease)	Fats, oil and grease are mainly characteristic of kitchen greywater. Previous studies have shown that accumulation of grease and oil in the soil can affect the passage of water in the soil by making the soil hydrophobic.
Biological properties	Bacteria, viruses and *E.coli*	Pathogens are introduced in greywater by handwashing after toilet use, washing nappies and soiled clothes, anal cleansing, showers and uncooked vegetables. Indicators include the total coliforms, *enterococci* and *E.coli*. The number of microorganisms found in greywater depends on the source of wastewater. Thus, microorganisms can be detected from any source.

3.2.3 Greywater categories

Greywater is placed in two classes based on its quality: (i) light greywater or low strength greywater, and (ii) dark greywater or high strength greywater (see **Figure 2.2**).

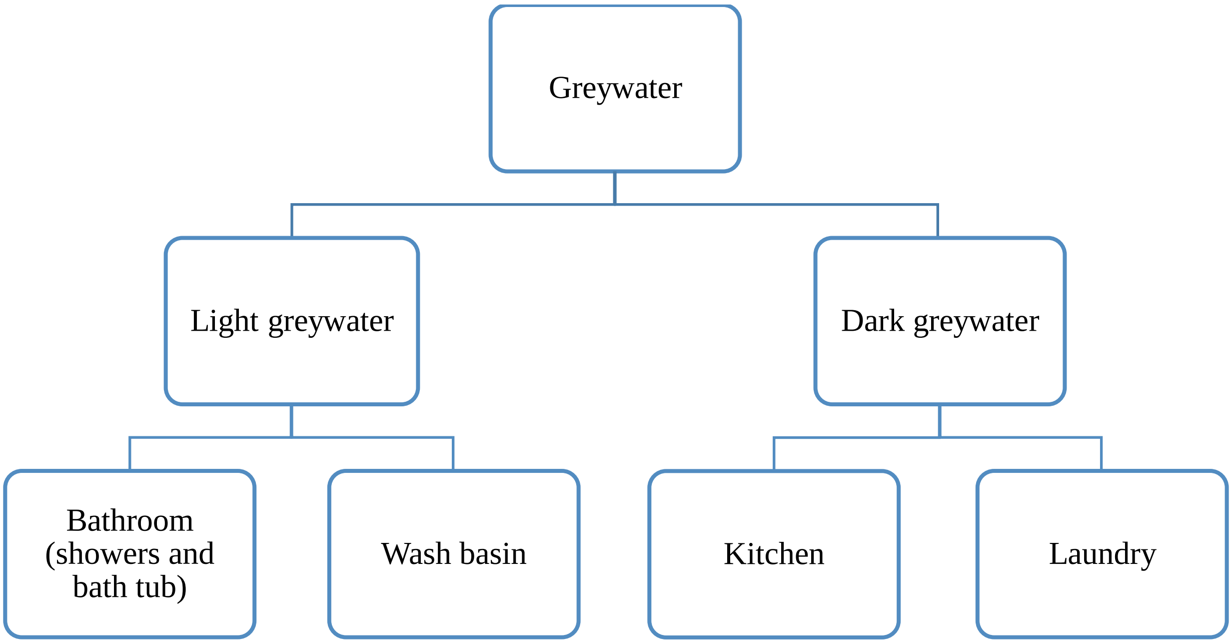


Figure 2.2: Greywater types and its sources, (modified from Ghaitidak and Yadav, 2013)

Light greywater also known as low strength greywater, refers to the less contaminated streams of wastewater, *i.e.*, generated from bath tubs, showers, and bathroom wash basin (Friedler and Hadari, 2006; Friedler *et al.*, 2013). This category of greywater might contain soap, toothpaste, shaving scream, food residues and bacteria from mouth wash. However, it can also contain faeces-related pathogens from washing hands after excretion and bathing, as well as skin and mucus tissue pathogens (Birks and Hills, 2007). In contrast, dark greywater refers to the heavily polluted streams of greywater (Penn *et al.*, 2012) and generally contains heavy detergents such as bleach (Birks and Hills, 2007). This type of greywater is usually wastewater generated from the kitchen sink, dishwasher, washing machine, and laundry (Friedler *et al.*, 2013). Dark greywater is known as the major contributor of COD in greywater (Krishnan *et al*, 2008).

2.4 EFFECT OF GREYWATER ON SOIL QUALITY

Soil quality gives an indication of how well the soil functions to promote agricultural productivity. Reduction in soil quality can lead to soil degradation, thus reducing soil productivity. Irrigation water quality has a large impact on soil physical, chemical and biological properties. Previous studies have shown that greywater reuse for irrigation can alter some of the soil properties such as the soil pH, EC, soil structure (Sawadogo *et al.*, 2014;

Kanawade, 2015) and release of greywater into the soil can have a negative impact on its quality (Mohamed *et al.*, 2018).

2.4.1 Greywater impact on soil physical properties

2.4.1.1 Soil structure and bulk density

Irrigation with greywater can deteriorate soil structure through clay dispersion. Results obtained by Maxey and Meehan (2009) showed greywater produced from bathing with solid bathroom soaps damages the structure of the soil by enhancing slaking of soil aggregates, especially in the case of heavy textured and weakly structured soil. The reason for this was due to the high sodium (Na) content in solid soaps which promotes soil clay dispersion. Clay dispersion affects soil permeability and drainage, and causes erosion and crusting. A decline in the bulk density of silty clay soil due to the dispersion and sedimentation of clay particles was observed by Abedi-Koupai *et al.* (2006)

2.4.1.2 Soil hydraulic conductivity, water retention, capillary rise and hydrophobicity

Hydraulic conductivity of soils has been known to vary with soil type and configuration of pore spaces. Maimon *et al.* (2017) reported that one of the environmental risks of greywater irrigation is its effect on soil hydraulic properties. A study conducted by Mohamed *et al.* (2018) in Malaysia using a clay soil indicated that the saturated hydraulic conductivity (K_{sat}) of these soil significantly decreased due to laundry greywater irrigation. Similar findings were obtained in a field experiment conducted in the Borkhar region in Iran under dry climatic conditions on Aridosols by Abedi-Koupai *et al.* (2006). Moreover, Sawadogo *et al.*, (2014) also reported a declining K_{sat} in sandy loam soils. This reduction was attributed to clay dispersion caused by alkalinity and sodicity of surfactant rich greywater (Sawadogo *et al.*, 2014). The use of greywater with high suspended solids may also reduce K_{sat} of soils because the soil pore spaces may have been filled with the solid particles such as organic matter (Abedi-Koupai *et al.*, 2006). Abedi-Koupai *et al.* (2006) added that microbial growth in the soil voids may also result in the restriction of water movement. Therefore, reduction in soil hydraulic conductivity can reduce infiltration, thus reducing soil permeability.

Capillary rise, which refers to the upward movement of water in the soil, is one of the phenomena affected by greywater application. Capillary rise has both a positive and a negative impact on the soil. Plants use water from below the root zone using capillary rise, but this also contributes to accumulation of salts in the soil. Wiel-Shafran *et al.* (2006) showed that irrigating with surfactant-rich laundry greywater reduced the capillary rise in soil. This resulted from the accumulation of surfactants at the surface which reduce surface tension and capillary pressure, thus reducing capillary action.

Accumulation of surfactants from laundry greywater can give rise to water repellence in fine quartz sandy soils (Maimon *et al*. (2017). In addition to this, application of greywater containing vegetable oil, laundry powder and bar soap also increased hydrophobicity of sandy loam soil (Travis *et al*., 2010)

2.4.2 Greywater effect on soil chemical properties

2.2.4.1 Soil pH, electrical conductivity (EC) and sodicity.

Many studies have shown that greywater irrigation increases the pH and EC of most soils (Maxey and Meehan, 2009; Holgate *et al.*, 2011; Sawadogo *et al.*, 2014; Mohamed *et al.*, 2018). This increase is due to the use of alkaline and saline chemical detergents. In contrast to this, Mzini and Winter (2015) reported that kitchen greywater containing food particles can lower the pH of the soil leading to soil acidity. They hypothesized that application of kitchen greywater containing food remains such as tomatoes (containing citric, lactic and other organic acids) and cooking oil (containing fatty acids) can acidify or lower the pH of the soil.

The EC of soils has been reported to increase with the application of greywaters (Sawadogo *et al.*, 2014). Maxey and Meehan (2009) showed that greywater generated from solid bathroom soaps had higher EC values as compared to other bathroom products and therefore land application of this greywater induced soil salinity. However, contrasting results were reported by Albalawneh *et al.* (2016) who revealed a declining EC on sandy loam soils irrigated with treated (filtered) greywater. They reasoned that this reduction was due to calcium precipitation and concluded that irrigating with greywater does not have a negative impact on the soil EC**.**

Mohamed *et al.* (2018) reported that the cation exchange capacity (CEC), exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) of clayey soils increased when irrigated with greywater generated from powder laundry detergent. Travis *et al.* (2010) and Negahban-Azar *et al.* (2013) observed a significant increase in the sodium absorption ratio (SAR) of the soils due to the application of surfactant-rich greywater on sandy and sandy loam soils. Furthermore, application of composite laundry and bathroom greywater also elevated the SAR of soils, while no significant change was observed on soils when irrigated with shower greywater (Siggins *et al.*, 2016). Similar SAR increases were reported by Al-Hamaiedeh and Bino (2010) on silty clay soils.

2.4.2.2 Inorganic constituents

Finley *et al.* (2009) and Maxey and Meehan (2009) reported that bathroom and laundry greywater contain essential plant nutrients (N, P, K, Mg, Ca, S, Na, B and Zn). Generally, these nutrients are found in small quantities. Irrigating with greywater containing nutrients can alter soil nutrient composition. When untreated greywater was used for irrigation the Ca, Mg, Na and B concentration in the soil increased (Travis *et al*., 2010; Siggins *et al*., 2016). Maxey and Meehan (2009) found that greywater from body washes had high K content, while shampoos had higher P content as compared to other bathroom products. Elevated nitrogen and phosphorus contents were observed on soils irrigated with composite bathroom and laundry greywater. Similar trend occurred due to laundry greywater irrigation (Negahban-Azar *et al.*, 2013; Sawadogo *et al.*, 2014). Washing powders used for laundry previously contained high phosphorus (P) levels (Birks and Hills, 2007), however, due to stricter environmental laws this is no longer true (Mulders and Kgaa, 2012). Solid soap tends to contain high Na levels as demonstrated by Maxey and Meehan (2009). Sharvelle *et al*. (2010) states that high Na content in soil can affect its quality. High levels of Na lead to sodic soils and sodicity causes swelling and dispersion of soil clays, surface crusting and pore plugging (Bauder *et al.*, 2011).

A field experiment conducted on Hutton soils in the Eastern Cape Province in South Africa, using composite bath and laundry greywater, containing high levels of Cl^-, HCO_3^-, and Na^+, resulted in a slight increase of some heavy metals in the topsoil. Although this increase was not significant, continuous application over a long period of time can lead to accumulation in the soil (Mzini and Winter, 2015).

2.4.2.3 Organic constituents

Greywater contains organic substances and most of these substances originate from kitchen greywater (Eriksson *et al.*, 2002). As discussed previously, kitchen sink and dishwasher greywater contains food remains, oils and fats, and are thus high in organic matter. Albalawneh *et al.*, (2016) stated that irrigating the soil with greywater reduces organic matter in the soil. Previous studies have shown that the chemical oxygen demand (COD) and biological oxygen demand (BOD) of the heavily polluted streams of greywater (*i.e.*, laundry and kitchen greywater) are usually higher than that of light greywater (Birks and Hills, 2007; Jamrah *et al.*, 2008). Since COD and BOD measure the biodegradability, this shows that the organic matter in dark greywater is more biodegradable than that of light greywater (Morel and Diener, 2006). Surfactants are one of the main constituents in soaps and detergents (Mulders and Kgaa, 2000). Greywater application on soils resulted in higher concentration of surfactants. However, in soil amended with biosolids, surfactant concentration are lower than in greywater irrigated soils (Sharvelle *et al.*, 2010).

Results obtained by Siggins *et al.* (2016) in a study conducted in New Zealand on sandy soils, show that application of laundry greywater or laundry greywater combined with bathroom greywater did not significantly affect organic C content of soils. However, a significant reduction in organic C percentage was observed from application of shower greywater on surface soil. This might have been due to enhanced decomposition.

2.4.3 Greywater impact on soil microbiological properties

Soil microbes are involved in the decomposition of organic matter and the cycling of nutrients. As greywater contains microbes (Rose *et al.*, 1991), its reuse has been proven to affect soil microbial activity. Previous studies have assessed soil microbial properties through measuring, microbial biomass, basal respiration and dehydrogenase activity (Siggins *et al.*, 2017). Kanawade (2015) observed growth of microorganisms in laundry greywater irrigated soils is mainly due to high levels of surfactants. The presence of nutrients, such as phosphate and nitrate, and organic materials in greywater streams also promotes microbial growth (Eriksson *et al*., 2002). However, the use of high pH (above 9) greywater has been known to limit microbial activity (Maxey and Meehan, 2009). Therefore, decreasing microbial activity will then reduce the decomposition of organic matter. Sharvelle *et al.* (2010) and Siggins *et al.* (2017) reported high numbers of *E.coli* and *enterococci* bacteria in soils irrigated with composite bathroom and laundry greywater. Consequently, faecal coliform bacteria increased in the soil.

Soil microbial contamination of greywater can indirectly pose a health hazard to humans. Dixon *et al.* (1999) argued that crops irrigated with greywater are a possible risk to human health when consumed in high quantities. Nevertheless, the incidence of disease is dependent upon more than just the concentration of pathogenic organisms; factors of exposure, health and age of the individuals should also be considered. Dixon *et al.* (1999) concluded that greywater is not fit for use due to some pathogen contaminants. However, some microbes present in the soil can affect crop growth and its quality.

2.5 GUIDELINES FOR GREYWATER REUSE FOR IRRIGATION

In some areas, greywater have been informally reused for irrigation. Guidelines regarding greywater reuse have been developed in many countries. This is done in order to reduce the use of potable water and ensure that greywater is safe to use. Guidelines are generally set to avoid its negative impact on the soil, plant, environment and human health.

2.5.1 International guidelines

In Arizona (USA) greywater is not suitable for surface irrigation for food crops, except nut trees and citrus, and it should not contain chemical from cleaning the car parts (Oron *et al.*, 2014). It is advised that greywater should be used immediately, as storage promotes microbial activity and odour (Jeppesen, 1996). Some countries prefer that greywater should first undergo pre-treatment to reduce its contamination when applied through pipes to prevent the blockage by large particles such as food (Ahmed *et al.*, 2015). The normal pH range for irrigation water is from 6.5 to 8.4 (Bauder *et al.*, 2011). However, most of the guidelines for wastewater reuse allow a pH range of 6-9. In Omani and California, greywater suitable for irrigation should have BOD_5 less than 20 mg L^{-1} and suspended solids < 30 mg L^{-1} (Ahmed *et al.*, 2015). Additionally, guidelines for greywater reuse by Dixon *et al.* (1999) are based on limiting the consumption of microorganisms found in greywater for human health reasons (**Table 2.2**). Greywater application could induce pathogen contamination in the soil which is then transferred to the crop and if ingested raw, transferred to humans.

Table 2.2: The numbers of bacteria found in greywater known to cause infection when ingested (Dixon *et al.*, 1999)

Microorganisms	**Number known to cause infection**
Salmonella Typhosac	10^6-10^8
Shigella Dysentri	10^3
Pathogenic enteric bacteria	10^6-10^8
Poliovirus 1	72 (oral)
Echoviru 12	35 (oral)
Adenoviru 4	1 (nasal

2.5.2 South African guidelines

According to a pamphlet compiled by RAND WATERS and Van Staden (2015) as guidelines for greywater reuse in Gauteng, greywater is only suitable for irrigating trees, flowers, shrubs and lawn. According to these guidelines:

- Only laundry greywater generated from biodegradable laundry detergents is suitable for irrigation.
- Kitchen greywater is not suitable for irrigation unless it does not contain blood from washing raw meat, grease, oil or pesticides.
- Bathroom greywater (i.e. shower, bath and hand basin greywater) generated from the use of biodegradable products is suitable for irrigation.
- Greywater should not be stored, as this elevates rapid growth of microorganisms due to the breaking down of organic material, therefore leading to anaerobic conditions which leads to unpleasant smells.

In South Africa greywater reuse studies for irrigating vegetable crops have been conducted. Based on results presented by Rodda *et al.* (2010) and Rodda *et al.* (2011), water-quality guidelines for greywater reuse for small-scale irrigation were developed (see **Table 2.3**). These guidelines were developed to assist users in the following manner:

- Minimise the risks of illness in handlers of greywater and greywater-irrigated produce, or consumers of greywater-irrigated produce
- Decrease the dangers of reduction in growth or yield in plants/crops irrigated with greywater and
- Minimise the risks of soil and environmental degradation.

Table 2.3: Recommended water quality parameters of greywater used for irrigation by small-holder farmers in SA (Rodda *et al.*, 2011).

Greywater constituents	**Preferred range (water quality range)**	**Maximum acceptable level**	**Suitable for short term application**	**Water quality not recommended for irrigation use**
Physical constituents				
Oil and grease (mg L^{-1})	< 2.5	2.5 – 10	10 – 20	> 20
Suspended solids (mg L^{-1})	< 50	50 – 100	> 100	> 100
Chemical constituents				
pH	6.5 – 8.4	6 – 9	6 – 9	< 6 or > 9
Electrical conductivity (mS m^{-1})	< 40	40 – 200	200 – 540	> 540
Boron (mg L^{-1})	< 0.5	0.5 – 4.0	4.0 – 6.0	> 6.0
Chemical oxygen demand (COD, mg L^{-1})	< 400	400 – 5000	> 5 000	> 5 000
Sodium adsorption ratio (SAR)	< 2.0	2.0 – 5.0	5.0 –15.0	> 15.0
Total inorganic nitrogen (mg L^{-1})	< 10	10 – 20	20 – 60	> 60
Total phosphorus (mg L^{-1})	<10	10 – 15	15 – 50	> 50
Microbiological constituent				
E. coli (colony-forming units, CFU·100 mg L^{-1})	< 1	1 – 10^{3} (1 – 1 000)	10^{3} – 10^{5} (1 000 – 100 000) Range can be extended to 107 (10 000 000) if irrigation is sub-surface.	> 10^{7} (> 10 000 000)

2.6 CONCLUSIONS

Previous studies have shown that greywater has vastly different compositions depending on the type of chemical used, volume of water used and its source. Greywater may contain elements that can be beneficial or detrimental to plants and pollute soil with pathogens which are a risk to human health. However, some greywater sources such as the bathroom are considered less polluted than those that use heavy detergents, i.e., laundry and kitchen greywater.

Based on chemical components of greywater, application of greywater has been shown to alter some soil properties. Many studies demonstrated that the pH, EC, SAR, CEC and Na content of the soil increase in soil irrigated with greywater. High levels of Na pose a serious hazard to heavier textured soils and can lead to sodicity and degradation of soil structure. Build-up of salts can lead to crop damage. The use of greywater containing oils, fats, grease and large amounts of surfactant can increase the hydrophobicity and reduce hydraulic properties of both sandy and heavy textured soils.

Several studies have illustrated how greywater irrigation affects soils with a single texture class, however no studies have incorporated the vulnerability of the different soil types (originating from different parent material) with varying soil properties such as Fe content, clay mineralogy, clay dispersion capacity, organic matter content, to greywater degradation. Knowledge of impact of greywater on dissolved organic carbon (DOC) removal is also lacking. The effect of bathroom, laundry and kitchen greywater on soil properties have been well studied, nevertheless, few studies have compared the outcomes associated with application of greywater from different sources (i.e. bathroom, laundry and kitchen) on the same soil.

CHAPTER THREE

GREYWATER STREAMS CHARACTERISATION AND SELECTION

3.1 INTRODUCTION

Greywater contributes about 70 % of the household wastewater (Friedler, 2004; Noutsopoulos *et al.*, 2017; Oteng-Peprah *et al.*, 2018) and its reuse for irrigation purposes, especially in water scarce countries, is increasing to promote water conservation. However, greywater has been reported to contain some pollutants that may negatively influence crop quality and soil properties (Bauder *et al.*, 2011). Hence, it is very important to assess its quality in order to evaluate its reuse potential and examine its acceptability for reuse.

Some nutrients in irrigation water can be found in toxic amounts, thus compromising the quality of irrigation water (Ayers and Westcot, 2007). Irrigation water quality is assessed based on salinity hazard, sodicity and toxicity of specific ions such as Cl^-, SO_4^{2-}, BO_3^{3-} and NO_3^- (Bauder *et al.*, 2011). The quantity of these water constituents generally depends on the type and amount of dissolved salts (Ayers and Westcot, 2007), thus the need for greywater characterisation. The variation in greywater composition result from the type and choice of chemicals used either for laundry, dishes, cleaning and bathing (Oteng-Peprah *et al.*, 2018). The lifestyle of members in the household can also influence greywater composition (Rose *et al.*, 1991).

Individual greywater streams vary substantially in composition, as some streams are likely less polluted and thus environmentally hazardous than others (Ghaitidak and Yadav, 2013). Many greywater application studies make use of a composite sample of all the greywater streams (Lubbe *et al.*, 2016; Maimon *et al.*, 2017) because combining certain streams of greywater improves quality (Rodda *et al.*, 2010). However, this would mean that a household would need to have a greywater harvesting system. Certain greywater streams are easier to capture and reuse than others. Greywater from laundry and dish washing machines are the easiest to capture due to ease of drainage hose access, whereas, shower and bath water can be captured manually using buckets, if direct access to the drains is not possible. The main objectives of this chapter are (a) to characterise major streams of domestic greywater in terms of the water quality parameters in comparison to tap water, (b) to select a representative example of each major type of greywater for use in the subsequent soil application experiments.

3.2 MATERIALS AND METHODS

3.2.1 Greywater sample collection and pH and EC characterisation

Domestic greywater samples from different sources *viz*; shower, bathtub, kitchen sink, floor wash, dishwashers and washing machines were collected from several members of the Soil Science Department at Stellenbosch University. Each participant filled out a form indicating the type of greywater collected, the detergents or chemicals used, shower duration time and the amount of water produced by washing machines per wash cycle. A total of 95 samples were collected and were analysed for pH and electrical conductivity (EC) on arrival using Metrohm Swiss made 8.27 pH lab and Jenway 4510 conductivity meter, respectively. The pH and EC readings were then used to screen the greywater sources for subsequent selection in the water and soil quality study.

3.2.2 Laundry detergent selection and greywater preparation

Laundry greywater is one of the largest streams of greywater (Ghaitidak and Yadav, 2013). As the chemical composition of laundry detergents can vary, an initial screening study was undertaken in order to select representative liquid laundry detergent (LLD) and powdered laundry detergent (PLD). Seven LLDs and six PLDs produced by major manufacturers were obtained from a local supermarket and greywater solutions were prepared using the manufacturers recommended dosage rates and the typical volume of wash water for a front-loading washing machine on a regular washing cycle (typically 25 L). In the case of liquid detergents, precise volumes of 2.2 and 3 ml could be pipetted using a micropipette to make up 1 L solution for analysis. As the manufacturer's recommended dosage of the PLD was expressed as volume, the densities of these detergents needed to be determined so that a precise mass could be used when making up smaller volumes of greywater solutions.

3.2.2.1 Powdered laundry detergent (PLD) solution preparation

Cylindrical cores with a height of 3.05 cm and an inside diameter of 4.75 cm (volume = 53.93 cm^3) were filled with the PLDs and the mass of these detergents were determined. The densities of the powders were then calculated using the mass of the PLD and the volume of the cylindrical core as shown in formula below. The PLD wash water solutions were prepared in 1 L volumetric flasks using the equivalent mass needed for the manufacturers' dosage and tap water (refer to **Table 3.1** below).

$$Bulk\ density\ (Pb) = \frac{Mass\ of\ washing\ powder}{Volume\ of\ cylindrical\ core} \qquad \text{Eq. 3.1}$$

$$Volume\ of\ cylinder = \pi r^2 h \qquad \text{Eq. 3.2}$$

Table 3.1: The density calculated from mass of powdered laundry detergent (PLD) and volume of the cylindrical core, mass and volume of powdered detergents per wash cycle prepared 1 L using tap water.

Powdered laundry detergents	Mass of PLD in cylinder (g)	Volume of Cylindrical core cm^3	Density ($g\ cm^{-3}$)	Manufacturer recommended volume (Ml) per wash cycle per L	Mass of PLD added to 1 Litre (g)
PLD 1	29.43	53.93	0.55	5.00	2.75
PLD 2	28.57	53.93	0.53	7.20	3.82
PLD 3	29.68	53.93	0.55	7.20	3.96
PLD 4	31.56	53.93	0.59	7.20	4.25
PLD 5	34.56	53.93	0.64	7.20	4.61
PLD 6	31.08	53.93	0.58	9.60	5.57

- PLD = Powdered Laundry Detergents, g = grams, cm^{-3} = per cubic

3.2.2.2 Chemical analysis of the liquid and powdered laundry detergent greywater solutions (pH, EC, Ca, Mg, K and Na)

The pH and EC of LLD and PLD detergent greywater solutions were measured using Metrohm Swiss made 8.27 pH lab and Jenway 4510 conductivity meter, respectively. The Ca, Mg, K and Na contents were determined using a VARIAN AA240FS Fast Sequential Atomic Absorption Spectrometer (AAS). The Ca, Mg and Na concentrations were then used to calculate the sodium adsorption ratio (SAR) of the laundry greywater solutions using the following formula:

$$\mathbf{SAR} = \frac{Na^{+}}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}} \qquad \text{Eq.3.3}$$

where Na, Ca and Mg concentrations are expressed in $mmol_c\ L^{-1}$. The representative LLD and PLD detergents were selected by choosing detergents with the closest pH, EC, Na and SAR values to that of the mean of all the LLD and PLD detergents, respectively.

3.2.3 Shower greywater preparation

Bathing (showers and baths) produce the largest volumes of domestic greywater (Rose *et al.*, 1991). Due to the drought/water stress conditions in the Western Cape, residents were encouraged to only shower for 2 minutes or less. It also has become a municipal bylaw that all houses should use water-saving shower heads. If making use of typical water-saving showerhead, with a flow rate of approximately 7.5 L min^{-1}, then about 15 litres of water would be used per 2 minutes showering event. During the domestic greywater screening study, it was ascertained that most people make use of solid bar soaps, body wash, hair conditioner and shampoos for bathing and therefore shower greywater solution was prepared using these substances. According to the shampoo and hair conditioner manufacturer, each person is estimated to use at least 5 ml of shampoo and 5 ml conditioner per shower. A study was performed to estimate how much solid soap each person uses per shower event. This entailed supplying five members of the department of Soil Science each with a pre-weighed oven-dried bar of soap. The members were asked to take a typical 2 minutes shower using it and then return the soap the next day, where it was oven-dried again and weighed to determine the mass of soap used. The amount of body wash used per shower was estimated to be around 20 ml. Therefore, shower greywater was prepared according to the composition shown in Table 3.2 below, and it was ensured that the pH and EC of the shower greywater was similar to that of the domestic shower and bath water solutions that were obtained during the initial screening study (**Figures 3.1 and 3.2**). The pH and EC of solutions of the individual shower greywater constituents prepared using the amounts specified in Table 3.2 are shown in Table 3.3 below. Solid soap contributes to increasing the pH of shower greywater while bodywash contributes more to the salt content (**Table 3.3**).

Table 3.2: Formulation of shower greywater solution.

Constituents	Amounts
Tap water	15 L
Shampoo	5 ml
Conditioner	5 ml
Bodywash	20 ml
Bar soap	1.25 g

Table 3.3: The pH and EC of individual shower constituent (per bath *i.e.* in 15 L water) prepared in tap water.

Components	**pH**	**EC (mS m^{-1})**
Tap water	6.27	6.21
Body wash	6.03	13.20
Shampoo	6.43	9.45
Conditioner	6.46	6.43
Solid bar soap	7.49	8.08
Shower greywater solution	6.94	16.74

3.2.4 Dishwasher greywater collection

Dishwasher greywater (20 L) was collected straight from an actual dishwasher cycle using a major brand of pelletized detergent and then stored in the freezer to prevent microbial growth and decomposition of organics before analysis or use in subsequent soil application experiments.

3.2.5 Water quality analysis

The selected greywater samples, namely; (a) shower (SH), (b) liquid laundry detergent (LLD), (c) powdered laundry detergent (PLD) and (d) dishwasher (DW) were characterised in duplicate in terms of the following water quality parameters: pH, EC, Ca, Mg, K, Na, P, ammonium, nitrate, chloride, sulphate and chemical oxygen demand (COD) and compared to tap water taken from Stellenbosch University. All the samples were analysed by an accredited commercial laboratory, Bemlab (Pty) Ltd., Somerset West. Additionally, the turbidity of the greywaters was measured using a Thermo Scientific ORION AQUAfast (AQ3010) turbidity meter. It is important to note that, SH, LLD and PLD greywater which will be used in soil quality experiment, are all synthetic greywaters except for DW greywater

3.2.6 Statistical Analysis

The data was analysed statistically using a one-way ANOVA to test for significant differences in the water quality parameters of the four greywater streams and tap water. A Fisher's Least Significant Difference test was used to test which means are different from each other at 95% confidence level. All the statistical analyses were performed using Statistica (version 13.5.0.17).

3.3 RESULTS AND DISCUSSION

3.3.1 pH and EC of collected domestic greywater samples

According to the South African water quality guidelines for agriculture use, the target quality pH for irrigation water should be between 6.5-8.4 and the electrical conductivity (EC) should be less than 40 mS m^{-1} (DWAF, 1996). The greywater pH (**Figure 3.1**) and EC (**Figure 3.2**) results show that only greywater generated from the shower or bath, and liquid laundry detergent (LLD) were within the acceptable quality range, whereas greywater generated from powdered laundry detergent (PLD), dishwasher (DW) and floor wash (FW) had pH and EC values greater than the target quality values. Moreover, greywater generated from the kitchen sink dishwater had an acidic pH (5.36) with higher electrical conductivity (121.2 mS m^{-1}) which were similar to the results reported by Halalsheh *et al.* (2008). These values were also not within the acceptable range for irrigation water. Acidic pH in kitchen greywater may have resulted from the presence of foods high in acid such as tomatoes and cooking oil (Al-Jayyousi, 2003). The use of acidic dish washing liquid detergents might have also lowered pH of this greywater**.** Subsequently, from the pH and EC results, four representative streams of greywater were selected for the soil application experiments (Chapters 5 and 6) and were then sent for a comprehensive water quality analysis. These selected greywater streams included two “acceptable” streams, i.e., shower and liquid laundry detergent greywater streams, and two “unacceptable” streams, i.e., dishwasher and powdered laundry detergent greywater streams. The selection of the other greywater streams (shower and laundry) was also based on their relative importance in terms of quantities generated. These greywater streams are known as largest domestic sources of greywater by volume; with shower producing the largest quantity followed by laundry greywater (Al-Mughalles *et al*., 2012; Oteng-Peprah *et al*., 2018).

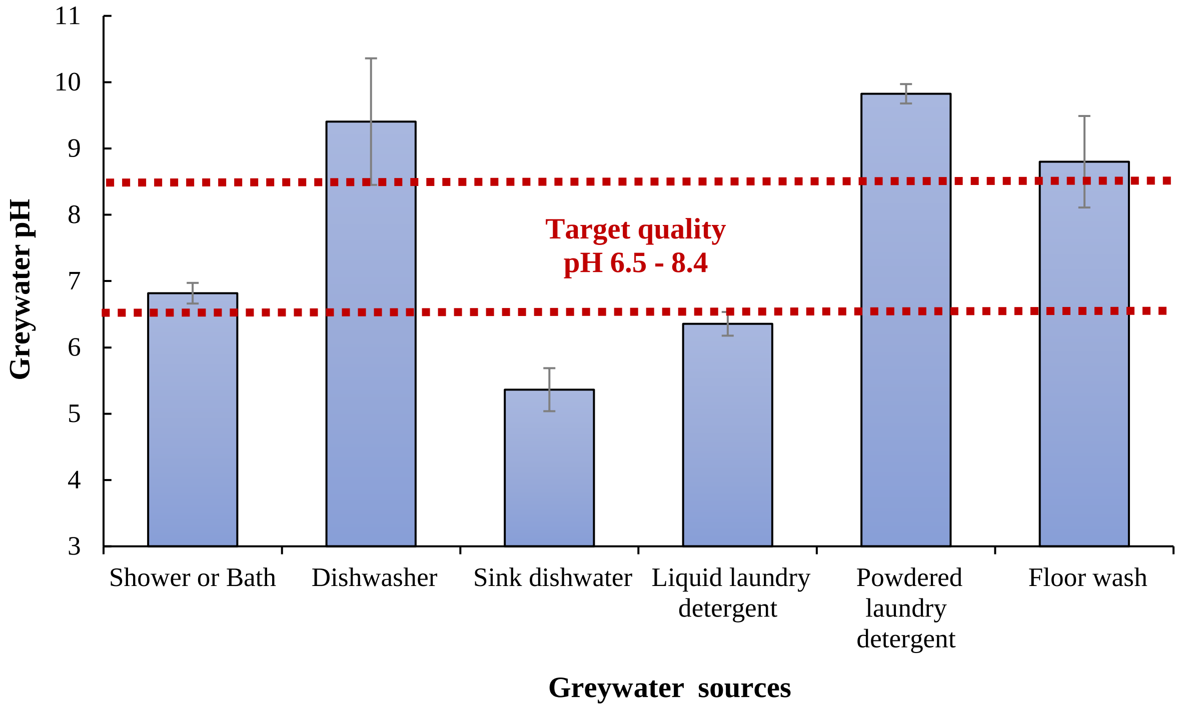


Figure 3.1: The mean pH of greywater samples from different sources (showers or bath, kitchen sink dishwater, dishwasher and laundry).

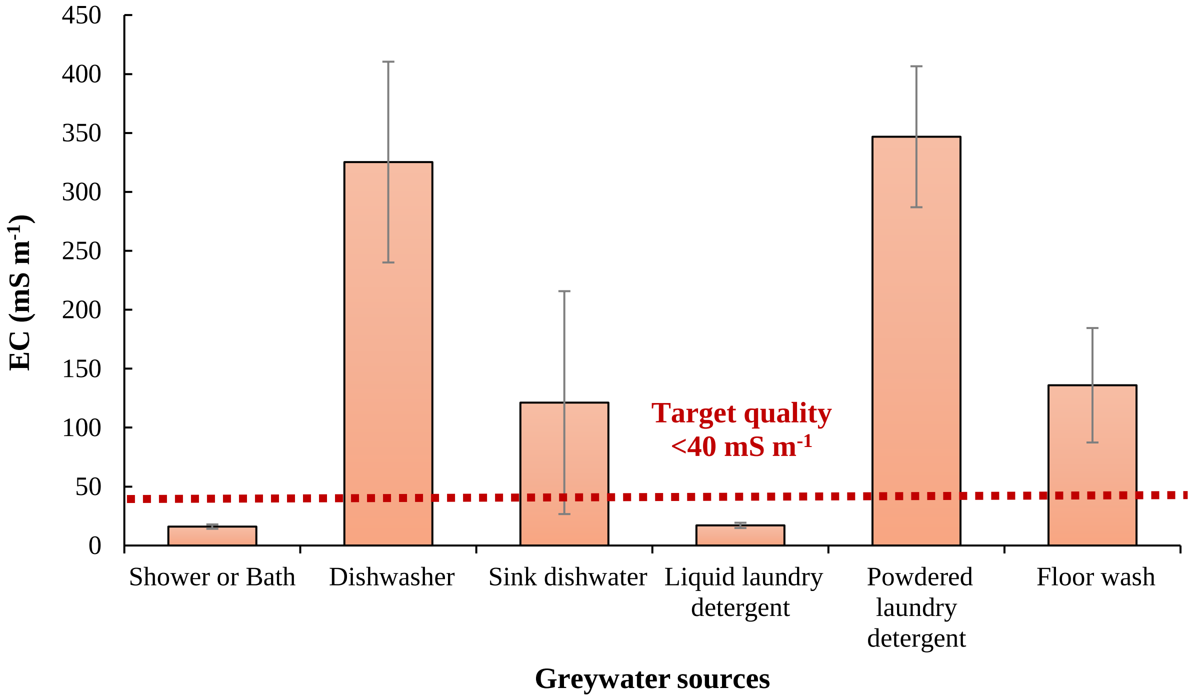


Figure 3.2: The mean electrical conductivity (EC) of greywater samples from different sources (showers or bath, kitchen sink dishwater, dishwasher and laundry).

3.3.2 Laundry detergent selection

The pH, EC, Na and SAR results for laundry detergent greywater solutions are shown in Table 3.4. The pH of the wash water for liquid detergents varied from 7.0 to 7.4 while that of the powdered laundry detergents ranged from 10.4 to 10.7. The average maximum value specified in literature for the pH of powdered laundry detergent wash water was 10.8 (Stevens *et al.*, 2011) and the pH values of all PLD wash water in this study (**Table 3.4**) were slightly below the reported value. Misra and Sivongxay (2009) and Misra *et al.* (2010) reported LLD pH and EC that were higher than the ones used in this study. The average pH of the LLD greywater was 7.3 while the average for PLD was 10.6. The PLD wash water solutions also had high average EC of 439.7 mS m^{-1} while that of LLD was 24.3 mS m^{-1}. A strong significant positive correlation was found between laundry greywater stream's sodium (Na) content and EC ($r = 0.99$, $p < 0.05$), indicating that mainly the greywater's Na content was determining the EC. Based on the average LLD and PLD pH, EC, Na and SAR results, LLD 6 was selected for use to represent the liquid detergents while PLD 4 was selected the powdered detergents as they provided the closest match to the parameter averages (**Table 3.4**). Therefore, these selected detergents were used in the production of the two synthetic streams of laundry greywater to ensure consistency in the soil quality experiment.

Table 3.4: The pH, EC, Na and SAR of wash water generated from laundry liquid detergents (LLD) and laundry powered detergents (LPD) with bolded values showing the averages.

Detergent Wash water	pH	EC (mS m^{-1})	Na (mg L^{-1})	SAR
Tap water	6.8	7	6.6	1
LLD 1	7.4	15	29.5	4
LLD 2	7.4	15	23.8	3
LLD 3	7.3	18	32.4	4
LLD 4	7.3	21	38.4	5
LLD 5	7.0	21	36.6	4
LLD 6	7.4	24	47.6	5
LLD 7	7.4	37	75.9	10
AVG Liquids	**7.3**	**24.3**	**46.2**	**5.7**
PLD 1	10.7	318	727.8	41
PLD 2	10.7	377	923.6	27
PLD 3	10.5	409	939.0	41
PLD 4	10.7	436	1038.3	40
PLD 5	10.6	538	1222.6	50
PLD 6	10.4	560	1360.5	20
AVG Powders	**10.6**	**439.7**	**1035.3**	**36.5**

- AVG =Average, LLD =liquid laundry detergent, PLD = powdered laundry detergent

3.3.3 Water quality analysis

Results shown in Table 3.5 below presents a detailed water quality analysis of the four selected streams of greywater and tap water for the subsequent research chapters. These results represent the averages and show high variability for most of the assessed water quality parameters.

3.3.3.1 Physical parameters

3.3.3.1.1 Turbidity

The values obtained for turbidity measurements of different greywater streams vary significantly and were found to be in the range of 0.38–578.5 NTU (**Table 3.5**). Figure 3.3 show a visual display of tap water and the selected greywater streams. Tap water was clear and had a turbidity value of 0 NTU followed by LLD greywater with an average turbidity value of

0.38 NTU. Dishwasher greywater was the most turbid (highest value) compared to other greywater streams (SH, LLD and PLD) and tap water. This was mainly due to presence of food particles and high salt content. The turbidity of PLD greywater was influenced by high salt content. PLD laundry greywater was the second most turbid followed by shower. Rose *et al.* (1991) reported a turbidity range of 28-96 on bath water while turbidity values between 39-296 were reported on laundry wash water. In this study both SH and PLD greywater turbidity values were within these reported range. Additionally, higher SH and laundry greywater turbidity values (348 and 328 NTU) were reported by Jamrah *et al*. (2008). Furthermore, it should be noted that there are no target or restriction values for turbidity of irrigation water in the South African (RSA) irrigation water guidelines.

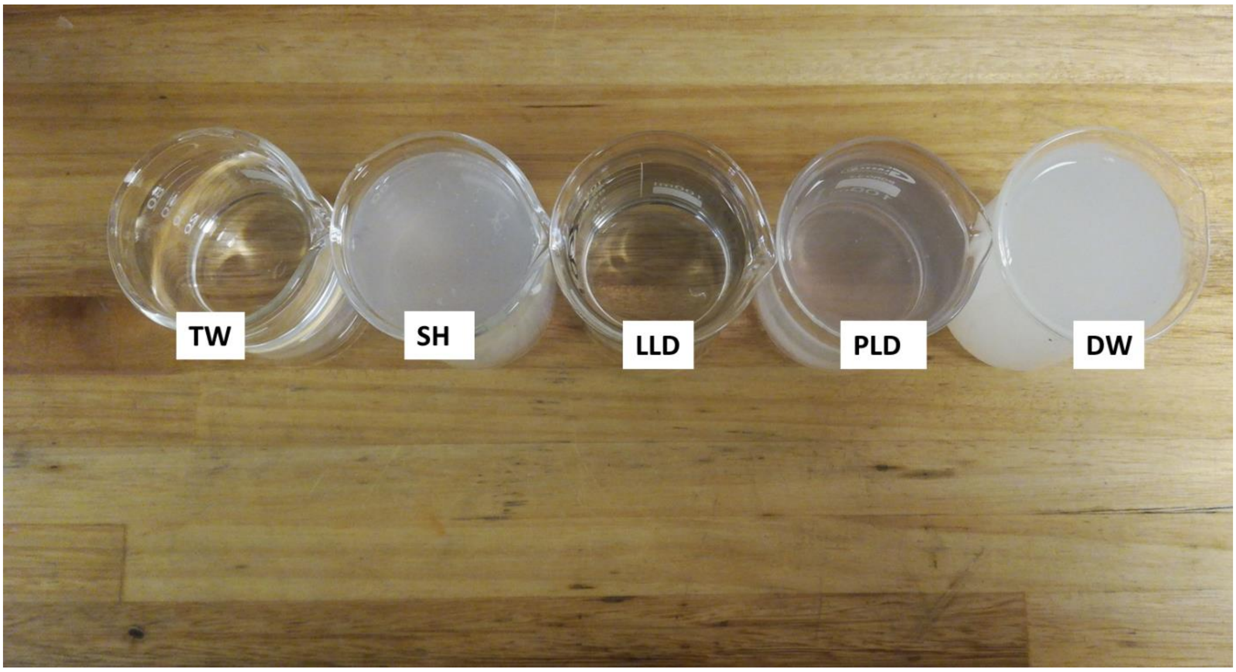


Figure 3.3: Visual display of tap water (TW) and four streams of greywater namely; shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW).

3.3.3.2 Chemical parameters

3.3.3.2.2 pH

The dishwasher (DW) and powdered laundry detergent (PLD) greywater streams had an alkaline pH (9.34 and 10.67) due to the use of sodium carbonates in their formulation, while shower and liquid laundry detergent greywater streams had pH values close to neutral (6.97 and 7.3). The average pH of greywater generated from powdered laundry detergent (PLD) was significantly higher than other greywater streams and tap water (TW), followed by greywater generated from the dishwasher, then liquid laundry detergent (LLD) greywater. Only the average pH of shower greywater was not significantly different from that of tap water. The pH of the PLD greywater in this study is similar to the greywater's pH results (10.8) reported by Rose *et al*. (1991) and Stevens *et al.* (2011). Pinto *et al.* (2010) also reported a similar greywater pH value (10.5), however, it should be noted that the greywater source(s) in that study were not specified. Additionally, it is also important to note that the pH of SH, LLD and PLD greywater solutions in this section were similar to the average pH of the domestic greywater samples obtained in section 3.3.1.

3.3.3.2.2 Electrical conductivity (EC) and total dissolved solids (TDS)

The powdered laundry detergent (PLD) had a significantly higher electrical conductivity (EC) and total dissolved solid (TDS) compare to other greywater streams and tap water, followed by the dishwasher, while among the four streams of greywater shower greywater had the lowest EC and TDS. The use of large quantities of salts in powdered laundry and dishwasher detergents contributed to high electrical conductivity (EC). The EC of PLD and DW greywaters (450 and 424 mS m^{-1}) were approximately 11 times more than the recommended irrigation EC (< 40 mS m^{-1}). The EC of the greywater solutions for SH, LLD and PLD were also similar to the average EC of the domestic greywater samples reported in section 3.3.1. Additionally, the highest TDS value was reported in PLD greywater and was almost twice that of laundry greywater reported by Jamrah *et al.* (2008), 2140 mg L^{-1}, followed by the DW greywater (TDS = 2717 mg L^{-1}) then liquid laundry detergent greywater and shower with tap water having significantly the lowest TDS value.

3.3.3.2.3 SAR and Na

The sodium (Na) content allowed in irrigation should be less than 70 mg L^{-1} and the recommended sodium adsorption ratio (SAR) of irrigation water should be less than 2 (DWAF, 1996). Results in Table 3.5 showed that only tap water (TW) and shower (SH) greywater meet both these standards. Even though the Na content of the liquid laundry detergent (LLD) greywater was within the acceptable range (<70 mg L^{-1}), its SAR value (4) was 2 units higher than the DWAF 'acceptable' value. However, according to the guidelines by Rodda *et al.* (2011) for wastewater re-use for irrigation purposes, this SAR value is within the allowable range but only for short-term use. Greywater generated from PLD had the significantly highest SAR (147) with high Na content (1337.7 mg L^{-1}) compared to other greywaters and tap water. The SAR value of DW greywater (50.5) was almost 3 times lower than the PLD, while its Na content was 1017.3 mg L^{-1} which was similar to that of the PLD greywater. This indicates that calcium (Ca) and magnesium (Mg) contents in DW greywater were also fairly high.

Consequently, in terms of the Na content and SAR, both PLD and DW greywaters were of poor quality.

3.3.3.2.4 Elemental composition

The greywater boron (B) contents were very low and were only detectable in the PLD and DW greywater streams in small quantities. The trace metal (Zn, Mn, Fe and Cu) contents of all the greywater streams were relatively low and ranged between 0-0.825 mg L^{-1} (**Table 3.5**). On average, the laundry greywaters contained highest Cu contents (0.50 and 0.55 mg L^{-1}). Dishwasher greywater had the highest levels of chlorides (1067.5 mg L^{-1}), P (111.93 mg L^{-1}) and bicarbonates (427.6 mg L^{-1}), likely due to the food wastes, dishwashing table salt, and dishwashing detergents (Mulders and Kgaa, 2012). The PLD wastewater contained the highest levels of carbonates (1280.5 mg L^{-1}) and sulphates (1541.5 mg L^{-1}), attributed to the use of sodium carbonates and sulphates as builders in the powdered laundry detergents (Patterson, 2009; Mulders and Kgaa, 2012; Taylor, 2013). The LLD greywater also contained significant sulphate content (126.5 mg L^{-1}) which was higher than the SH, DW and TW. The concentration of P and Cl in SH and LLD greywater streams were relatively low and similar to those in tap water. Ammonium-N was only detected in SH (4.79 mg L^{-1}) while hydroxides (9.89 mg L^{-1}) were only detected in PLD greywater.

3.3.3.2.5 Chemical oxygen demand (COD)

Chemical oxygen demand (COD) is one of the indexes used to estimate total organics in waste water and includes both biodegradable and non-biodegradable forms of organic matter (Płuciennik-Koropczuk and Myszograj, 2019). The COD values of the greywater streams ranged between 560–2400 mg L^{-1} (**Table 3.5**). Results from Table 3.5 show that the more turbid streams of greywater i.e., LLD, PLD and DW, had significantly higher COD contents than the less turbid stream (SH). Dishwasher greywater had highest COD content (2400 mg L^{-1}) likely due to contamination with food particles, grease and oils (Friedler, 2004). The COD content of the laundry greywaters (LLD and PLD) were not significantly different from each other. Taylor (2013) also reported similar high LLD COD contents (1006 mg L^{-1}), however, the reported PLD COD contents were lower ranging from 365-464 mg L^{-1}. The COD value (560 mg L^{-1}) of SH was higher than that of TW (<6.21 mg L^{-1}), however, it should be noted that this difference was not statistically significant. Al-Hamaiedeh and Bino (2010) suggested that low water consumption, yields high COD values.

Table 3.5: Physical and chemical characteristics of tap water and four selected types of greywater (with bold numbers indicating values outside the DWAF target quality for irrigation water)

		Greywater streams				
Parameters	**Tap water (TW)**	**Shower (SH)**	**Liquid laundry detergent (LLD)**	**Powdered laundry detergent (PLD)**	**Dishwasher (DW)**	**RSA Irrigation standards**
Turbidity (NTU)	0.00	69.80	0.38	90.05	578.50	-
pH	6.60d	6.97d	7.30c	**10.67a**	**9.34b**	6.5-8.4
EC (mS m^{-1})	6.00d	16.00c	19c	**450a**	**424.50b**	< 40
TDS (mg L^{-1})	34.80e	114d	242.5c	**4211.50a**	**2717b**	< 450
SAR	0.50d	1.80d	**4.70c**	**147.80a**	**50.50b**	< 2
Na (mg L^{-1})	4.60	18.20	44.10	**1337.70**	**1017.30**	< 70
COD (mg L^{-1})	<6.21c	560c	1170b	1353b	2400a	-
B (mg L^{-1})	<0.08	<0.08	<0.08	0.30	0.11	<5
Cl (mg L^{-1})	12.60	22.90	10.80	47.50	**1067.5**	<100
CO_3^{2-} (mg L^{-1})	0.00	0.00	0.00	1280.50	0.00	-
HCO_3^{-} (mg L^{-1})	9.90	9.90	55.50	<4.02	427.60	-
SO_4 (mg L^{-1})	2.00	55.00	126.50	1541.50	66.50	-
P (mg L^{-1})	<0.01	0.11	0.06	5.45	111.93	-
NH_4-N (mg L^{-1})	<0.28	4.79	<0.28	<0.28	3.71	< 5
NO_3-N (mg L^{-1})	<0.36	<0.36	<0.36	<0.36	<0.36	< 5
Cu (mg L^{-1})	0.21	0.19	0.505	0.55	0.09	< 5
Zn (mg L^{-1})	<0.03	<0.03	0.04	0.04	0.66	< 5
OH	0.00	0.00	0.00	9.36	0.00	-
Total Fe	0.15	0.19	0.13	0.28	0.83	< 5
Total Mn	0.00	0.09	0.01	0.01	0.38	<5

***Notes:** EC = electric conductivity, SAR= Sodium Adsorption Ratio, TDS = total dissolved solids, COD = chemical oxygen demand, NTU = nephelometric turbidity unit, Na = Sodium, Cl = Chloride, CO_3^{2-} = Carbonates, HCO_3^{-}= Bicarbonates $SO_{4=}$ Sulphate, P= Phosphorus, NH4–N= ammonia–nitrogen, NO3–N = nitrate–nitrogen, Cu= Copper, Zn= Zinc, OH = Hydroxide, Fe = Iron, Mn = Manganese

*Statistically significant differences between tap water (TW) and the greywater streams (SH, LLD, PLD and DW) at $p<0.05$ are denoted by different letters for a given water quality parameter

3.4 CONCLUSIONS

Results from this chapter highlighted that there is variability in water quality parameters of greywater streams, even those generated from the same stream such as liquid and powdered laundry detergents. These differences were mainly due to the type of detergent used. The pH and EC of SH and LLD greywater streams were within the acceptable irrigation range while those of the dishwashing sink, PLD, DW and floor wash were not within the allowable limit. Based on the pH and EC quality, four representative greywater streams namely; SH, LLD, PLD and DW, were selected i.e., two streams of better quality (SH and LLD) and two of worst quality (PLD and DW). The selected greywater streams also contribute to larger volumes of the wastewater produced from household activities excluding toilet wastewater. The quality of SH greywater did not differ that much from tap water (except for its EC and TDS) due to the use of chemical products and its water quality parameters were within the acceptable irrigation spectrum. The LLD greywater was also of better quality compared to PLD and DW, however, its use for irrigation purposes should be monitored due it’s to high SAR (4.7) which is slightly above the irrigation limit of 2. The PLD and DW greywaters were of poor irrigation quality due their alkaline pH values and high SAR values. DW greywater also had high P and Cl^- content, which may result in toxicity of these elements in the soil when this water is used for irrigation. None of the greywaters contained significant amounts of trace metals (Zu, Cu, Fe and Mn) or nutrients like N and B. Therefore, among the four selected streams, greywater generated from laundry powdered detergent and dishwasher were poor in terms of quality and represented the most polluted streams, while shower and liquid laundry detergent greywaters were less polluted.

CHAPTER FOUR

SOIL SAMPLING AND CHARACTERISATION

4.1 INTRODUCTION

The purpose of this chapter is to describe selection and characterisation of representative soil samples from the major forms occurring in the Cape Town and Stellenbosch urban areas that were used in this MSc study.

4.2 METHODS AND MATERIALS

4.2.1 Soil sample collection

Twenty topsoil samples were taken from gardens around Cape Town and Stellenbosch urban areas. Samples were collected from the five major soil types identified using regional soil maps provided by the Agricultural Research Council – Institute for Soil Climate and Water (ARC-ISCW) Pretoria. The five major soil types include: 1) aeolian sands which typically occur near coastal areas (sands group; Arenosols), 2) alluvial deposits near rivers (alluvium group; Fluvisols), 3) soils originating from granite parent material (granite group; Planosols), 4) soils originating from shale parent material (shale group; Lixisols/Acrisols) and 5) highly weathered, apedal red or yellow colluvial soils (chromic group; Chromic Lixisols/Acrisols) (**Figure 4.1**).

The aeolian sands are marine-derived, windblown sands that occur along the low altitude coastal regions. They can be divided into two groups, the calcareous sands, closer to the ocean and the more leached, acidic sands that occur 5-15 km from the coast (Schloms *et al.*, 1983). The alluvial soils occur in valley bottoms and have a loamy sand texture. The granitic soils occur on the weakly dissected upland planes, as well as at higher elevations on the mid- to footslopes of the Cape Fold Mountains. Many of these soils are duplex in nature, with colluvial granitic material overlying truncated granitic pallid zones related to the African erosion surface. The shale soils are found in a similar terrain position as the granitic soils and also predominantly duplex soils. In both the duplex shale and granite derived soils that were sampled, a degree of subsoil and topsoil mixing had taken place during garden preparation or house construction. The deep, chromic, red and yellow colluvial soils occur on the lower midslopes of the Cape Fold Mountains between altitudes of 150 and 300 m and are derived from highly weathered colluvial deposits dating back to the early Tertiary period (Schloms *et al.*, 1983). They are considered palaeosols as their ferrallitic weathering occurred under more humid conditions compared to the modern Mediterranean climate (Schloms *et al.*, 1983).

Figure 4.1 shows the sampling locations in relation to the broad soil groups. Topsoils were sampled at a depth of 0-20 cm using an auger, while the subsoil samples were taken from a depth of 30-60 cm. The soils were air dried and sieved through a 2 mm sieve. The following physical and chemical soil properties were determined: particle size distribution, water dispersible clay, pH, EC, soil organic carbon, exchangeable bases and acidity, citrate-buffered dithionite (CBD) iron and clay separation.

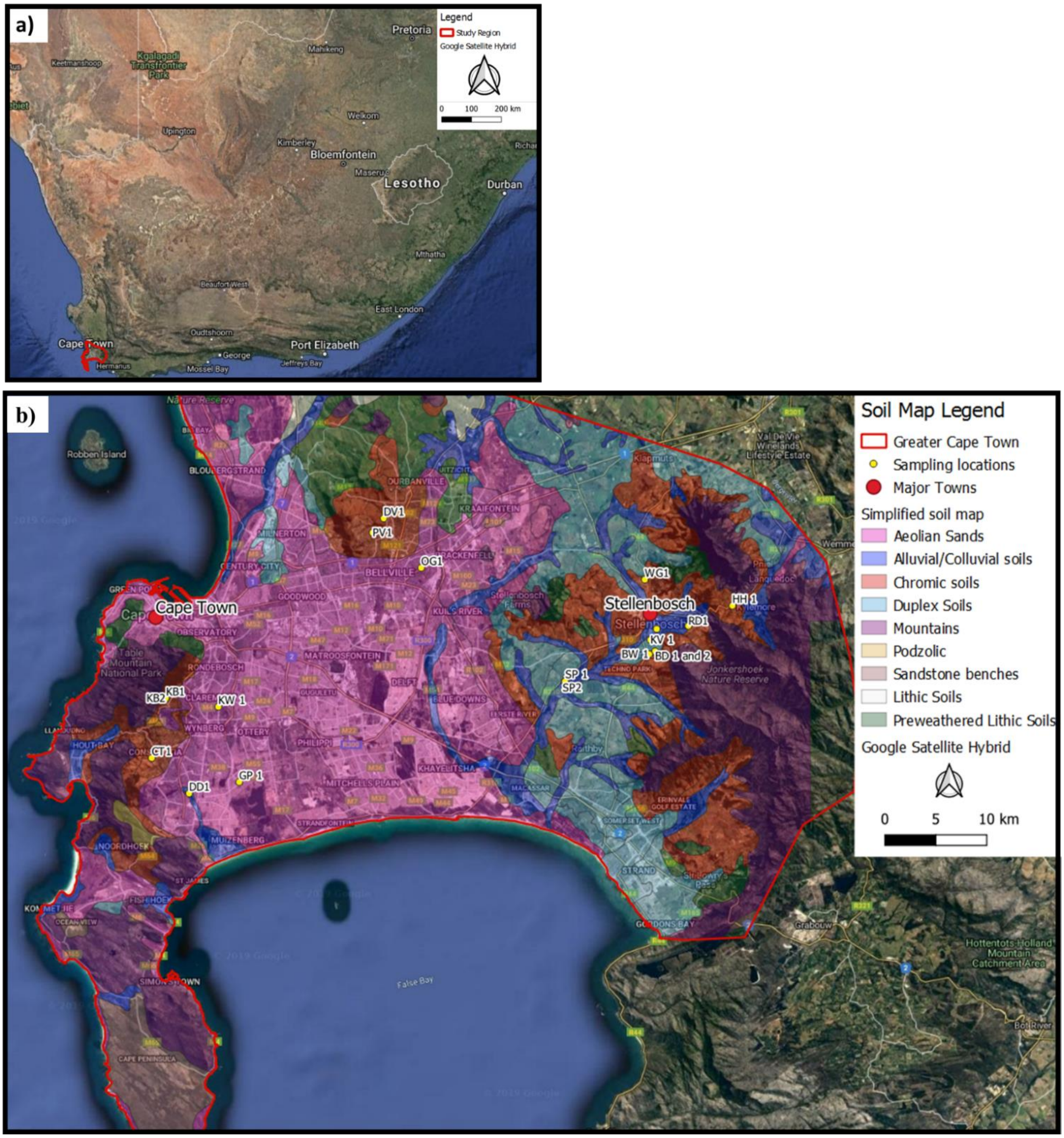


Figure 4.1: Cape Town and Stellenbosch soil map showing the sampling locations indicated by the dots; Granitic and Shale soils occur within the map units Duplex, Preweathered Lithic and Lithic soils.

4.2.2 Mineralogical soil properties

4.2.2.1 Extractable iron (Fe): Dithionite-citrate-bicarbonate

Citrate-buffered dithionite (CBD) extractable Fe was determined following the standard procedure developed by (Mehra and Jackson, 1960). Soil samples were passed through a 0.180 mm sieve and 4 g of these soils was placed in a centrifuge tube with 125 ml capacity. A volume of 40 ml of 0.3 M sodium citrate and 5 ml of 1 M $NaHCO_3$ were added to the soil. The tube containing the soil solution was placed in a water bath set at 77 ^{o}C, and it was made sure that the temperature does not exceed 80^{o}C. The temperature was allowed to stabilise before 1 g of sodium dithionite ($Na_2S_2O_4$) powder was added. The solution was stirred rapidly for one minute and placed back in the hot water bath. The soil samples were kept in the water bath for 15 minutes and intermittently for further 15 minutes. The tubes were centrifuged at 2000 rpm for 10 minutes and the clear supernatant was decanted into 500 ml volumetric flask. The extraction described above was repeated until all the iron (Fe) in the soils was completely removed (which was indicated by the grey soil colour). The soil residue in the centrifuge tubes was washed with 60 ml of distilled water and then warmed to 77^{o}C before centrifuging at 2000 rpm for 10 minutes. The supernatant was transferred into the 500 ml volumetric flask. The volumetric flask was filled up to 500 ml with distilled water. After the extraction process, the Fe content was determined using AAS and the detected concentrations were expressed as a mass percentage of the soil.

4.2.2.2 Clay mineralogy

Clay separation for x-ray diffraction (XRD) analysis was done based on the methods proposed by Harris and White (2008). Clay mineralogy was only determined on selected soils from three soil groups namely; Spier 1 (SP1) and Kirstenbosch 2 (KB2) from the granite soil group, Brandwag 1 (BW1) and Durbanville 1 (DV1) from the shale soil group, and Constantia 1 (CT1), Bo-Dalsig 2 (BD2) and Protea Valley 1 (PV1) from the chromic soil group. These soil groups were mainly selected because they were more rich in clay. Thus, no samples from the aeolian sand and alluvium soil were used for the determination of clay minerology. Each of the 7 soil samples was saturated with both magnesium chloride ($MgCl_2$) and potassium chloride (KCl), making a total of 14 samples. The soils were dispersed with water. The dispersed clay fraction was decanted and flocculated through the addition of 1 M HCl. The flocculated clay fraction was split, and cation saturation was accomplished by making up approximate solutions of 0.5 M $MgCl_2$ and 1 M KCl respectively, using the clay suspensions. The K- and Mg- clay slurries were shaken by hand and centrifuged at 1000 rpm for 3.5 minutes to dewater the samples. Each sample was washed again using 0.5 M $MgCl_2$ and KCl solutions and thereafter excess salt was removed by washing the samples with a 1:1 methanol-water solution. The concentrated clay fraction was transferred to a dialyses tube and placed in a water bath until the water bath tested free of chlorides. The dialysed clay samples were air dried and grounded by hand using a mortar and pestle. The prepared samples were then sent to iThemba Laboratories in Cape Town for XRD analysis at angles ranging from 4 to 60 degrees.

4.2.3 Physical soil properties

4.2.3.1 Particle size distribution

The particle size distribution of the soil samples was determined to assess soil texture using the method described by the Soil Classification Working Group and Macvicar (1991). Soil samples were pre-treated with hydrogen peroxide to remove organic matter and citrate-bicarbonate-dithionite solution was used to remove iron (Fe) oxides. The elimination of cementing and flocculating compounds was done in order to enhance the separation of soil aggregates. Subsequently, the soils were dispersed by adding 10 cm^3 of Calgon (a dispersing agent prepared from mixing sodium hexametaphosphate with sodium carbonate). The suspension was then transferred to a dispersion cup and mixed with an electric mixer (Hamilton Beach HMD300 Commercial Drink Mixer) for 5 minutes. The dispersed sample was washed on a 0.053 mm sieve, which allowed the silt and clay fraction to pass into a 1 dm^3 cylinder via a plastic funnel. The sand fraction was retained in the sieve and was oven dried at 105^{o}C. The dried sand was transferred to a nest of sieves arranged from top to bottom with decreasing size from 1 mm, 0.5 mm, 0.25 mm, 0.106 mm and 0.053 mm. This was done to separate different sand fractions. The sieves were shaken for 10 minutes on an Endecott test sieve shaker to separate the individual sand fractions and a sieve receiver was placed at the bottom of the arranged sieves to collect any additional silt and clay fractions. The silt and clay fractions were determined using the pipette method where the filled cylinder (subjected to a constant temperature) was thoroughly stirred vertically for 30 seconds and after an appropriate time interval, 25 ml of the suspension was drawn, discharged on an evaporating dish, dried to a constant mass and weighed. All the soil fractions were expressed as mass percentages following the calculations specified by the Soil Classification Working Group and Macvicar (1991). The soil textural classes of the soils were also determined.

4.2.3.2 Water dispersible clay

The water dispersible clay method is similar to the particle size analysis, however, the cementing and flocculating compounds such as organic matter and iron oxides were not removed (IUSS Working Group WRB, 2015). In the WDC experiment, deionised water was used as a dispersing agent instead of Calgon. Deionised water was added to the soil and mixed with an electric mixer for 5 minutes. The sand fractions were separated through sieving and the fine silt and clay fractions were determine using the pipette method. The coarse silt was obtained from the percentage difference between 100% and sum of sand, fine silt and clay (USDA, 1996). The WDC of the soils was expressed as both the percentage of soil mass (Eq. 4.1) and total clay mass (Eq. 4.2). The water dispersible clay (WDC) and Calgon dispersible clay (CDC) (**section 4.2.2.1**) were used to calculate the percentage WDC of the soil total.

$$\%WDC\ of\ the\ soil\ mass = \frac{Mass\ of\ pipetted\ clay\ (g) \times 100}{Total\ soil\ mass\ (g)} \qquad \text{Eq. 4.1}$$

$$\%WDC\ of\ the\ soil\ clay\ mass = \frac{\%WDC\ of\ the\ soil\ mass \times 100}{Calgon\ dispersed\ clay\ or\ total\ clay\ content (\%)} \qquad \text{Eq. 4.2}$$

4.2.3.3 Soil colour

The soil colours were determined using the Munsell Soil Color Chart (Color, 1994).

4.2.4 Chemical soil properties

4.2.4.1 Soil pH and Electrical Conductivity (EC)

The soil pH was measured in both deionised water and 1 M KCl using 1:2.5 soil to water ratio as described by The Non-affiliated Soil Analysis Work Committee (1990). The soil electrical conductivity (EC) was measured in deionised water at 1:2.5 soil to deionised water ratio (AgriLASA, 2004). The pH and electrical conductivity (EC) measurements were taken with a Metrohm Swiss made 8.27 pH meter and Jenway 4510 conductivity meter.

4.2.4.2 Total Carbon and Nitrogen and organic carbon

The total C and N content of each sample was determined through the dry combustion method as conferred by Nelson and Sommers (1982) using a vario MACRO cube elementar analyser. Walkley-Black organic C was determined by the Elsenburg Plant Laboratory using a standard method described in The Non-affiliated Soil Analysis Work Committee (1990).

4.2.4.3 Exchangeable cations (Ca, Mg, Na and K) and exchangeable acidity

The exchangeable cations and exchangeable acidity were determined as outlined by Thomas (1982). Exchangeable cations (Ca, Mg, Na and K) were extracted with ammonium acetate

(NH_4OAc, pH = 7.0) using the centrifuge method. The collected supernatants were then sent for cation analysis and were determined using VARIAN AA240FS Fast Sequential Atomic Absorption Spectrometer (AAS). The exchangeable acidity of the soil samples was determined using the 1 M KCl extraction method. Effective cation exchange capacity (ECEC), exchangeable sodium percentage (ESP) and base saturation were calculated from the exchangeable cations and acidity.

4.2.5 Statistical analysis

A one-way ANOVA was used to test for significant differences between the soil properties and a Fisher's Least Significant Difference test was used for means separation at 95% confidence level. All the statistical analyses were executed using Statistical (version 13.5.0.17).

4.3 RESULTS AND DISCUSSION

Soil physical and chemical properties for 20 soil samples allocated into five soil groups are presented in Tables 4.1 and 4.2 below.

4.3.1 Citrate-buffered dithionite iron (CBD Fe)

The Fe content of all the soil groups varied from 0.39 to 2.32 % (**Figure 4.2**). The chromic soil group had significantly the highest Fe content (>2%) hence the strong yellow to red soil colours, followed by the shale and granite soils, with the aeolian sand having the least but not significantly different from that of alluvium soils. The CBD Fe significantly correlated with clay content ($r = 0.76$, $p<0.05$).

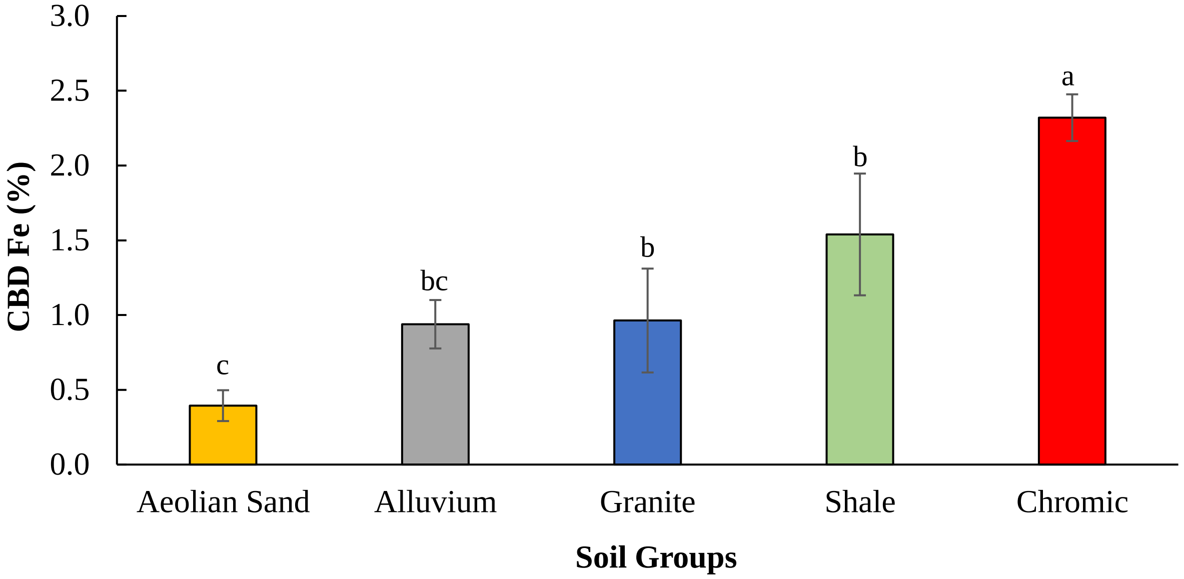


Figure 4.2: The average citrate-buffered dithionite iron (CBD Fe) content of different soil groups. Statistically significant differences are indicated by the letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$ with error bars representing the standard error (SE) within the soil groups.

4.3.2 Clay mineralogy

The type of mineral present in the soil can influence many soil aspects such as soil pH through cation and anion exchange capacity (CEC and AEC) and clay dispersion (Chorom *et al.*, 1994). Soils can be composed of more than just one clay mineral and thus, have mixed clay mineralogy. Figures 4.3 - 4.5 show clay mineralogy of seven selected soils from three of the more clay-rich soil groups, namely; granite, shale and chromic. These soils were chosen because they showed contrasting behaviours in terms of dispersivity. The clay mineralogy of the two granite-derived soils (SP1 and KB2) were dominated by 1:1 clays. SP1 consisted of mainly kaolinite (7.2, 4.45, 4.18, 3.56, 2.57, 2.34, 1.99, 1.67 and 1.49 Å) with possible traces of chlorite (14-15 Å), and goethite (4.18, 3.35 and 2.19 Å), while KB2 consisted mainly of kaolinite and halloysite (7.5 Å), with traces of gibbsite (4.85 and 2.34 Å) and goethite (**Figure 4.3**). Similar to the granite-derived soils, the clay mineralogy of the shale-derived soils, BW1 and DV1, also consisted mainly of kaolinite, with traces of goethite, gibbsite and chlorite (**Figure 4.4**). The clay fraction of the chromic soils (CT1, BD2 and PV1) also consisted predominantly of kaolinite, with some goethite and possibly hematite traces. Only CT1 contained considerable amounts of gibbsite (**Figure 4.5**).

The clay mineralogy results revealed an abundance of kaolinite clay in all the analysed soils (**Figures 4.3- 4.5**). However, it is important to note that even though kaolinite is dominating in all the soils, the presence of other clay minerals play a crucial role and can influence the behaviour of the soils. Kaolinite clays are basically 1:1 non-expanding clay characterised by low cation exchange capacity due to their low surface area (Brady and Weil, 2017). Another 1:1 clay mineral that was detected was halloysite which was observed only in the granite-derived soils. Halloysite is very similar to the kaolinites, however, it contains a layer of water (H_2O) molecules between the tetrahedral and octahedral layers (Sparks, 2003). Unlike the kaolinite clays, the stability of halloysite is easily influenced by water (Tan, 2010). Furthermore, soils containing Fe and Al oxide (goethite, hematite and gibbsite) clay minerals, are highly weathered and normally have low CEC due to their positive surface charges which make them more stable. Traces of non-expanding 2:1 layer silicate chlorite were only present in two soils, SP1 (granite group) and BW1 (shale group). The surface charge of the low reactivity clay minerals (e.g. kaolinite, halloysite, gibbsite, goethite and hematite) vary with soil pH.

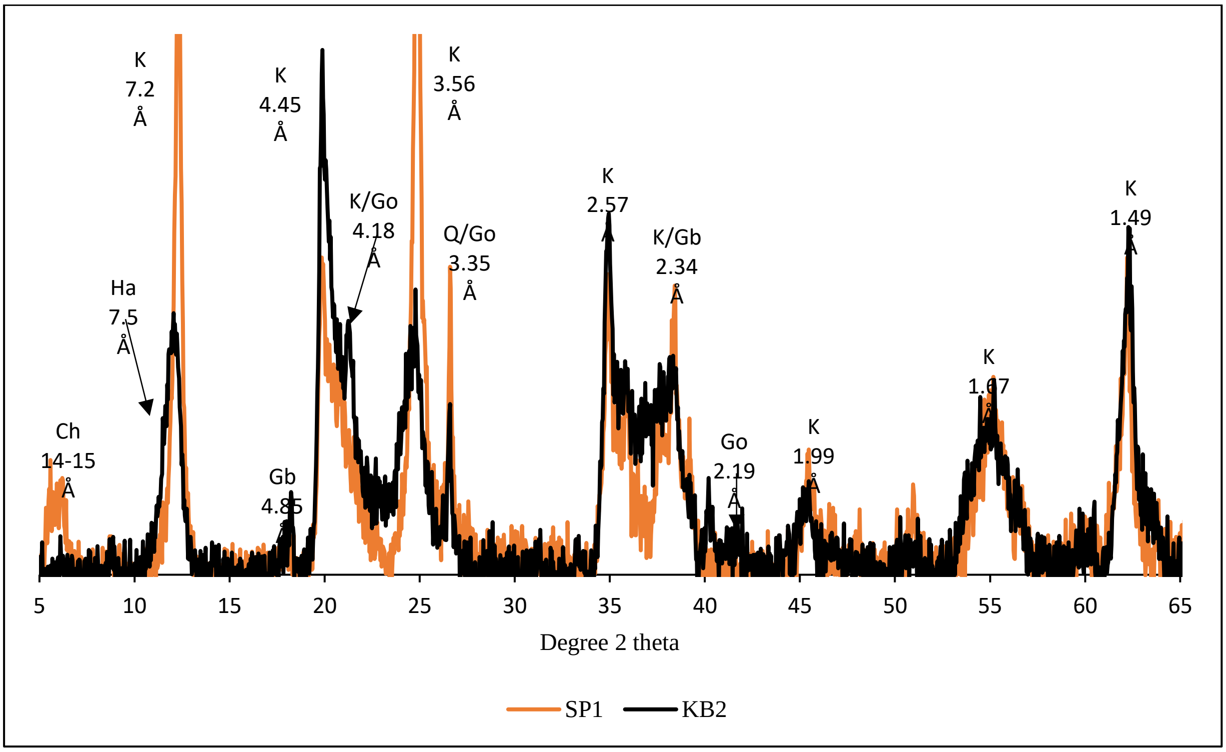


Figure 4.3: XRD spectra of SP1 and KB2 soil samples from the granite soil group (Ch = chlorite, Ha = halloysite, K = kaolinite, Gb = gibbsite, Go = goethite, Q = quartz).

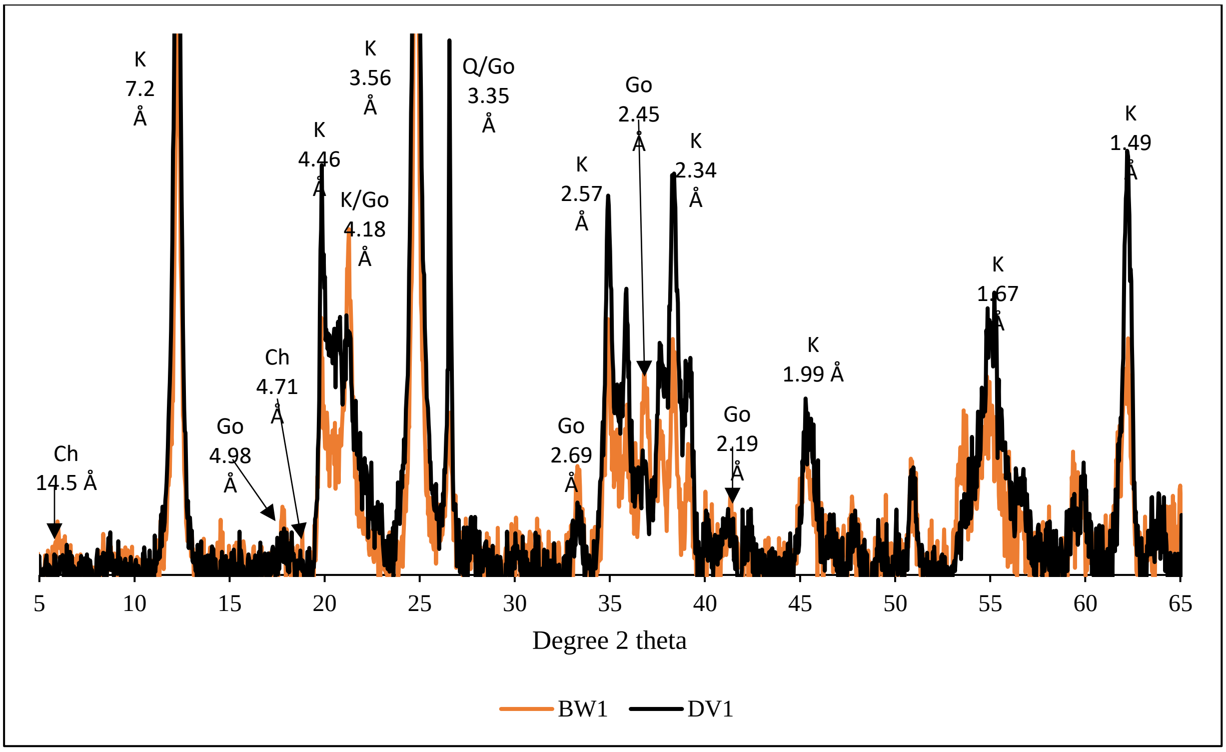


Figure 4.4: XRD spectra of BW1 and DV1 soil samples from the shale soil group (Ch = chlorite, K = kaolinite, Gb = gibbsite, Go = goethite, Q = quartz).

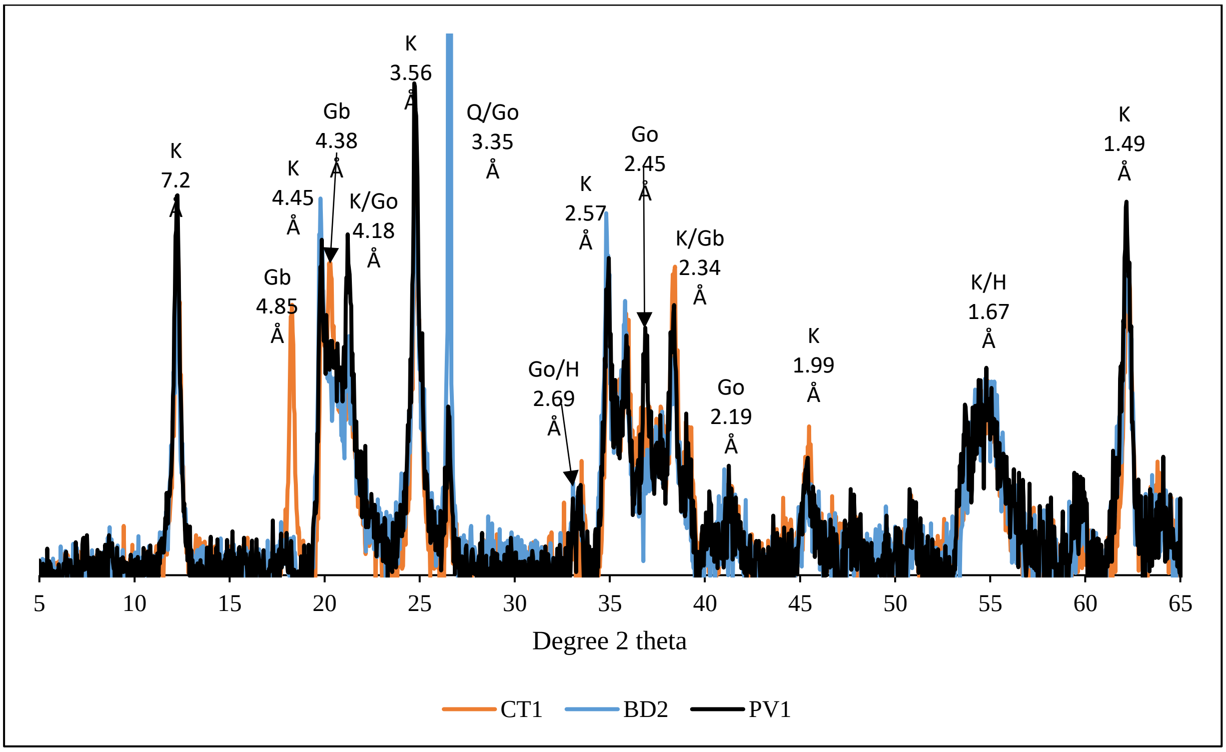


Figure 4.5: XRD spectra of CT1, BD2 and PV1 soil samples from the chromic soil group (K = kaolinite, Gb = gibbsite, Go = goethite, Q = quartz, H = hematite).

4.3.3 Soil texture and colours

Results for the soil texture and colour are presented in **Table 4.1** below. Soils allocated to the Aeolian sands group belonged to the sand textural class and had dark grey to greyish brown soil colours. The alluvium and granite derived soils had loamy sand to sandy loam soil textures. The alluvium soils displayed dark grey, dark greyish brown, greyish brown and brown soil colours while the granites had grey, dark greyish, brown and pale brown soil colours. These soil groups showed bleached soil colours (greyish) and had low CBD Fe content (see **Figure 4.2)**. A pink soil colour was observed on one of the shale soils (DV1) while the other soils in this group had brown to pale brown colour hence on average the CBD Fe of these was higher than the sands, alluvium and granites soils group. The shales soil had variable texture ranging from sandy loam, sandy clay loam to loam soils. Additionally, the last soil group i.e. chromic had light yellowish brown, reddish brown, strong brown and yellow red colours due to high CBD Fe **(Figure 4.2)**.

4.3.4 Clay and water dispersible clay contents

The average clay content of the soil groups varied from 5.33 - 22.68 % **(Figure 4.6).** The chromic and shale soil groups had significantly the highest clay content followed by granite soils, with the aeolian sands having the lowest clay but not significantly different from alluvium (**Figure 4.6**). The % water dispersible clay of soil mass ranged from 3-13 % **(Figure 4.7).** The %WDC of the soil mass of the chromic and shale was also high but in this case not significantly different from that of granite derived soils (**Figure 4.7**). However, it is important to note that when relating the %WDC of soil clay mass, on average the granite soil group had the highest percentage even though it was not significantly different from that of chromic, shale and alluvium soil groups (**Figure 4.8**). This means that much of the clay in granite-derived soils can be easily dispersed by just water because they are bleached and have low CBD Fe. The iron (Fe) oxides help stabilize the clay. Thus, these soils are more vulnerable to structural destabilization.

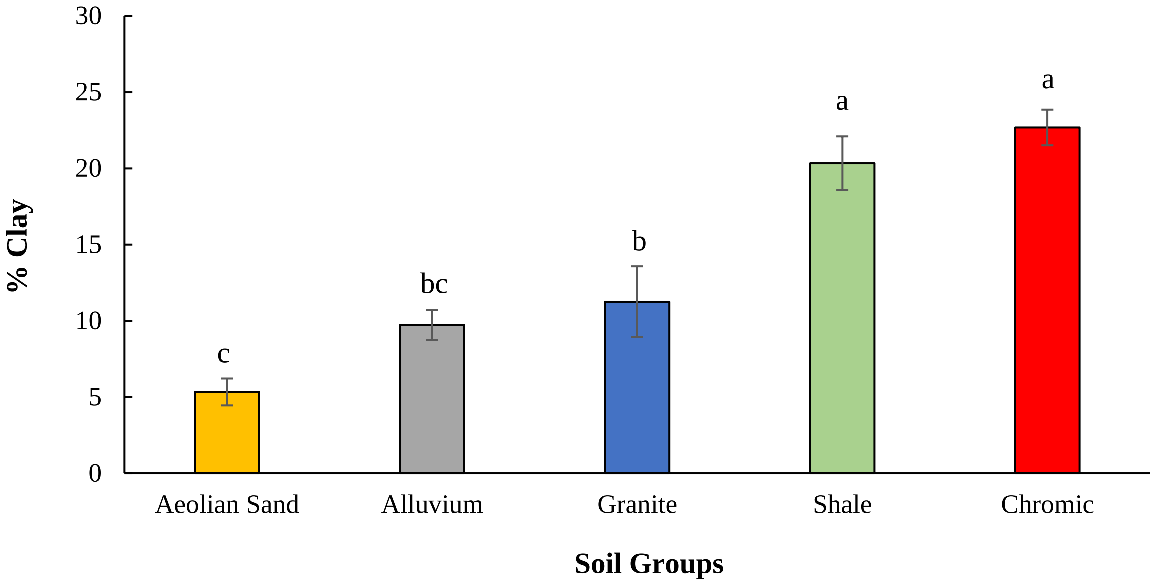


Figure 4.6: The average clay percentage of the soil groups with statistical significant differences indicated by the letters of significance tested using Fisher’s Least Significant Difference test at p< 0.05. The error bars indicate the standard error (SE) within the soil groups.

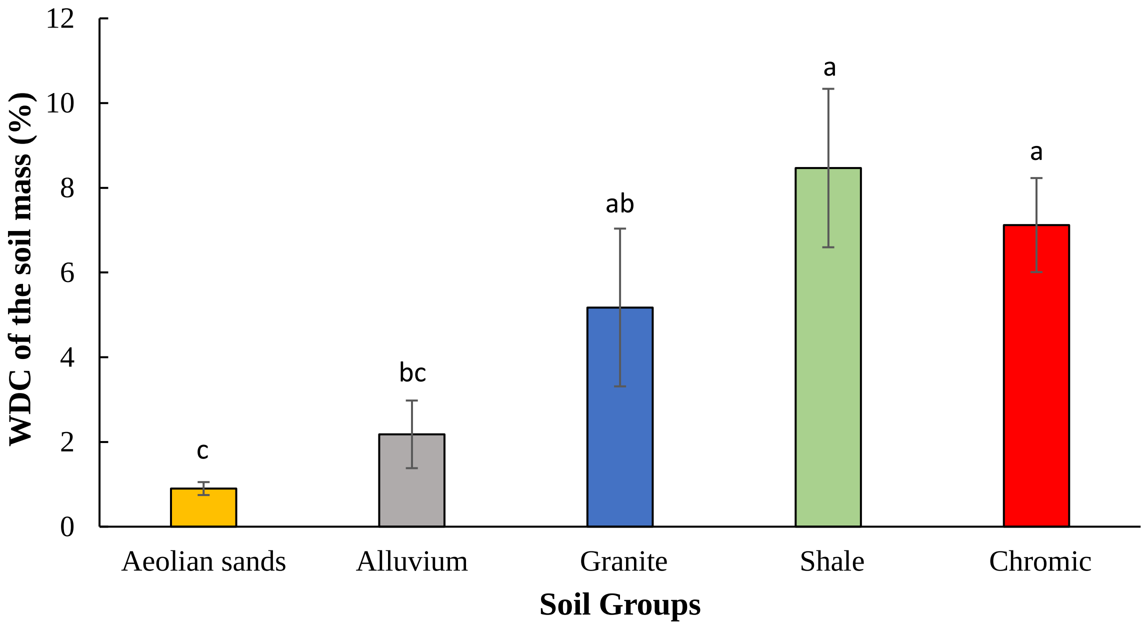


Figure 4.7: The average water dispersible clay percent of the soil groups with the statistical significant differences indicated by the letters of significance tested using Fisher’s Least Significant Difference test at p< 0.05. The standard error (SE) is indicated by the error bars.

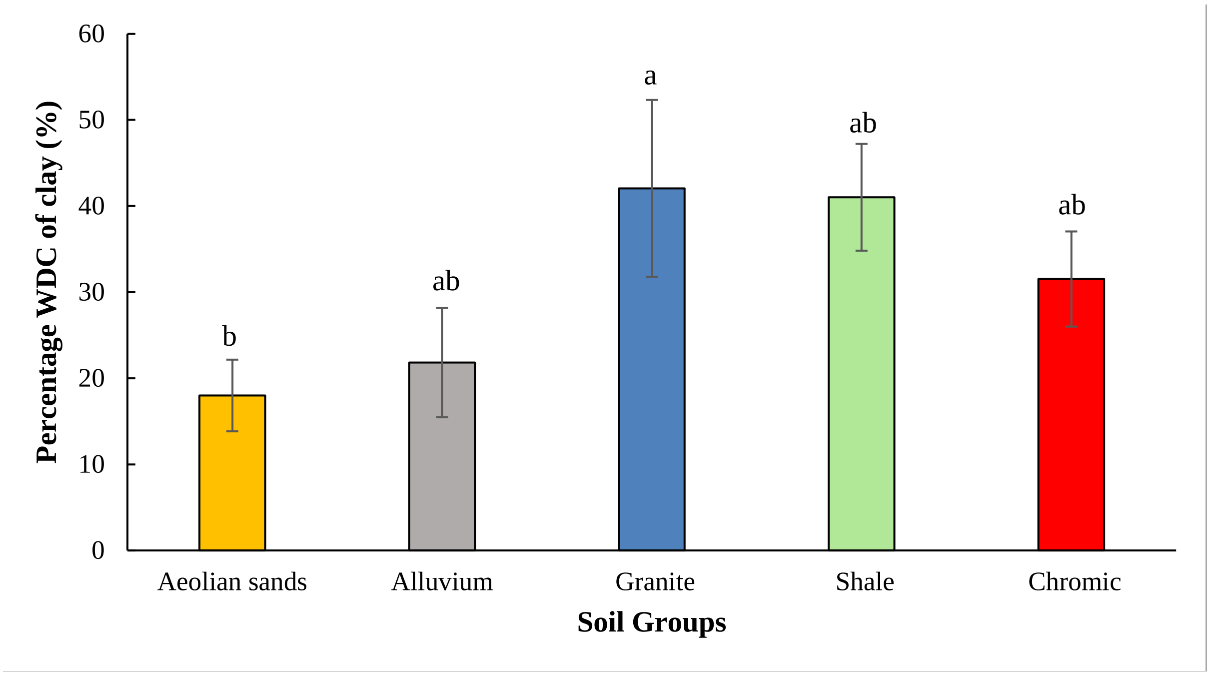


Figure 4.8: The average WDC percentage of the soil total clay of different sloil groups. Statistically significant differences are indicated by the letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$ with error bars representing the standard error (SE) within the soil groups.

4.3.5 Soil pH, exchangeable sodium percentage (ESP) and base saturation

The pH (H_2O) of the soil samples within and between the soil groups varied considerable from acidic to alkaline (see **Table 4.2**). The average pH of the aeolian sand, granite, shale and chromic soil groups were relatively alkaline (greater than 7) and significantly higher than the alluvium soils which had a slightly acid pH (**Figure 4.9**). It is important to note that soils with alkaline pH are 'unexpected' in the Western Cape since the Western Cape Region is under the fynbos biome and soils under this type of vegetation normally have an acidic pH. High soil pH values observed in this study might have resulted from cement contamination in the urban soils. Likewise, the base saturation of all the soils were relatively high, ranging from 97.45 to 99.99%.

The exchangeable sodium percentages (ESP) of the soil groups varied from 0.8 to 7.0% (**Table 4.2**), indicating that none of the soils were sodic (ESP < 15%).

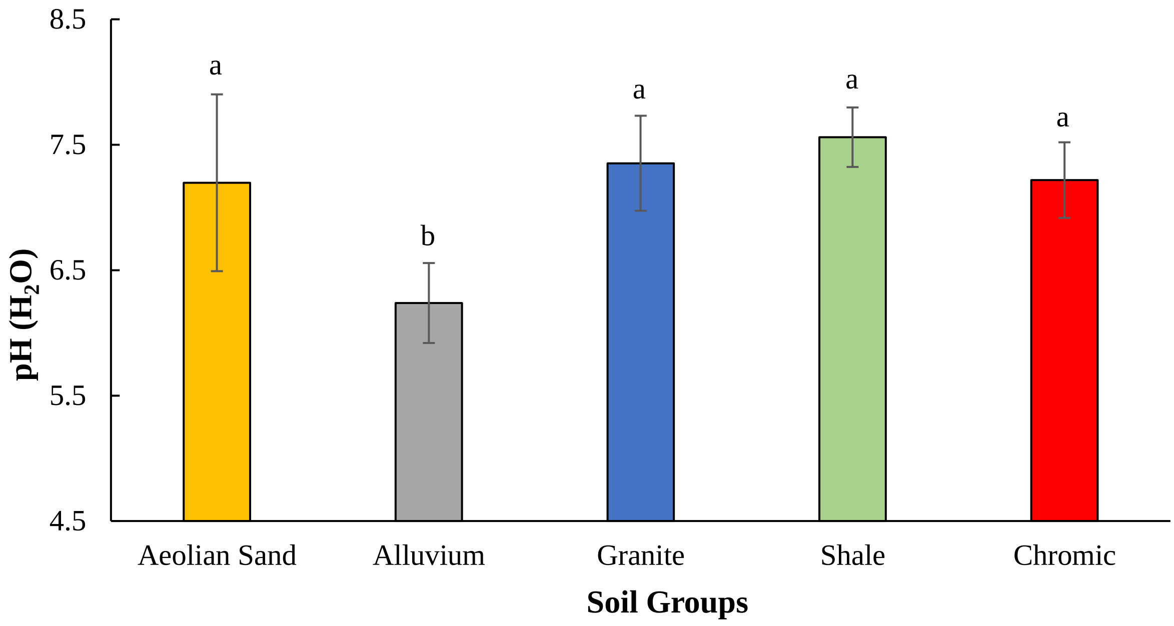


Figure 4.9: The average pH of five soil groups (aeolian sand, alluvium, granite, shale and chromic) with statistical significant differences indicated by the letters of significance tested using Fisher's Least Significant Difference test at $p< 0.05$. The error bars indicate the standard (SE) within the soil groups.

4.3.6 Total carbon

The total C content of the soil groups ranged from 1.69 to 3.85 % and there were no significant differences between the soil groups (**Figure 4.10**). However, it should be noted that on average the more clay soils (shale and chromic soils) had higher total C compared to sandy soils.

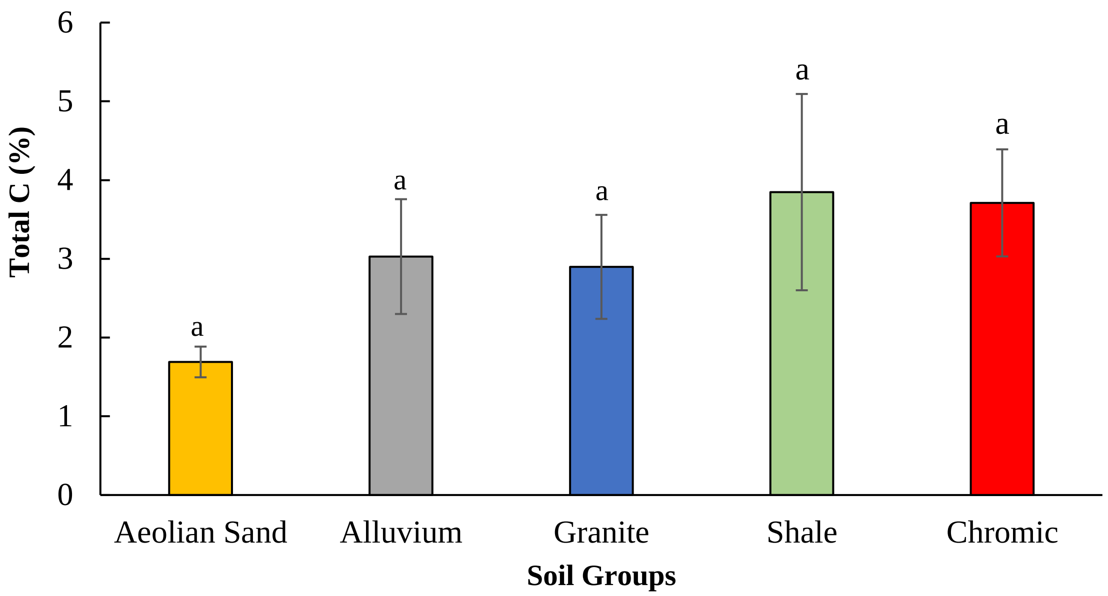


Figure 4.10: The total carbon content of different soil groups. Statistically significant differences are indicated by the letters of significance tested using Fisher's Least Significant Difference test at $p< 0.05$. The error bars indicate the standard error (SE).

Table 4.1: Soil samples, sampling locations, soil groups and soil physical properties.

Soil Samples	Location	Soil Groups	Sand	Silt	Clay (%)	Texture	WDC (%)	%WDC of soil clay	Munsell Soil Colour
OG1	Bellville, CPT	Aeolian Sand	91	5	4	Pure sand	0.8	20.0	10YR 5/2
GP1	Grassy Park, CPT	Aeolian Sand	90	5	5	Sand	1.2	24.0	10YR 5/2
KW1	Kenilworth, CPT	Aeolian Sand	87	6	7	Sand	0.7	10.0	10YR 4/1
SU1	University, STB	Alluvium	78	14	8	Loamy sand	1.6	20.0	10YR 4/1
SU2	University, STB	Alluvium	74	17	9	Sandy loam	2.9	33.7	10YR 5/3
RD1	Rozendal, STB	Alluvium	70	22	8	Sandy loam	1.2	15.0	10YR 5/3
KV1	Kriegeville, STB	Alluvium	71	18	11	Sandy loam	0.3	2.7	10YR 4/2
DD1	Dreyersdal, CPT	Alluvium	73	14	13	Sandy loam	4.9	37.7	10YR 5/2
KB1	Kirstenbosch, CPT	Granite	77	15	8	Loamy sand	1.2	15.0	10YR 5/3
KB2	Kirstenbosch, CPT	Granite	76	11	13	Sandy loam	8.3	63.8	10YR 6/3
SP1	Spier, STB	Granite	66	17	17	Sandy loam	8.4	49.4	5YR 5/1
SP2	Spier, STB	Granite	74	19	7	Loamy sand	2.8	40.0	10YR 4/2
WG1	Welgevonden, STB	Shale	59	24	17	Sandy loam	6.4	37.6	10YR 6/3
BW1	Brandwag, STB	Shale	55	24	21	Sandy clay loam	6.8	32.4	10YR 5/3
DV1	Durbanville, CPT	Shale	47	30	23	Loam	12.2	53.0	7.5YR 7/4
CT1	Constantia, CPT	Chromic	58	22	20	Sandy clay loam	10.3	51.5	10YR 6/4
PV1	Protea Valley, CPT	Chromic	54	25	21	Sandy clay loam	5.3	25.6	5YR 4/4
BD1	Bo-Dalsig, STB	Chromic	56	21	23	Sandy clay loam	6.1	26.5	5YR 5/4
BD2	Bo-Dalsig, STB	Chromic	42	31	27	Clay loam	9.2	34.5	5YR 4/6
HH1	Helshoogte, STB	Chromic	53	23	23	Sandy clay loam	4.7	19.6	7.5YR 5/6

Table 4.2: Soil sample names, sampling locations, soil groups and soil chemical properties.

Soil Samples	Location	Parent Material	Soil pH (H_2O)	EC mS m^{-1}	Total C	Ca	Mg	Na	K	ECEC	Exc. Acidity	CBD Fe	ESP %	Base saturation %
						(cmolc kg^{-1})								
OG1	Bellville, CPT	Aeolian Sand	7.98	183.1	1.89	18.49	0.67	0.82	0.45	20.43	0.00	0.4	4.0	99.99
GP1	Grassy Park, CPT	Aeolian Sand	7.82	27.3	1.30	12.79	0.55	0.27	0.14	13.78	0.03	0.2	2.0	99.76
KW1	Kenilworth, CPT	Aeolian Sand	5.79	20.7	1.88	7.05	0.77	0.24	0.26	8.51	0.18	0.6	2.8	97.86
SU1	University, STB	Alluvial	6.14	13.5	2.39	10.22	1.31	0.23	0.29	12.07	0.02	1.1	1.9	99.81
SU2	University, STB	Alluvial	6.41	6.7	0.99	4.17	0.56	0.12	0.31	5.21	0.05	1.5	2.4	99.04
RD1	Rozendal, STB	Alluvial	5.32	52.6	2.42	9.06	0.57	0.45	0.30	10.66	0.27	0.6	4.2	97.45
KV1	Kriegeville, STB	Alluvial	7.29	105.7	5.06	24.42	1.82	0.21	0.67	27.22	0.10	0.9	0.8	99.63
DD1	Dreyersdal, CPT	Alluvial	6.03	71.8	4.28	13.63	1.73	0.59	0.65	16.79	0.18	0.7	3.5	98.92
KB1	Kirstenbosch, CPT	Granite	7.45	18.0	4.40	16.44	1.31	0.20	0.31	18.45	0.19	2.0	1.1	98.96
KB2	Kirstenbosch, CPT	Granite	6.27	13.8	1.23	10.92	0.63	0.24	0.18	12.03	0.05	0.9	2.0	99.56
SP1	Spier, STB	Granite	8.01	23.4	2.68	14.11	2.20	0.45	0.75	17.52	0.01	0.6	2.6	99.93
SP2	Spier, STB	Granite	7.68	35.4	3.28	18.41	1.99	0.35	1.09	21.92	0.08	0.4	1.6	99.62
WG1	Welgevonden, STB	Shale	7.74	85.0	2.88	19.56	1.65	0.34	0.93	22.54	0.06	1.4	1.5	99.72
BW1	Brandwag, STB	Shale	7.85	156.5	6.32	24.76	2.81	0.36	1.49	29.49	0.07	2.3	1.2	99.75
DV1	Durbanville, CPT	Shale	7.09	92.6	2.34	11.84	1.36	1.01	0.25	14.53	0.08	0.9	7.0	99.43
CT1	Constantia, CPT	Chromic	6.17	28.6	2.84	8.94	1.57	0.43	0.57	11.60	0.09	2.8	3.7	99.20
PV1	Protea Valley, CPT	Chromic	7.11	61.1	4.40	19.96	2.26	0.26	0.99	23.58	0.12	2.2	2.7	99.11
BD1	Bo-Dalsig, STB	Chromic	7.26	15.8	1.70	14.94	0.40	0.19	0.64	16.24	0.07	1.9	1.1	99.48
BD2	Bo-Dalsig, STB	Chromic	7.98	28.7	3.94	20.47	1.18	0.19	0.33	22.23	0.06	2.3	1.2	99.57
HH1	Helshoogte, STB	Chromic	7.57	82.4	5.68	20.20	3.00	0.66	0.94	25.03	0.22	2.5	0.9	99.72

4.4 CONCLUSION

The sampled soil groups from the Cape Town and Stellenbosch urban region varied mainly in terms of texture and CBD Fe content. The shale and the chromic soils had a significantly higher clay content compared to the other soil groups, while the chromic soil had significantly higher CBD Fe (> 2%) compared to the other groups. The clay mineralogy of the soils consisted of low activity clay minerals, predominantly kaolinite or halloysite, with traces of goethite, gibbsite and chlorite. The shale soils had the highest percentage of water dispersible clay (as a percentage of the total soil mass), while the granite soils had the highest percentage water dispersible clay (as a percentage of the total clay content). The soils generally had an alkaline pH, with high base saturation and low exchangeable Na content.

CHAPTER FIVE

SUSCEPTIBILITY OF URBAN SOILS FROM THE CAPE TOWN AND STELLENBOSCH AREAS TO DEGRADATION BY GREYWATER

5.1 INTRODUCTION

Greywater reuse for irrigation can conserve the use of clean water but soil application of greywater is known to have both positive and harmful effects on soil properties (Siggins *et al.*, 2016). Ayers and Westcot, (2007) claim that the problems caused by irrigation water vary in terms of degree or intensity depending on soil type, climate and crop. Greywater contains many chemicals which can be beneficial to the soil or plant, yet have detrimental effects when found in toxic quantities. These chemicals originate from the use of household chemical detergents such as soaps, shampoos, body wash, hair conditioner, dishwasher salts, dish liquid soaps, liquid and powdered laundry detergents (Eriksson *et al.*, 2002). Therefore, when greywater is used for irrigation, the chemicals contained in this water tend to interact with both the soil and soil solution (Misra and Sivongxay, 2009) leading to alteration of some soil properties such as water infiltration, soil pH and EC, organic matter and essential nutrients (Sawadogo *et al.*, 2014; Siggins *et al.*, 2016; Maimon *et al.*, 2017).

Water movement in soils is one of the factors influenced by many soil and water characteristics. These properties include clay content which is known to influence water percolation, and this is also the part of the soil where most of the soil chemistry takes place such as adsorption of nutrients (Sparks, 2003). Clay also plays an important role in holding the soil particles together thus stabilizing soil structure (Amézketa, 1999). The stability of soil aggregates is known to influence plant growth through aeration, water percolation and retention (Stevenson, 1994). Based on the quality of the water solution, clay can either flocculate or disperse. Therefore, the flocculation and dispersion of soil clay affects water penetration in soils. Soil or water sodicity and pH are the main influencers of clay dispersion. Clay mineralogy also plays a major role in soil dispersion as discussed in the previous chapter (section 4.3.1).

The saturated hydraulic conductivity (K_{sat}) is an essential parameter for understanding soil hydrology or water movement and closely related to soil infiltration rate and soil permeability. Soil texture is known as the main influencer of the K_{sat} of the soil with low K_{sat} in clay soil (Blanco-Canqui *et al.*, 2010). However, in addition to soil texture, a study carried out by Suarez *et al.* (1984) using solutions of the same sodium adsorption ratio (SAR) showed that an increase in the solution pH can decrease the saturated hydraulic conductivity of soils due to clay dispersion.

Humus which refers to the stable form of organic material, is one of the important soil quality parameters (Stevenson, 1994). Similar to clays, soil organic matter plays a vital in stabilizing soil structure, improving soil water holding capacity and aeration and enhancing nutrient availability (Sparks, 2003). It is important to note that many soil-greywater irrigation studies have focused more on greywater impact on soil organic matter content (Siggins *et al*., 2016), however to my knowledge no work has been done on how greywater irrigation influences dissolved organic carbon (DOC) losses from the soils. Therefore, more information on soil organic carbon leaching is required.

This research unit focusses on screening the vulnerability of a wide variety of typical Cape Town and Stellenbosch urban area soils in terms of susceptibility to degradation by four selected greywater streams. These greywater streams were selected in Chapter 3 and include greywater generated from the shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW). Due to varying laundry greywater's composition (as discussed in Chapter 3), comparative degradability of the soil groups was assessed using a harmful (PLD) and less harmful (LLD) greywater while the vulnerability of soils using all four greywater streams was also evaluated. A soil column infiltration experiment was used to examine the effect of the greywaters on soil permeability, DOC and clay removal. Soil leachates were screened to establish the salt and contamination attenuation of the soils. Leachate quality is important. Some studies have examined leachate pH and EC.

5.2 OBJECTIVES

a) To determine the susceptibility of the five major urban soil groups to degradation (hydraulic conductivity reduction and dissolved organic carbon removal) by liquid and powdered laundry detergents.
b) To compare the effect of shower (SH) and dishwasher (DW) greywater to the laundry detergent greywaters on hydraulic conductivity and dissolved organic carbon (DOC) removal of selected soil samples.

5.3 MATERIALS AND METHODS

Soils collected from five major soil groups in Chapter 4 (**Section 4.2.1**) were used in this study and were characterised for the physical (particle size analysis, water dispersible clay) and chemical properties (citrate-buffered dithionite Fe and total carbon) as described in the previous chapter. All 20 soil samples were used for determining the susceptibility of the urban soils to physical degradation by laundry greywaters, so that relative degradability of the soil groups could be assessed using a harmful (PLD) and less harmful (LLD) greywater. However, for comparing the effect of SH and DW greywaters to the laundry detergent greywaters, a smaller number of soil samples were used, comprising of 2-3 soil samples from each soil group (11 samples in total).

5.3.1 Soil column infiltration study

Assessment of the possible effects of irrigating with greywater produced from the shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) on soil permeability, DOC and clay removal compared to irrigating with clean municipal water (TW), was determined in a laboratory soil column infiltration study.

Soil leaching column tubes with a height of 11 cm and an inside diameter of 3.5 cm were constructed from white 40 mm Ø Polyvinyl Chloride (PVC) plumbing waste pipe (**Figure 5.1**). A black PVC stopper was glued at the bottom of the column tube and five holes were drilled in the stopper to allow the passage of water as shown in Figure 5.1 below.

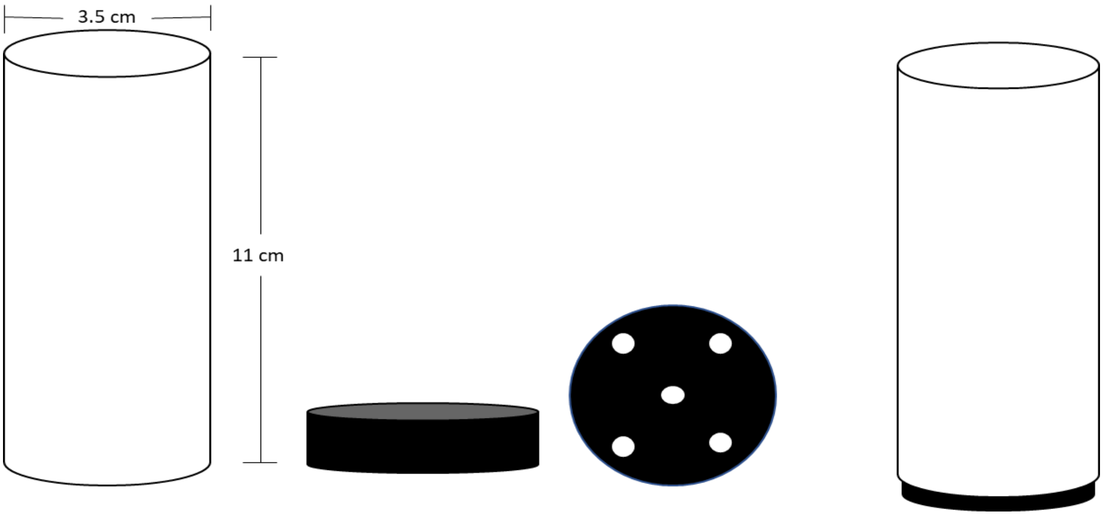


Figure 5.1: The construction of leaching soil column tubes

After the construction of the leaching soil column tube, the collected soil samples were packed in the leaching column tubes as illustrated in Figure 5.2 below. However, before packing these soils, a medium-fine sand was glued at the inner side of the column tube walls to prevent preferential flow (Gibert *et al.*, 2014). Gravel [washed with Calgon dispersing solution (prepared from sodium hexametaphosphate and sodium carbonate) and water to remove clay] with diameters between 2 and 4 mm was placed in the stopper at the bottom of the leaching soil column tubes to allow free drainage. A glass wool (mass = 0.11 g) was placed on top of the gravel before adding the soil to prevent soil particles from passing through. Thereafter, dry soil samples were packed in the leaching soil columns to a volume of 67.35 cm^3 by mechanical shaking, up to a height of 7 cm. The mass of each soil in the leaching column tubes was recorded. A Scotch-Brite^{TM} scour pad disk was placed on top of the soil to prevent soil compaction and/or soil dispersion due to the initial impact of water drops during water application. It should be noted that marks inside the leaching column tubes were made at 7 and 8 cm heights from the inside top of the stopper, i.e. at 7 cm for the soil packing and at 8 cm for 1 cm water application pressure.

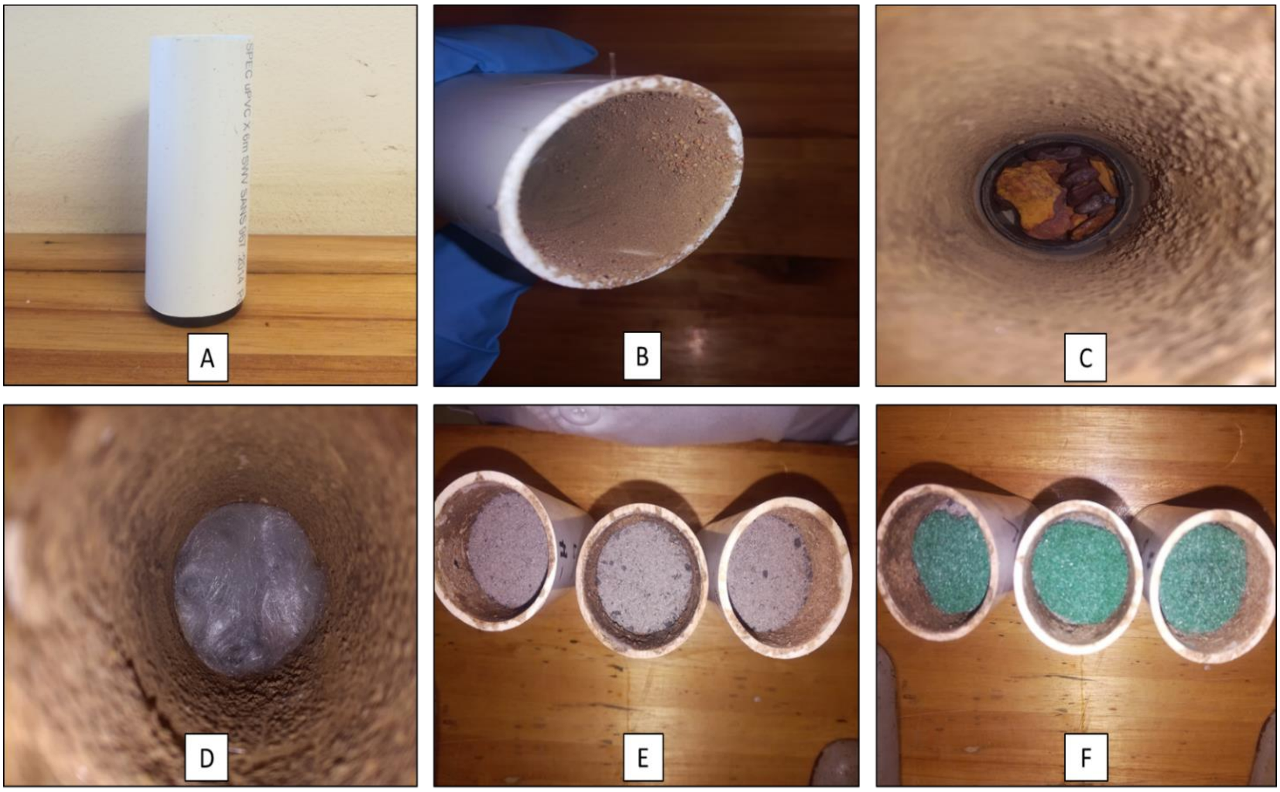


Figure 5.2: (A) a constructed soil column tube, (B) sand lining inside the column tube wall, (C) gravel placement at the bottom of the soil column tube, (D) glass wool placed above the gravel, (E) soil packed inside the column tube and (F) a Scotch-Brite^{TM} scour pad disk place on top of the packed soil.

5.3.1.1 Infiltration experiment

An infiltration experiment was conducted to examine the impact of 200 mm greywater [synthetic shower (SH), liquid laundry detergent (LLD) and powdered laundry detergent (PLD), and dishwasher (DW)] application on soil permeability, DOC and clay removal compared to 200 mm tap water (TW) application. The soil infiltration experiment was set up as shown in

Figure 5.3. In this experiment, the soils packed in leaching columns (see **Section 5.3.1.2)** and 100 ml burette were clamped on a retort stand (**Figure 5.3**), 200 mm of tap water and the greywater samples were added to the burettes. Soil permeability was assessed through measuring the soil saturated hydraulic conductivity (K_{sat}). The saturated hydraulic conductivity (K_{sat}) of the soils was measured using Darcy's law by applying the water treatments (tap water and greywater samples) at a constant head or pressure of 1 cm. The amount of water leached out at specific time intervals was quantified. Then afterwards, the following equation was used to calculate the K_{sat} of the soil:

$$Ksat = \frac{\Delta V \times L}{\Delta t \times Ah} \qquad \text{Eq. 5.1}$$

Where;

K_{sat} = saturated hydraulic conductivity, ΔV= the volume of water measured in a time, L= over a specimen of length (= 7 cm), A= cross-sectional area (= πr^2) and h = head pressure (= 1 cm)

For all the soil samples there were three replicates for each soil per tap water and greywater applied. The soil leachates were collected using a glass beaker of known mass and some of the physical and chemical properties of these leachates were measured.

Note: One millimetre (mm) of water is equivalent to one litre of water per square meter (L m^{-2}), therefore this was used to convert 200 mm to millilitres (192 ml) of water that should be added to the area of soil in the leaching column tubes (in this case to an area of 0.00096 m^2).

Surface area

$$A = \pi r^2 \qquad \text{Eq. 5.2}$$

$$A = \pi(1.75\ cm)^2$$

$$A = 9.6\ cm^2$$

$$A = 0.00096\ m^2$$

Converting 200 millimetres of water to millilitres

1 mm of water = 1 L m^{-2} of water

$$200\ mm\ of\ water\ =\ 200\ L\ m^{-2} \times 0.00096\ m^2$$

$$ml\ of\ water\ = 0.192\ L\ \times \frac{1000\ ml}{1\ L}$$

$$Therefore, ml\ of\ water\ applied = 192\ ml$$

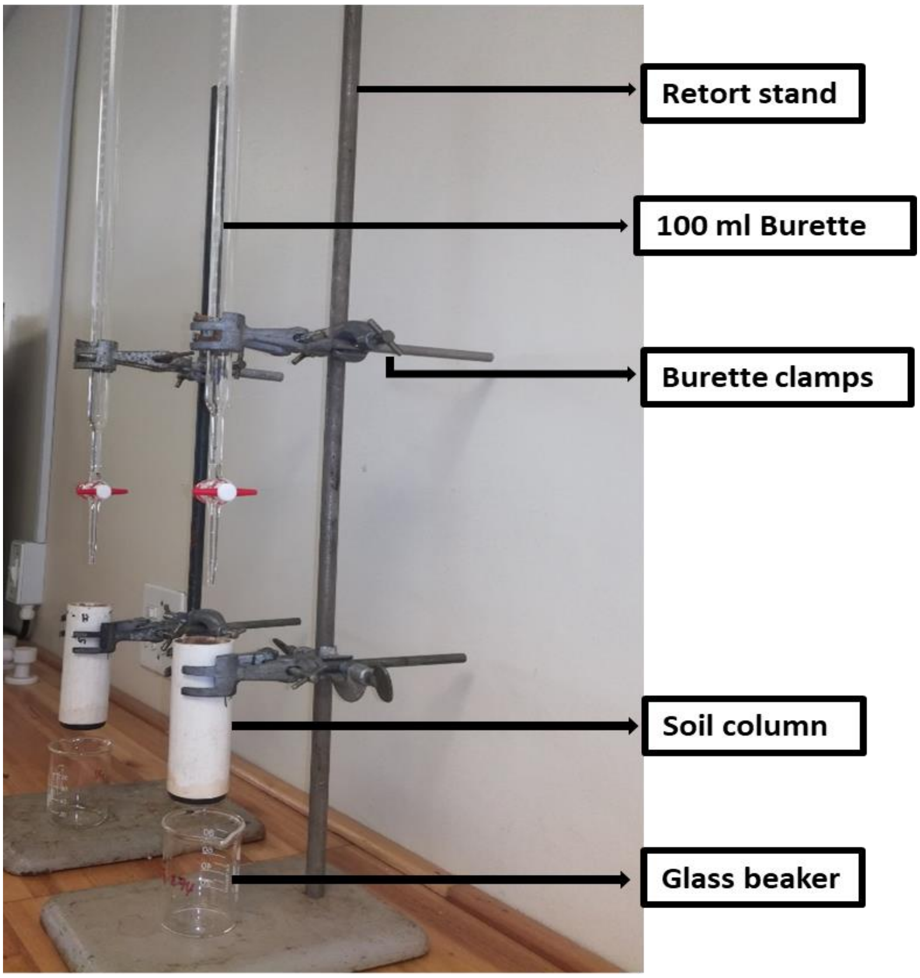


Figure 5.3: The infiltration experiment set up.

5.3.2 Soil leachate analysis

The total volume of leachates from each soil was recorded and the time taken for 200 mm of the water treatments (i.e., either tap water or the greywaters) to pass through the soil column was recorded. The following leachate quality parameters were measured:

5.3.2.1 pH and EC

The pH and electrical conductivity (EC) of the tap water, shower, LLD, PLD and DW greywater and leachates from soils irrigated with these water treatments were measured using Metrohm Swiss made 8.27 pH lab and Jenway 4510 conductivity meter, respectively.

5.3.2.2 Absorbance

Leachate absorbance was measured as an approximation of the dissolved organic carbon (DOC) amount removed from soils as a result of applying different water treatments with varying composition. The absorbance of the leachates was first measured between 200 to 900 nm wavelength range using the Jenway 7315 spectrophotometer. However, since fulvic acids, which are the most soluble form of organic material, have been proven to be highly absorbed at 350 nm wavelength (Gan *et al.*, 2007) and De Wuilloud *et al.* (2003) also used the same wavelength (350 nm) to determine humic and fulvic acids amounts in natural water. This wavelength (350 nm) was then used to measure leachate absorbances to estimate the amount of DOC removed from soil by the application of the greywaters and tap water. The water treatment solutions (tap water and greywaters) were used as blanks *i.e.* tap water (TW) was used for tap water leachates, SH greywater for SH leachates, LLD greywater for LLD leachates, PLD greywater for the PLD leachates and the DW greywater for DW leachates. Additionally, where necessary (such as when the maximum absorbance is greater than 1), the leachates were diluted with their original solution before soil application, either tap water or the greywaters, in order to give precise absorbance estimation.

5.3.2.3 Total C and N

The total C and N content of the tap water (TW), liquid laundry detergent greywater (LLD), powdered laundry detergent (PLD) greywater and soil leachates from these water treatments were measured using the vario MACRO cube elementary analyser.

5.3.2.4 Soil C loss estimation

There was a significant positive linear correlation between the soil leachate absorbance measured at 350 nm and the total C of the all the soil leachates generated from TW, LLD and PLD ($r = 0.74$ at $p < 0.05$). Therefore, a linear correlation equation was used to estimate the total carbon lost in each soil per 200 mm application of tap water and laundry greywaters. The following series of equations were used to estimate the % C leached out from each soil:

Soil leachate percentage carbon

The linear correlation equation was used to estimate % C in the soil leachates;

$$y = 191.27x - 1.1157 \qquad \text{Eq. 5.3}$$

Where; y = soil leachate absorbance at 350 nm and x = percentage carbon in the leachates (%C)

Total carbon in the leachates

The total volume of the soil leachates and the estimated percentage carbon from equation 5.3 was used to calculate the total amount of C removed from each soil using the following equation:

$$Leached\ C\ (ml) = \frac{\%\ leachate\ C}{100} \times Volume\ of\ leachates \qquad \text{Eq. 5.4}$$

Since 1 ml of water is equivalent to 1 g of water at room temperature, the volume of leached C was converted to mass of leached C. Thereafter, the initial total mass of C in the soil samples was calculated using the following equation;

$$Total\ mass\ C\ in\ \ soil\ sample\ \ (g) = Soil\ mass\ in\ columns\ (g) \times \frac{\%\ C\ in\ the\ soil}{100} \qquad \text{Eq. 5.5}$$

Therefore the % total C loss from each soil due to the water application was calculated by dividing the leached C (g) with the total mass of C in the soil sample using the following equation:

$$\%C\ loss\ of\ total\ C = \frac{Leached\ C\ (g)}{Total\ mass\ C\ in\ \ soil\ sample\ \ (g)} \times 100 \qquad \text{Eq.5.6}$$

5.3.2.5 Turbidity

Leachate turbidity was used as a measure of soil fine material (mainly silt, clay and organic matter) removal. The turbidity of the tap water, greywater samples and all the soil leachates were measured using a Thermo Scientific ORION AQUAfast (AQ3010) turbidity meter calibrated using four standard solutions namely; 800 NTU, 100 NTU, 20 NTU and 0.02 NTU.

5.3.2.6 Ash content

The total inorganic solids leached from the soils were estimated by determining the ash content of solid material from the TW, LLD and PLD leachates. This was measured by heating the leachate solid remains at 600 ^{o}C and the dry solid material was weighed before and after combustion.

5.3.3 Statistical analysis

All the statistical analyses were performed using Statistica. The infiltration experimental results were analysed statistically using a two-way ANOVA to test for significant differences among the soil types and treatment groups (greywaters and tap water leachates). A Fisher's Least Significant Difference test was used to test which means are different from each other at 95% confidence level. The correlations between and within the observations and soil properties were determined by Spearman Rank Order Correlation test at $p < 0.05$.

5.4 RESULTS AND DISCUSSION

5.4.1 The effect of laundry greywater application on soil permeability, dissolved organic carbon and clay removal on different soil groups

5.4.1.1 Leachate analysis

5.4.1.1.1 pH and EC

The average pH and EC of the water treatment solutions (TW, LLD and LPD) and leachates from different soil groups are presented in **Table 5.1** below. The pH of the soil leachates generated from TW application was higher than that of TW treatment solution pH, except for the alluvium soil group which was lower. The reason for this is because the pH of these soils (alluvium) were slightly acidic, which means that TW leachate pH was influenced by the soil acidity confirmed by a significant positive correlation between soil pH_{KCl} (**Table 5.2**) and TW leachate pH. The LLD greywater soil leachate pH was slightly lower than the LLD treatment solution's pH except for aeolian sand leachates which was higher. This was mainly influenced by the soil pH (**Table 5.2**) and basically means that the soils act as buffer, trying to bring the treatment solution's pH to its own pH. These results were in agreement with results reported by Misra and Sivongxay (2009) and Misra *et al.* (2010). Application of both TW and LLD greywater wash out salts in all the soil groups as indicated by an increased soil leachate EC in all the soil groups. The quantity of salts leached out of the soils was influenced by the amount of salts the soils contain. Similar results have been also reported by Misra and Sivongxay (2009) and Misra *et al.* (2010). The pH and electrical conductivity (EC) of the PLD greywater soil leachates were lower than that of the initial water treatment solution for all the soil groups. Therefore, application of the PLD greywater added alkalinity and salts to the soils, compared to TW or LLD greywater.

Table 5.1: The pH and electrical conductivity (EC) of soil leachates from tap water (TW), liquid and powdered laundry detergent greywaters. The bolded values indicate the initial values of the water treatment solution before soil application.

Soil groups	**Tap water (TW)**		**Liquid laundry detergent (LLD)**		**Powdered laundry Detergent (PLD)**	
	pH	**EC (mS/m)**	**pH**	**EC (mS/m)**	**pH**	**EC (mS/m)**
Treatment solution	**6.86**	**4.20**	**7.18**	**18.90**	**9.95**	**491.00**
Aeolian Sand	6.97ab	32.20b	7.41a	84.20ab	8.71a	478.80a
Alluvium	6.65b	48.80b	6.45b	55.00b	7.57c	362.70c
Granite	7.47a	42.00b	7.16ab	60.40b	8.03bc	423.80ab
Shale	7.35ab	98.30a	7.17ab	128.70a	7.95bc	435.30ab
Chromic	7.04ab	52.20b	7.17ab	67.20b	8.17b	388.10bc

*Statistically significant differences between the soil leachates of different soil groups are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$.

Table 5.2: Significant correlation coefficients (r) of soil properties and the measured soil quality parameters (K_{sat}, absorbance, pH, EC, turbidity and ash content) tested at $p<0.05$

Parameters	Soil and/or leachate properties	Spearman Rank Correlation coefficients (r)	Soil Properties	Spearman Rank Correlation coefficients (r)	Soil Properties	Spearman Rank Correlation coefficients (r)
TW K_{sat}	Clay (%)	-0.69	CBD Fe	-0.66	WDC of soil mass (%)	-0.45
LLD K_{sat}	Clay (%)	-0.75	CBD Fe	-0.69	WDC of soil mass (%)	-0.51
PLD K_{sat}	WDC of soil mass (%)	-0.68	Clay (%)	-0.55		
TW: LLD K_{sat}	WDC of soil mass (%)	-0.46				
TW: PLD K_{sat}	CBD Fe (%)	-0.46				
LLD: PLD K_{sat}	CBD Fe (%)	-0.73	Clay (%)	-0.65		
% Decrease LLD	%WDC of soil mass	0.46				
% Decrease PLD	CBD Fe (%)	-0.46				
TW leachate Abs	Soil total C (%)	0.70	Soil organic C (%)	0.50		
LLD leachate Abs	Clay (%)	-0.68				
PLD leachate Abs	Clay (%)	-0.68				
TW leachate pH	Soil pH (KCl)	0.46				
LLD leachate pH	Soil pH (KCl)	0.77	Soil pH (H_2O)	0.69		
TW leachate EC	Soil EC (mS m^{-1})	0.58				
LLD leachate EC	Soil EC (mS m^{-1})	0.88				
TW Ash content	TW Turbidity (NTU)	0.74	Soil EC (mS m^{-1})	0.73		
PLD Ash content	PLD Turbidity (NTU)	0.84				

5.4.1.1.2 Absorbance

Leachate absorbance was used to estimate dissolved organic carbon (DOC) loss in soil irrigated with tap water (TW), and liquid and powdered laundry detergent greywaters. Results obtained from comparing the three water treatments (**Figure 5.4**) revealed that application of 200 mm powdered laundry detergent (PLD) greywater yielded significantly the highest absorbances (4.06-13.66) in all the soil groups compared to tap water (1.16-1.72) and liquid laundry detergent (LLD) greywater (1.57-3.66). This means that PLD greywater significantly enhanced DOC removal from all the soils. This was mainly due to the PLD greywater's high pH (9.95) (**Table 5.1**) which caused the organic molecules to disperse as illustrated by Figure 5.5 below. The organic matter then becomes soluble in the soil solution which makes it easy to be leached out of the soil.

Organic matter is held in soil minerals by different types of bonds as illustrated in Figure 5.6 which differ in their capability to hold or resist the leaching of DOC. These include the electrostatic interactions, hydrogen bonding, Van der Waals (physical bond between clay and organic matter) and ligand exchange (Stevenson, 1994). Results revealed that the amount of DOC leached out from aeolian sands by PLD greywater application was significantly higher than that removed from any other soil group, while the chromic soils had significantly the lowest DOC removal (**Figure 5.4**). A possible explanation could be that the clay content of sandy soils is very low (see **Figure 4.6**) to form the types of bonds that stabilize carbon. Therefore they only have weak bonds with organic matter complexes bonded by weak Van der Waals forces (Brady and Weil, 2017), to hold it (non-polar quartz (sand) and non-polar regions of organic matter), thus organic matter is the least stabilized in sands (Lutzow *et al.,* 2006). The PLD leachate absorbance was significantly negatively correlated with the soil clay content (**Table 5.2**), which means that DOC loss decreases with increasing clay content. However, it is interesting to note that clay content of the shale and chromic soils were not significantly different (**Figure 4.6**), however, PLD leachate absorbance of the chromic soils (Fe-rich soils) was significantly lower than the shale soil group. This is likely due to the significantly higher content of Fe oxides in chromic soils (Figure 4.2) which are able to form stable complexes with organic matter by ligand exchange (Stevenson, 1994; Lutzow *et al.*, 2006) thus creating a strong covalent bond with organic material (**Figure 5.6**). This stabilises the soil organic matter, making the iron (Fe) rich soils more resistant to DOC removal.

Absorbances of LLD greywater leachates were not significantly different from those of TW in all the soil groups. A possible reason could be related to their similarity in terms of pH values (**Table 5.1**) which were close to neutral. TW leachate absorbance positively correlated with the soil organic and total carbon (**Table 5.2**) which means that DOC loss due to TW application was influenced by the soil organic and total carbon contents. Given there were no significant differences in the % C between the soil groups (**Figure 4.10)**, the DOC loss by TW applications also shows no significant variation. Nevertheless, the LLD leachate absorbance was influenced by the soil clay content (**Table 5.2**).

Additionally, it is important to point out that humus consists of fulvic acids, humic acids and insoluble humin (Sparks, 2003). Fulvic acids are known as the most soluble forms of organic matter (soluble in both low and high pH solution) while humic acids are only soluble at high pH solutions (Tan, 2010). In this study, it was visually observed that TW and LLD solubilize mostly fulvic acids, which are soluble at any soil pH (**Figure 5.7**), hence producing lighter (yellow) leachate colours. However, the PLD potentially solubilized both fulvic and humic acids, hence yellowish to dark brown leachate colours were observed (**Figure 5.7**). In addition to the pH, PLD greywater's ability to solubilize humic acids is related to the manufacturer's use of sodium carbonate (Na_2CO_3) in these detergents to remove food dyes such as wine spills in clothes (Mulders and Kgaa, 2012). This promotes dispersion of organic matter contained in clothes. Sodium carbonate (Na_2CO_3) is one of the basic chemicals used in the extraction of humic substances from soils (Stevenson, 1994; Tan, 2010). It should also be noted that the longer the PLD greywater stays in the soil solution in the sandy soils (i.e. aeolian sand and alluvium soils) the more soluble the organic matter becomes (see **Figure 5.8**). It can be visually observed that the leachate colour intensity becomes darker as the time of PLD greywater irrigation increases which basically means that more DOC is leached out with increasing time interval (**Figure 5.8**).

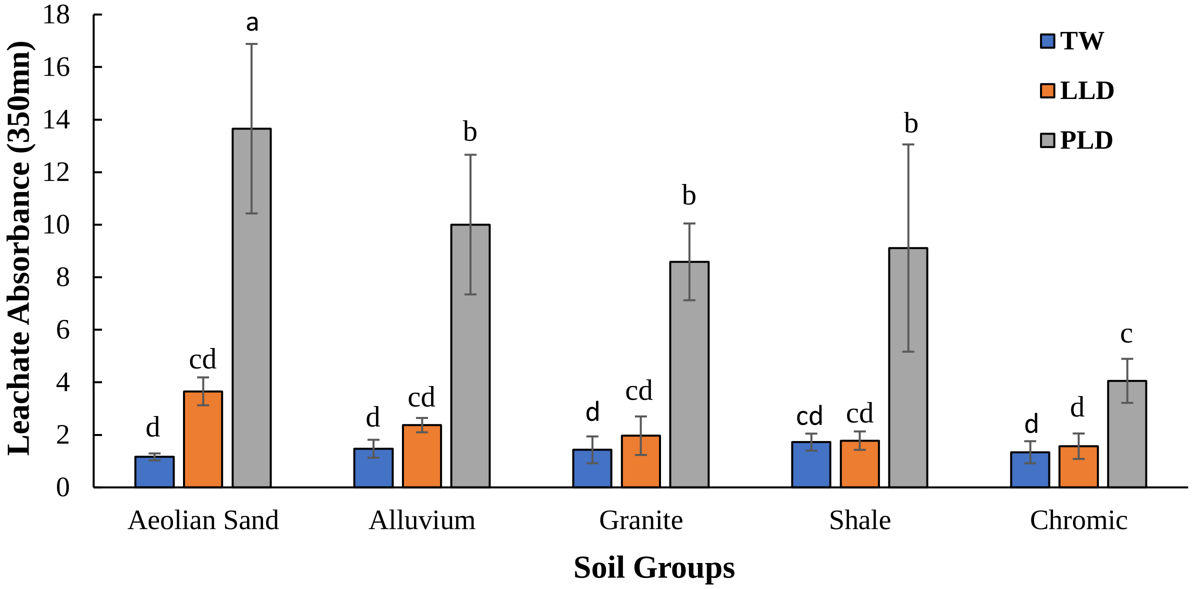


Figure 5.4: Leachate absorbance of different water treatments applied in different soil groups. TW = tap water, LLD = liquid laundry detergent, PLD = powdered laundry detergent. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05.

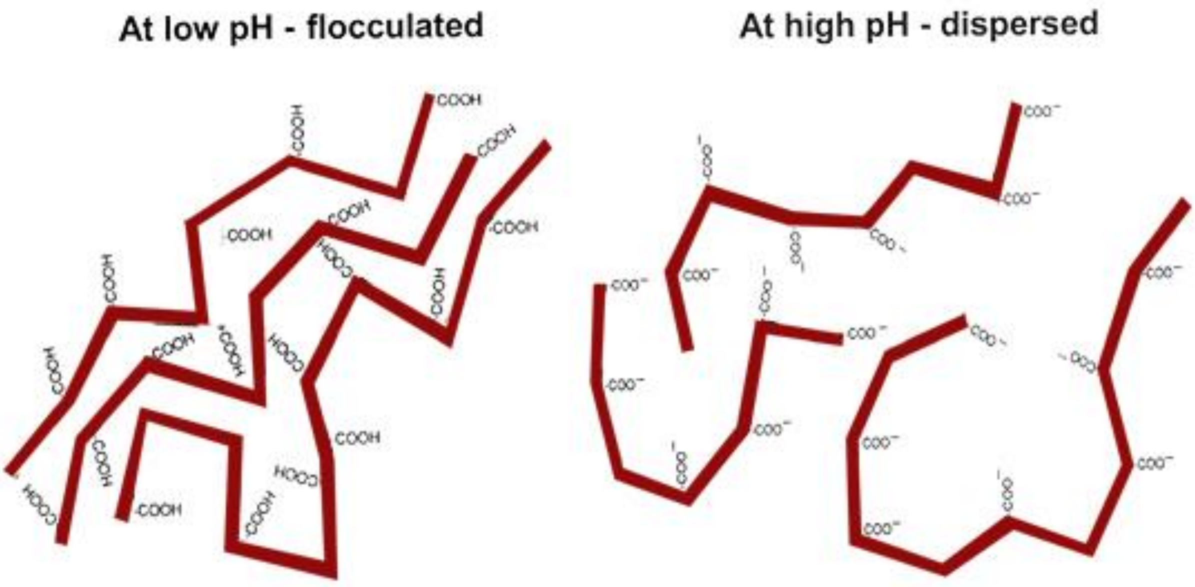


Figure 5.5: Illustration of the effect of solution pH on soil organic matter dispersion (Source: *https://wiki.ubc.ca/images/e/ea/Flocculation_and_Dispersion.jpg*)

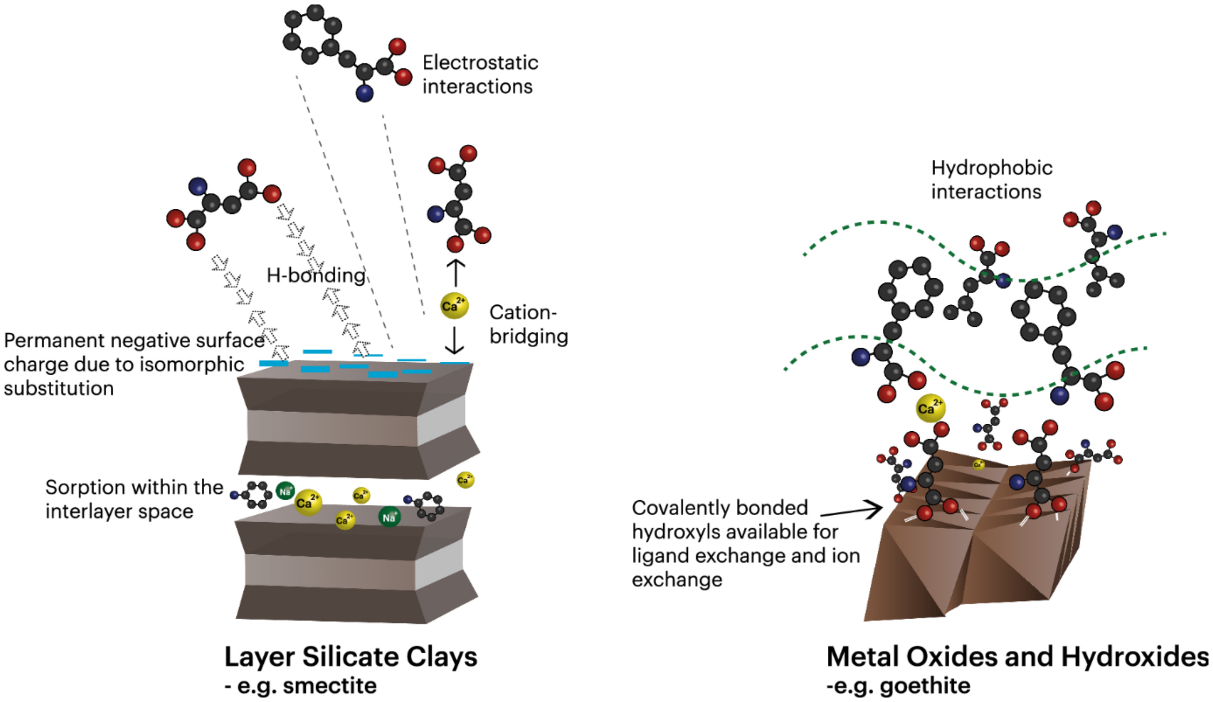


Figure 5.6: Illustrates the various organic matter stabilization mechanisms with soil layer silicates and metal oxides (Jilling *et al.*, 2018)

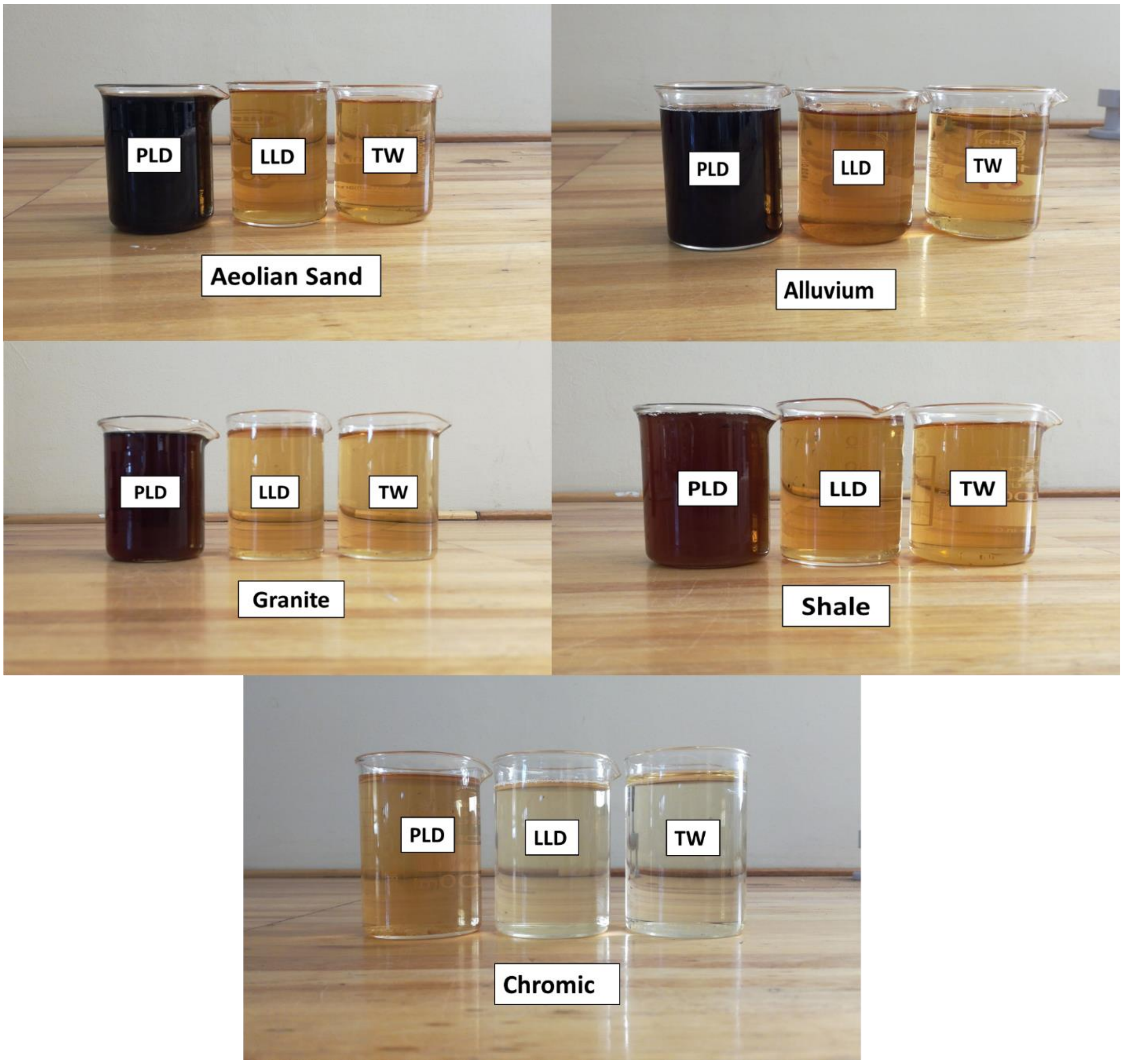


Figure 5.7: Tap water (TW), liquid laundry detergent (LLD) and powder laundry detergent (PLD) greywater leachates from different soil groups (aeolian sand, alluvium, granite, shale and chromic).

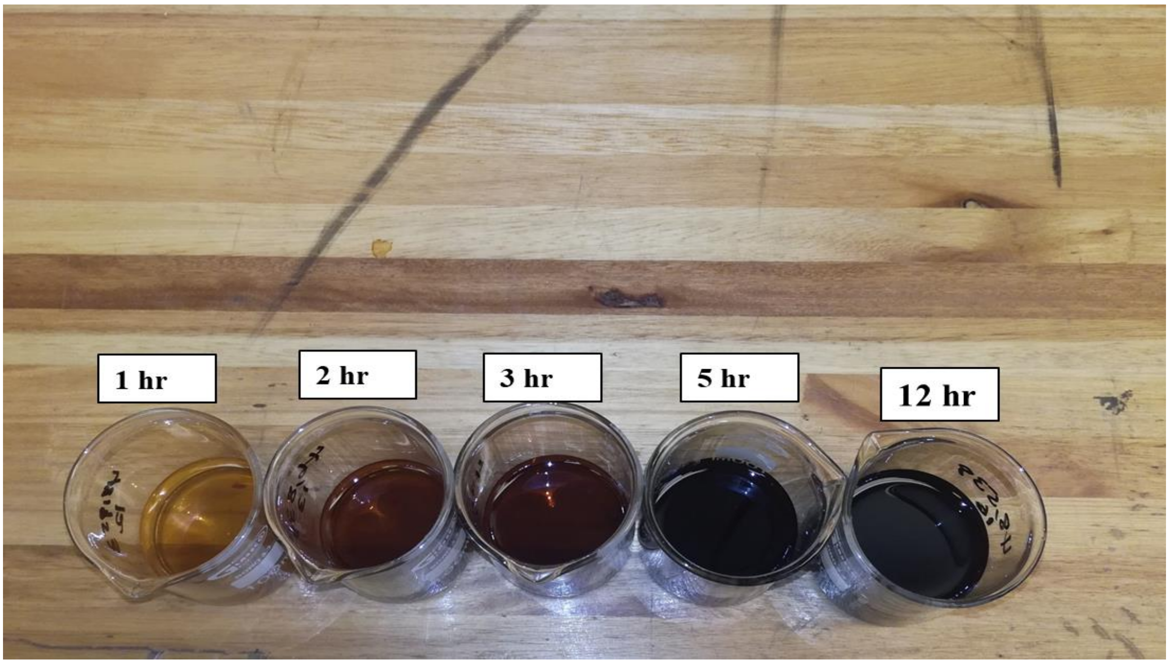


Figure 5.8: Visual display of powdered laundry detergent (PLD) greywater leachates of an alluvium soil collected at different time intervals (leachates after 1, 2, 3, 5 and 12 hours of 200 mm PLD application).

5.4.1.2.3 Total soil C removal

The total amount of soil carbon removed by powdered laundry detergent (PLD) greywater was estimated to be in a range of 1.46 to7.48%, followed by liquid laundry detergent (LLD) which varied from 0.79-1.92% and tap water (TW) with the range from 0.72 to 1.22% (**Figure 5.9**). The TW and LLD % C loss follow similar trends with leachate absorbance results which showed no statistically significant differences between these two water treatments across the soil groups. For the PLD greywater, aeolian sands still significantly had the highest C removal (7.48%), however, unlike the leachate absorbance, there was a clear distinction in the %C lost from alluvium, granite and shale-derived soil groups. The %C loss in alluvium soils (4.35%) was significantly higher than of granite (3.29%) and shale soils (2.52%). These results explain the DOC loss and soil clay relationship better as observed for the leachate absorbance in the previous section. Similar to the leachate absorbance the chromic soils had significantly the lowest % C loss (1.46 %). A visual display of PLD greywater leachates of different soil groups is shown in Figure 5.10. The aeolian sand had darker leachate colours compared to the more clayey soil.

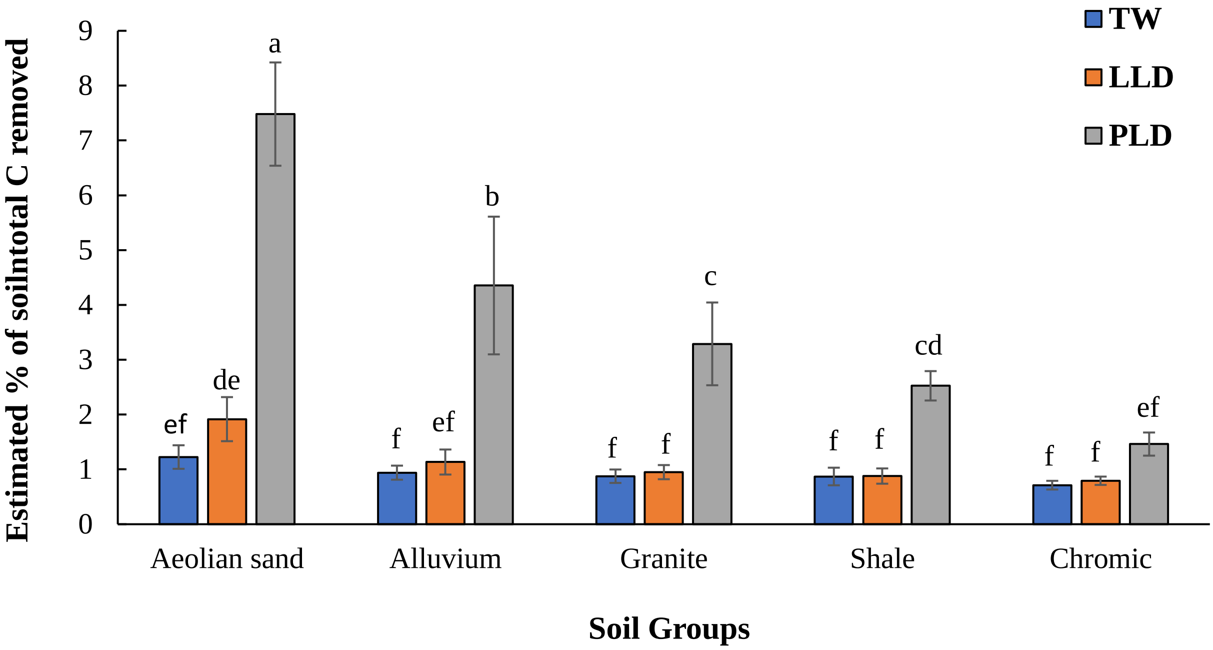


Figure 5.9: The estimated percentage total C lost from soil irrigated with 200 mm of tap water (TW), liquid laundry detergent (LLD) and powdered laundry detergent (PLD) greywaters. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p< 0.05$.

Figure 5.10: Visual display of PLD leachates from different soil groups illustrating the effect of clay content on DOC removal.

5.4.2.2.4 Turbidity and Ash content

Leachate turbidity and the ash content of the dried leachates were used to quantify the amount of soil solids leached out of the soil by the three water treatments (TW, LLD and PLD greywater). The turbidity of TW leachates was significantly lower than LLD and PLD leachates on aeolian sands only. There were no significant differences between treatments (i.e. TW, LLD and PLD) on other soil groups such as the alluvial, granite, shale and chromic. Results presented in Figure 5.11 showed that both LLD and PLD greywaters enhance leachate turbidity compared to TW. Application of PLD greywater resulted in the highest leachate turbidity due to enhanced clay and organic matter dispersion (discussed in the previous sections), followed by LLD greywater leachates. Leachates derived from aeolian sands were significantly the most turbid compared to other soil groups for both laundry greywaters (**Figure 5.11**). A possible reason for this is because sands have larger pores, therefore this make it very easy for finer soil particles (fine silt and clay) dispersed by high Na solutions especially PLD to be leached out. Since clayey soils have small pore spaces, the dispersed clay blocks these pores therefore inhibiting them from being washed out while also preventing the passage of water. Additionally, TW and PLD soil leachates turbidity significantly correlated with ash content of these soil leachates (**Table 5.2**). This means that increased leachate turbidity is mainly due to the solids leached out especially for the PLD greywater. The ash content of the TW leachates was a result of the leached salts which means that the ash content was composed of inorganic salts.

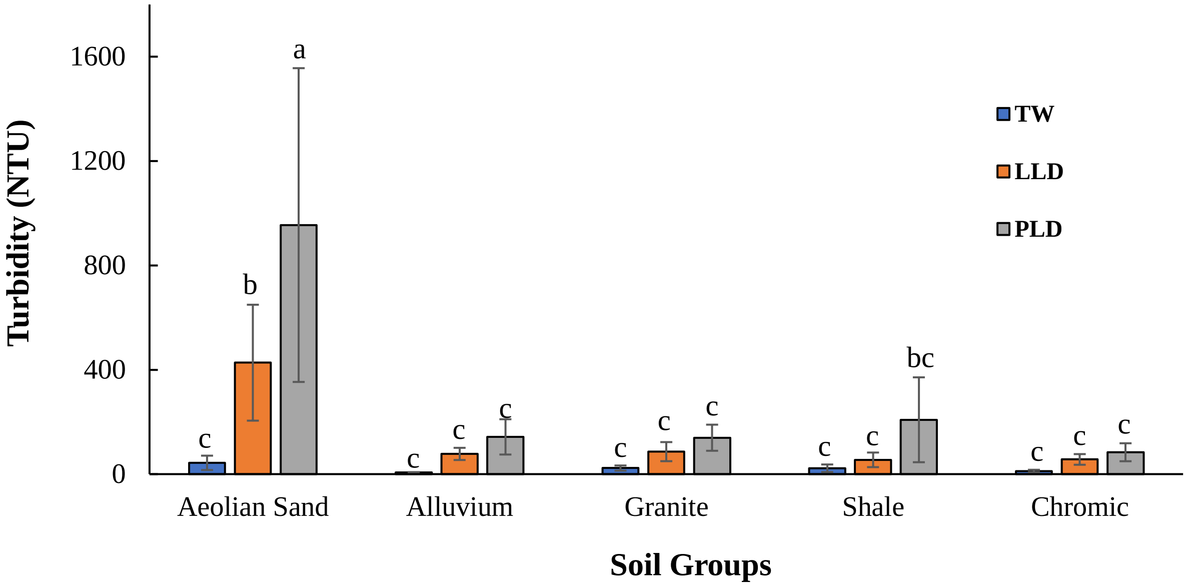


Figure 5.11: Turbidity of soil leachates from tap water (TW), liquid laundry detergent (LLD) and powdered laundry detergent (PLD) greywaters. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p< 0.05$.

5.4.1.1 Saturated hydraulic conductivity (K_{sat})

Soil permeability was assessed through measuring the soil saturated hydraulic conductivity (K_{sat}). Results presented in Figure 5.12 show that there was a significant change in the soil K_{sat} amongst the soil groups and water treatments. In general, the K_{sat} of soils is mainly influenced by soil texture which was also true in this study for the water treatments [i.e. tap water (TW), liquid and powdered laundry detergent (LLD and PLD) greywater] applied, confirmed by significant correlations between the soil K_{sat} and the particle size distribution (sand, silt and clay content). The clayey soils had the lowest K_{sat} compared to the sandy soils. Moreover, application of different water treatments i.e. TW, LLD and PLD greywaters, also caused variability in the K_{sat} of soils. This could be mainly due to the fact the water treatments differ in terms of quality as discussed in Chapter 3 and the quality of irrigation water has been known to alter some of the soil physical, chemical and biological properties as stated by several authors (Ayers and Westcot, 2007). In all the soil groups on average the K_{sat} of soils irrigated with tap water (TW) were higher than those irrigated with the laundry greywaters and varied from 0.77-5.76 cm min^{-1}, followed by LLD greywater K_{sat} which ranged from 0.41-4.39 cm min^{-1} and PLD greywater having the lowest range of 0.30-1.41 cm min^{-1} (see **Figure 5.12**).

Results from this study revealed that application of both LLD and PLD greywaters reduce the K_{sat} of the soils. Similar responses were reported by Mohamed *et al.* (2018) on an acid, clay soil. Even though the water quality parameters of LLD greywater were more acceptable for irrigation (see **Table 3.5**), the K_{sat} of soils irrigated with this water was 1.3-2.3 times slower than those irrigated with TW (**Figure 5.13**), equivalent to a K_{sat} reduction of 24-54%. The K_{sat} reduction by LLD greywater when compared to TW across the soil groups was only statistically significantly on the aeolian sand group. In Ferrosol clay soil, Misra and Sivongxay (2009) also reported K_{sat} reductions due to LLD greywater application when compared to tap water. The reduction in Ksat due to LLD greywater could be related to the presence of surfactants and Na-based builders and ion exchangers in the formulation of these detergents to promote soil dispersion and stain removal from fabric (Mulders and Kgaa, 2000; 2012).

Application of 200 mm powdered laundry detergent (PLD) greywater caused significant K_{sat} reduction in all the soil groups when compared to TW. However, when compared to the LLD, PLD K_{sat} was only significantly lower in the aeolian sand, alluvium and granite soil groups. The K_{sat} of soils irrigated with PLD greywater were 2.2-8.4 times slower than TW (**Figure**

5.14) and consequently decreased the soil infiltration rate by 47-82 %. Similar to the LLD greywater, PLD greywater also contain surfactants which are major components in laundry detergents together with high concentration of builders, thus enhancement of clay dispersion as explained for the LLD greywater above (Mulders and Kgaa, 2000). In addition to this, the elevated pH of PLD greywater (**Table 5.1)** causes soil particles to become more negatively charged, resulting in increased repulsion between the soil particles, thus observing maximum soil dispersion. Significant relationships between pH and clay dispersion have been established, where a similar trend has been reported (Suarez *et al.*, 1984; Chorom *et al.*, 1994). Furthermore, high Na contained in PLD greywater (refer to **Table 3.5**) tends to accumulate on soil cation exchange sites, this promotes clay dispersion and causes disaggregation of soil particles (Brady and Weil, 2017), thus degrading soil structure. Therefore, the dispersed clay blocks the soil pore spaces, thereby decreasing pore sizes. This reduces soil permeability and restricts water movement in PLD greywater irrigated soil. When looking at the K_{sat} ratio of TW compared to LLD and PLD, it can be seen that the granite and shale- derived soils were more prone to pore sealing due to the application of the laundry greywaters **(Figure 5.13 and 5.14)**, likely due to their susceptibility to clay dispersion (**Figure 4.8**). This relationship was confirmed by a negative significant correlation between the water dispersible clay (WDC) of soils and PLD K_{sat} ($r = -0.68$, $p<0.05$), which indicates that the higher the WDC, the lower the PLD soil K_{sat}. The granite and shale group infiltration were reduced by 81-82 % compared to that of TW. In contrast, the chromic soils were more resistant to K_{sat} reduction by PLD greywater (**Figure 5.6**). This can be partially attributed to high Fe content (see **Figure 4.2**) compared to the other soil groups confirmed by significant negative correlation between the %K_{sat} PLD decrease and CBD Fe (**Table 5.2**).

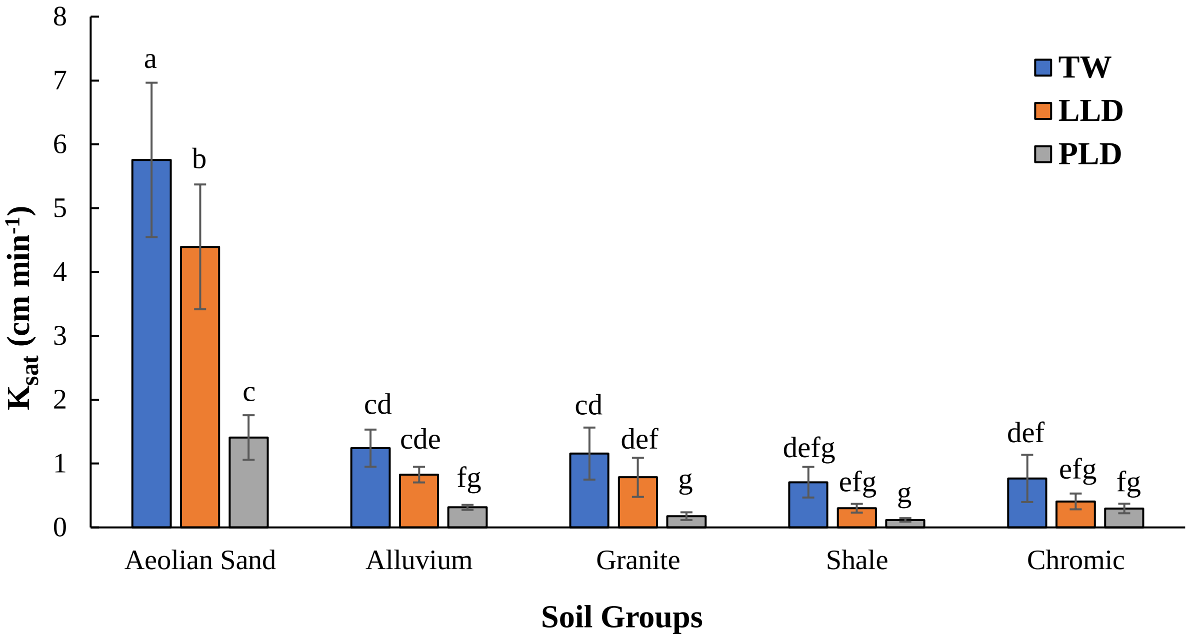


Figure 5.12: The saturated hydraulic conductivity (K_{sat}) of the soil groups from the application of tap water (TW), liquid laundry detergent (LLD) and powdered laundry detergent (LPD) greywaters. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$.

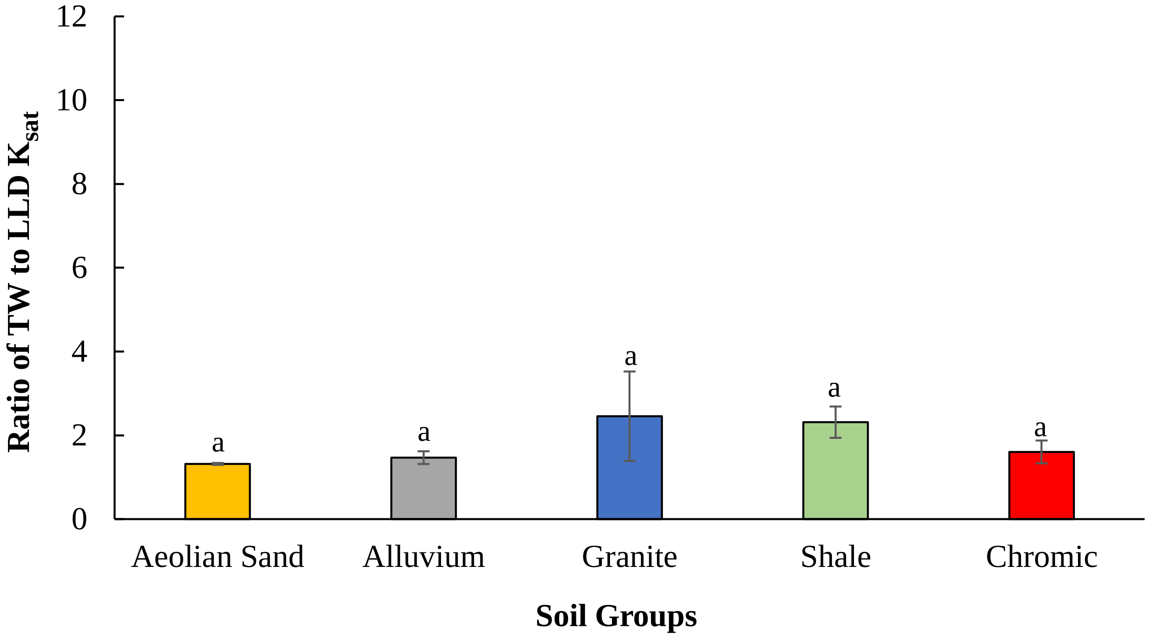


Figure 5.13: The ratio of the saturated hydraulic conductivity (K_{sat}) of TW to that of LLD greywater. Statistically significant differences are shown by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$.

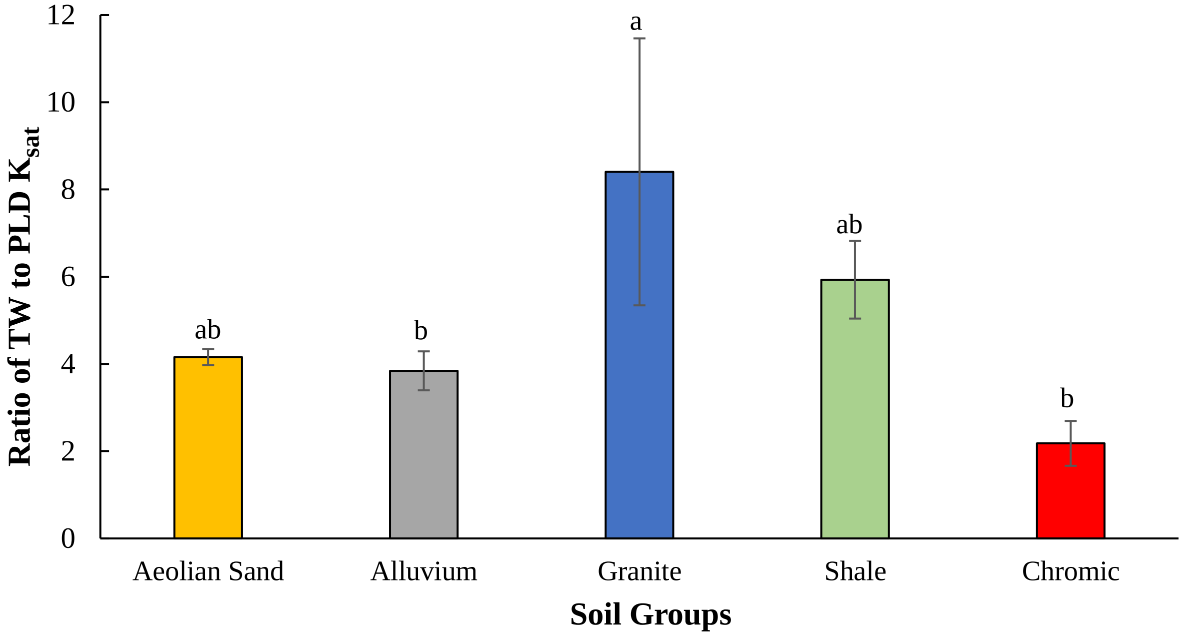


Figure 5.14: The ratio of TW saturated hydraulic conductivity (K_{sat}) to that of PLD greywater. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$.

5.4.2 Comparison of the effect of shower and dishwasher greywaters to laundry greywaters.

5.4.2.1 Soil saturated conductivity (K_{sat})

The soil hydraulic conductivity (K_{sat}) of the selected 11 soils irrigated with SH and DW greywater streams were not statistically different from those irrigated with TW and the two streams of laundry greywater (LLD and PLD) (**Figure 5.15**), even though these greywater treatments had varying composition (**Table 3.5**). Only the K_{sat} of PLD was significantly lower than that of TW. The soil clay content was the main influencer the water percolation of all water treatments except for PLD greywater which was mainly driven by %WDC of both the soil mass and the soil total clay mass (**Table 5.3**). Additionally, the SH and DW greywater soil K_{sat} were influenced by total clay, and %WDC of both soil mass and the soil total clay mass (**Table 5.3**). However, when the K_{sat} of TW irrigated soils was compared to the four greywater streams, the PLD treatment had the significantly the slowest rate of infiltration (5 times slower than TW) compared to the other greywater treatments (1.8-2.3 times slower) (**Figure 5.16**). The ratio of TW to LLD greywater's K_{sat} was significantly positively correlated %WDC of soil mass (**Table 5.3**).

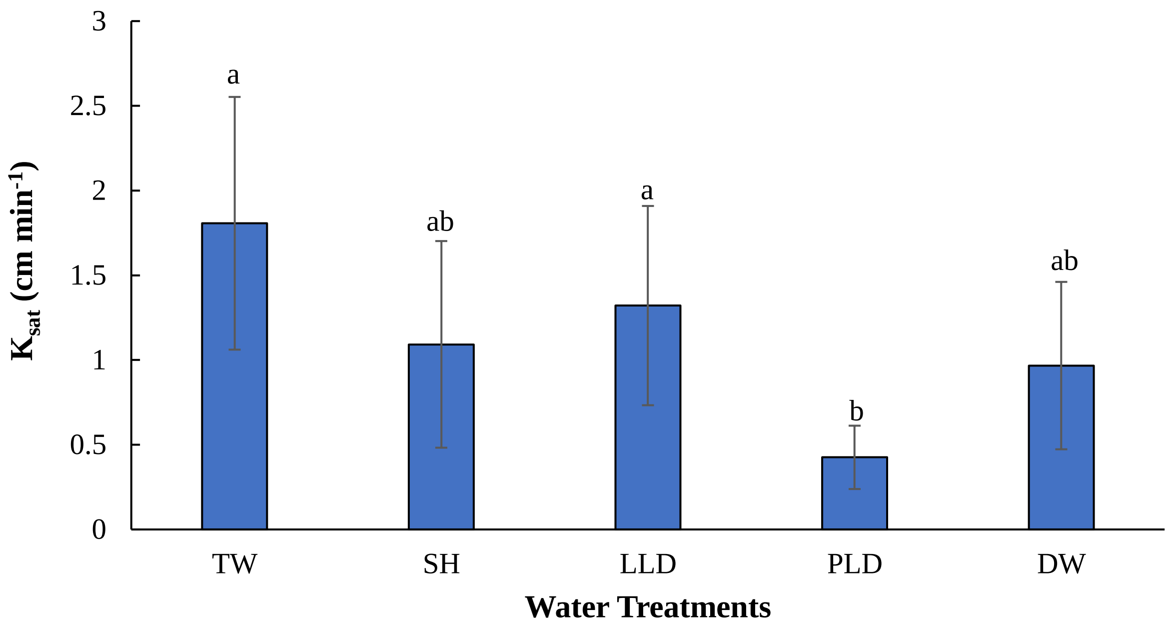


Figure 5.15: The soil saturated hydraulic conductivity as a result of applying different water treatments i.e. tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD). Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$.

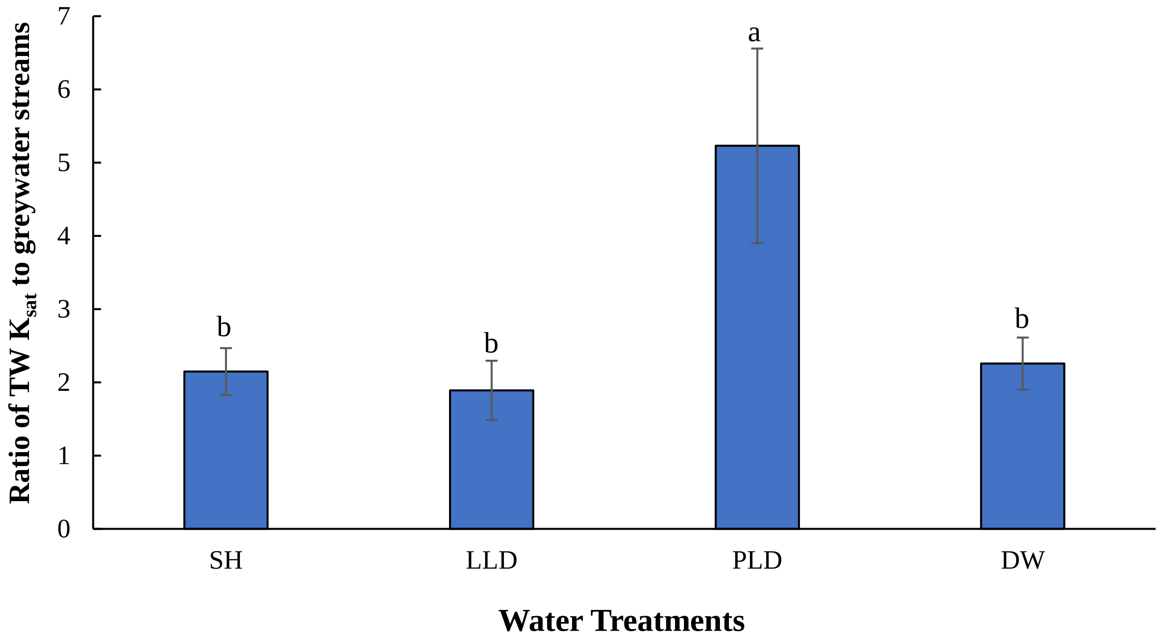


Figure 5.16: The ratio of tap water saturated hydraulic conductivity (K_{sat}) to that of the shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW). Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$

Table 5.3: Significant correlation coefficients (r) of water treatments *viz.* tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW), with the measured soil quality parameters (K_{sat}, absorbance, pH and EC) tested at $p<0.05$.

Parameters	**Soil and/or leachate properties**	**Spearman Rank Correlation coefficients (r)**	**Soil and/or leachate properties**	**Spearman Rank Correlation coefficients (r)**	**Soil and/or leachate properties**	**Spearman Rank Correlation coefficients (r)**	**Soil and/or leachate properties**	**Spearman Rank Correlation coefficients (r)**
TW K_{sat}	CBD Fe	-0.85	Clay (%)	-0.67				
SH K_{sat}	CBD Fe	-0.75	WDC of soil mass (%)	-0.69	WDC of clay mass (%)	-0.69	Clay (%)	0.61
LLD K_{sat}	CBD Fe	-0.76	Clay (%)	-0.66	WDC of soil mass (%)	-0.63		
PLD K_{sat}	WDC of clay mass (%)	-0.80	WDC of soil mass (%)	-0.70				
DW K_{sat}	WDC of soil mass (%)	-0.72	CBD Fe	-0.69	Clay (%)	-0.63		
TW: SH K_{sat}	-	-						
TW: LLD K_{sat}	WDC of clay mass (%)	0.66						
TW: PLD K_{sat}	-	-						
TW: DW K_{sat}	-	-						
TW leachate Abs	Soil total C	0.80						
SH leachate Abs	Soil total C	0.83						
LLD leachate Abs	Soil total C	0.67						
PLD leachate Abs	-	-						
DW leachate pH	Soil pH	0.76						
TW leachate turbidity	Soil total C	0.74						
LLD leachate turbidity	**LLD K_{sat}**	0.77						
DW leachate turbidity	WDC of soil mass (%)	-0.65	DW leachate Abs	0.65	DW EC	0.61		

5.4.2.2 pH and Electrical Conductivity (EC)

The average leachate pH values of leachates from all the water treatments are presented in Figure 5.17. The greywater leachate pH values were significantly higher than that of TW, except the LLD treatment. The PLD leachate was significantly higher than all the other treatments. It should be noted that the pH values of the PLD and DW solutions (**Table 3.5**) were higher than their leachates (**Figure 5.17**) which means that the soils act as a buffer reducing the pH.

DW greywater resulted in the highest soil leachate EC compared to tap water and other greywater streams, followed by the PLD greywater (**Figure 5.18**), even though the EC was observed to be lower than the PLD greywater (**Table 3.5**). The EC of DW greywater solution (**Table 3.5**) is lower than that of the DW leachate (**Figure 5.18**), indicating that DW greywater removes salts from the soils. This behaviour is similar to that observed for TW, SH and LLD. Only PLD greywater appeared to add salts to the soil.

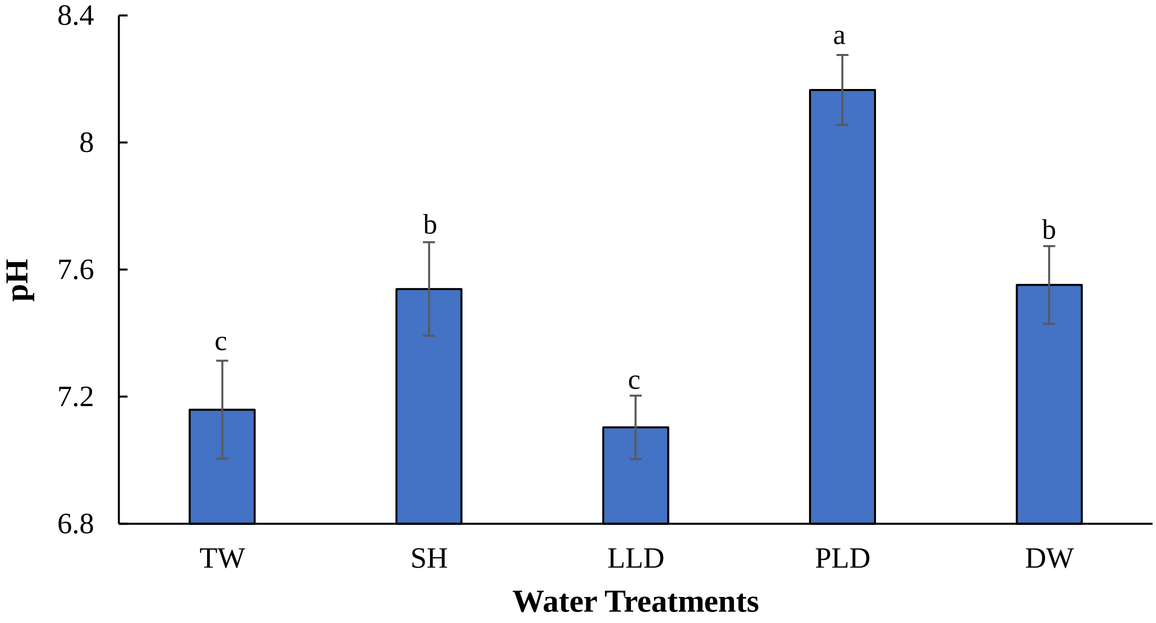


Figure 5.17: The mean soil leachate pH values of the tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) treatments on 11 selected soils. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$.

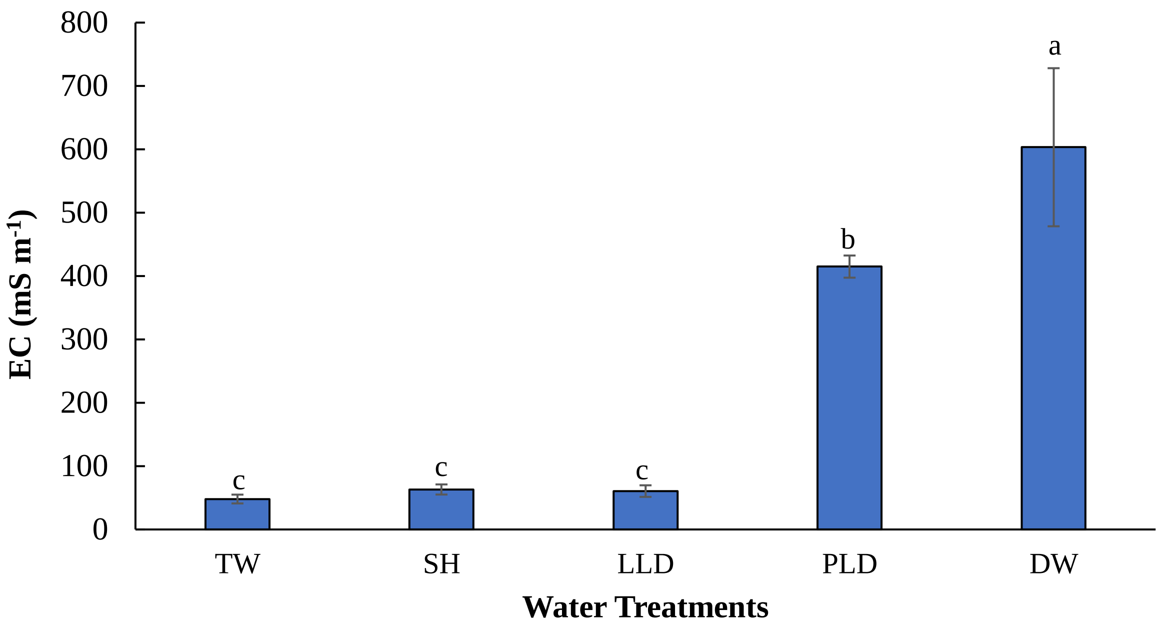


Figure 5.18: The mean soil leachate EC values (mS m^{-1}) of the tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) treatments on 11 selected soils. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p< 0.05$.

5.4.2.3 Dissolved organic carbon (DOC) removal

There were no significant different differences in leachate absorbance (350 nm) between SH and DW compared to TW or LLD (**Figure 5.19**), indicating that these greywater streams also do not promote DOC removal. The PLD greywater's leachate absorbance was significantly higher than all the other water treatments, indicating the greatest capability to remove soil organic carbon (SOC). The amount of DOC leached out by TW, SH and LLD water treatments was influenced by soil total C content (**Table 5.4**). As discussed in detail in section 5.4.2.2.2 that DOC removal in PLD irrigated soils is due to PLD's significantly higher pH and Na content. However, if we refer to the broad water quality analysis in Chapter 3, both PLD and DW greywater had high pH (9.95 and 9.34, respectively) and Na (1338 and 1017 mg L^{-1}, resp.) content yet the observed DW leachate absorbance was significantly lower. This could be related to the ability of these solutions to disperse soil clay. Since PLD greywater had significantly higher SAR (147.8) than DW (50.5) as shown in Chapter 3 (**Table 3.5**), the disaggregation of soil particles irrigated with this water treatment will occur to a greater extent compared to the DW. Therefore, this will loosen the bonds between the soil particles and organic matter, causing the leaching of significant amounts of DOC. Furthermore, the laundry detergent is designed to disperse soil from dirty clothing (as discussed in section 5.4.1), while dishwasher detergent is designed to remove food and fats from plates. The surfactants in these greywaters are different, i.e. those in DW greywater promotes foams while those of PLD promotes soil dispersion.

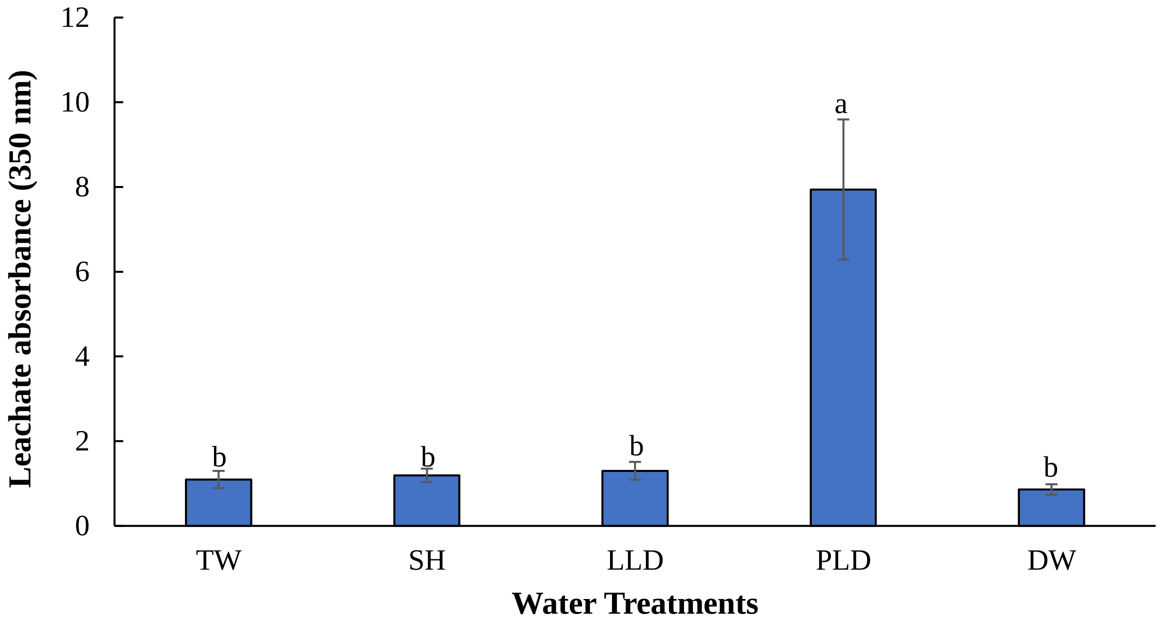


Figure 5.19: The average of soil leachate absorbance (at 350 nm wavelength) of the tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) treatments on 11 selected soils. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p< 0.05$

5.4.2.4 Turbidity

Results presented in Figure 5.20 showed that LLD, PLD and DW greywater streams enhanced leachate turbidity compared to SH and TW. TW turbidity was influenced by the soil total C content confirmed by a positive significant correlation (Table 5.3). Similar to the previous section soil leachates from the PLD greywater were the most turbid due to elevated clay and organic matter dispersion (see sections 5.4.2.1 and 5.4.2.3) followed by both LLD and DW greywater streams. Even though DW greywater had the highest turbidity (refer Table 3.5), its leachate turbidity was not significant different to that of LLD greywater. The LLD leachate turbidity was mainly influenced by the LLD soil K_{sat} confirmed by significant positive correlation (see Table 5.3) which means that the faster the water moves through the soil the more the leaching of finer soil particles. However, the DW leachate turbidity was influenced by several factors such as %WDC of the soil mass, its leachate absorbance and EC confirmed by significant negative and positive correlations (see Table 5.3). DW leachate turbidity increased with decreasing WDC of soil mass. This makes sense because the lower amount of dispersed clay the less blocked the soil pores become, thus allowing fine particles to be removed from the soil into the leachate. Additionally, elevated DW leachate absorbance (DOC removal) also increased the turbidity of DW.

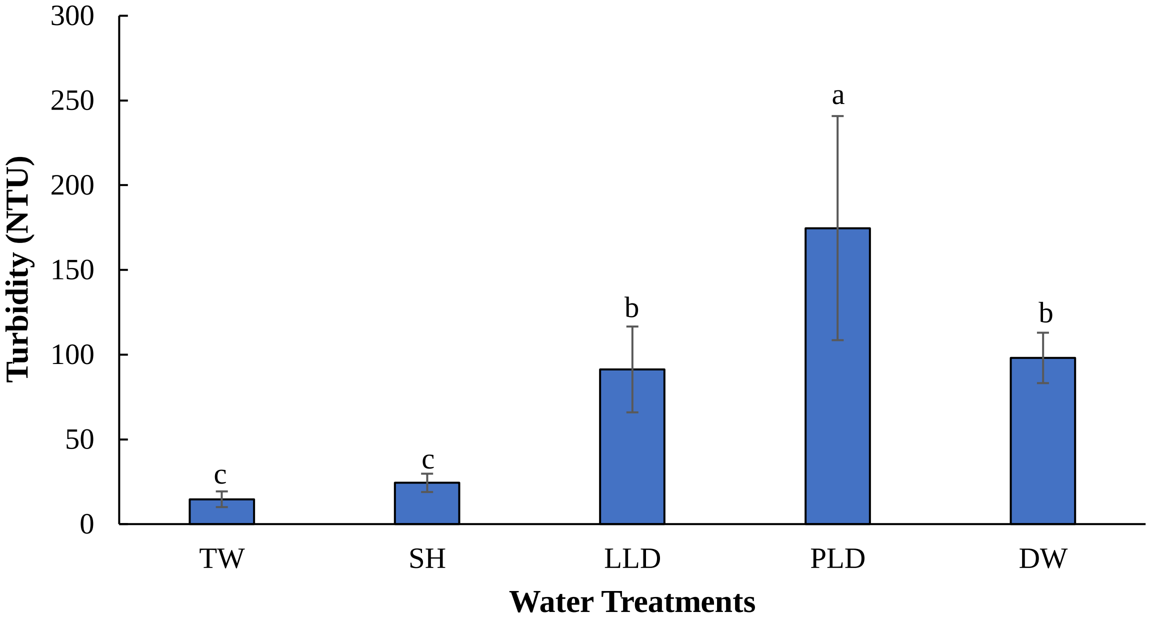


Figure 5.20: The mean soil leachate turbidity of the tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) treatments on 11 selected soils. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$

5.5 CONCLUSIONS

Application of 200 mm PLD greywater had significantly more detrimental effects on soil permeability, clay dispersion and DOC removal compared to 200 mm LLD or TW. This was mainly attributed to the high pH and SAR value of the PLD. PLD greywater added alkalinity and salts to the soils compared to LLD and TW as indicated by its leachate pH and EC. Both LLD and PLD greywaters reduced the soil permeability due to their SAR value and surfactant content. LLD K_{sat} was 1.32 - 2.34 times slower than that of TW, while PLD K_{sat} was 2.18 - 8.40 times slower than that of TW. It was found that the degree to which the laundry greywaters affected infiltration and DOC removal depended on the soil type. Soils with high WDC such as granite and shale were more inclined to infiltration reduction due their vulnerability to pore sealing while the chromic soils were the least susceptible likely due to the presence of iron oxides which stabilises soil structure. The aeolian sands were most susceptible to DOC stripping by PLD greywater while the chromic soil group was the least susceptible. The aeolian sands were also more prone to clay removal by PLD greywater as indicated by their high leachate turbidity. It was therefore concluded that greywater generated from PLD should not be used on soils while LLD greywater should be used cautiously, especially on granite or shale derived soils.

When comparing application of 200 mm of SH and DW on fewer soils, the K_{sat} and DOC removal of soils irrigated with SH and DW were statistically not different from those irrigated with TW or LLD. Nevertheless, the average SH K_{sat} was 2.15 times slower than TW, while DW K_{sat} was 2.25 slower. Additionally, DW significantly increased leachate turbidity compared to SH and TW while SH leachate turbidity was statistically not different from TW. PLD leachates were still the most turbid, while LLD leachates turbidity was not statistically different to DW. Despite, not being as destructive as PLD, DW possessed a high SAR (50.47) and Na content which makes it unacceptable for repeated irrigation of soils. Therefore, the effect of repeated irrigation of four greywater streams on soil quality will be assessed in the next chapter.

CHAPTER 6

EFEECT OF THE REPEATED GREYWATER APPLICATION AND WINTER RAINFALL LEACHING ON SOIL QUALITY

6.1 INTRODUCTION

Soil quality is generally defined as the soil's ability to perform necessary functions for plant growth. In agriculture, soil quality is assessed to improve plant production and yield. Depending on the researcher's interest, soil quality indicators may vary considerably. Some soil quality indicators normally studied include the soil aggregation and permeability, pH, electrical conductivity (EC), organic matter, essential plant nutrients such as N, P, K, Ca, Mg, Cu, Fe, Zn and Mn, and the presence of soil microbes. These properties influence each other, for example, the availability of plant nutrients is influenced by the soil pH and organic matter. Trace metals such as copper (Cu), iron (Fe), zinc (Zn) and manganese (Mn) are less soluble at pH greater than 7, whereas the presence of organic matter enhances the availability of these metal ions (Brady and Weil, 2017). Anion exchange capacity is also pH dependent with PO_4^{3-}, SO_4^{2-} and other anions more adsorbed at low pH (Tan, 2010). Irrigation water quality has a significant effect on soil quality. Long term application of bathroom, laundry and dishwasher greywater has been shown to increase the soil pH, salts, phosphorus and soil microbes (Turner *et al.*, 2013; Siggins *et al.*, 2016).

In the Mediterranean region of the Western Cape, greywater is only intended for reuse in the dry season (*i.e.*, summer) since rainwater is sufficiently available in the winter season. In Chapter 3 of this study, the four greywater streams were shown to have variable quality and it is therefore expected that their effect on the soil (as seen Chapter 5) will vary considerably. Few studies have been conducted in South Africa on the effect of the repeated application of individual greywater streams on soil characteristics, as most studies focus on the use of composite greywater samples (Lubbe and Rodda, 2016) which is perceptually considered more dilute (Rodda *et al.*, 2010). Certain greywater streams are easier to capture and use for irrigation than others, for example, laundry or dishwasher greywater simply requires extension of the drainage hose to apply it directly in gardens. However, capturing of the shower or bathwater requires either direct access to the household drains and some kind of pump (a high-tech greywater system), or requires buckets to manually capture and apply the water. Thus, there exists a need to examine the effect of the individual streams of greywater. Furthermore, no studies have been conducted on the soils of the greater Cape Town area.

The main aim of this research unit is to determine the effect of repeated application of the four selected streams of greywater in contrast to tap water on the two selected representative soils (vulnerable and non-vulnerable soil). The irrigation was scheduled to mimic typical summer application of greywater. The subsequent effect of winter rainfall leaching on greywater-irrigated soils was examined, to determine whether rainfall was successful at remediating the soils.

6.2 OBJECTIVES

a) To examine the effect of repeated application of shower, liquid laundry detergent, powdered laundry detergent and dishwasher greywater streams on soil quality.
b) To determine the impact of subsequent rainwater application on greywater-irrigated soils.

6.3 MATERIALS AND METHODS

6.3.1 Soil selection

Based on results presented in Chapter 5, two representative soil types were selected for this study. One of the soils that was vulnerable to physical degradation by the greywater streams was selected from the granite soil group *i.e.*, SP1 soil sample, and one non-vulnerable soil was selected from the chromic soil group *i.e.* BD1 soil sample. The two selected soils were both topsoil samples, taken from Spier wine farm (SP1) and Bo-Dalsig resident garden (BD1).

This study was conducted in two series of experiments. The first experiment was based on repeated application of tap water (TW) and the four selected greywater streams i.e., to mimic summer application rates, while the second experiment was based on leaching the soils with rainwater to mimic winter rainfall.

6.3.2 Summer greywater application experiment

A laboratory soil leaching column incubation experiment was set up using two selected representative soils types *i.e.*, granite (SP1) and chromic (BD1) soils. The two representative soils were packed in the soil column tubes constructed as explained in the previous chapter (**section 5.3.1**). However, in this chapter, the soils were packed to a volume of 86.59 cm^3 by mechanical shaking, up to a height of 9 cm. The soils were repetitively irrigated with the selected following water treatments namely:

a) Tap water (TW)
b) Shower (SH)

c) Liquid laundry detergent (LLD)
d) Powdered laundry detergent (PLD)
e) Dishwasher (DW)

It is important to note that SH, LLD and PLD greywater streams used in this research unit were synthetic, whereas dishwasher greywater was collected from actual dishwasher cycle (refer to Chapter 3).

In this experiment, the treatments (tap water and greywater streams) of known pH and EC (**Table 6.1**) were applied at typical garden irrigation rates during the driest month of February. The water holding capacity (WHC) of the soils were measured using the percolation method modified from Cassel and Nielsen (1986), where 25 g of dry soil samples were placed on a funnel with a filter paper, saturated with 100 ml of water and allowed to drain freely for 24 hours into a measuring cylinder. The same volume of water was also applied on a funnel with only a filter paper, so that this can be used as a correction factor. The amount of water drained was measured. The granite soil held 7.4 % of the total volume applied while the chromic held 8.5%. The water holding capacity of the granite soil (SP1) was lower than that of the chromic soil (BD1). However, for this experiment the WHC of the granite soil, which is lower so that the water application rates are the same the soils. The soils were first wetted to field capacity (FC) by applying 28.8 mm of the water treatments, and allowed to dry-out to approximately 50% of the water content between FC in the oven set at 30 °C , which is the approximate average maximum temperature in the Cape Town and Stellenbosch areas during the month of February. The soils were then repeatedly irrigated with 14 mm of the greywater streams and tap water to simulate a domestic irrigation and oven-dried to 50% FC over a period of 10 weeks. A total volume of 370 mm of treatment solution was applied during this experiment. Thus, the experimental design consisted of two soil types (granite-SP1 and chromic-BD1), five water treatments (TW, SH, LLD, PLD and DW) and six replicates (rep) per water treatment applied.

After the summer irrigation period, three of the six soil replicates per water treatment were taken and characterised for the soil physical (hydraulic conductivity, water dispersible clay and hydrophobicity), chemical (pH, EC, Total C & N, exchangeable basic cations and acidity, plant available P, Fe, Mn, Cu and Zn) and microbiological properties (soil microbial diversity and community structure). The remaining three soil replicates were used in the subsequent winter rain application experiment.

Table 6.1: The pH and electrical conductivity (EC) of tap water, shower, liquid laundry detergent, powdered laundry detergent and dishwasher (i.e. water treatments) used during the summer irrigation period.

Water treatments	**pH**	**EC (mS m^{-1})**
Tap water (TW)	6.69	6.40
Shower (SH)	6.76	19.95
Liquid laundry detergent (LLD)	7.34	26.00
Powdered laundry detergent (PLD)	10.67	510.0
Dishwasher (DW)	9.51	1914

6.3.3 Winter rainfall leaching experiment

6.3.3.1 Rainwater (RW) capturing and analysis

Rainwater was harvested from a roof in Brackenfell, Cape Town using a rainfall tank (5000 L) connected to the gutters. A 25 L plastic container was used to collect rainwater from the storage tank and stored in the fridge to prevent microbial growth during the rain application experiment. The chemical properties of the rainwater sample were determined. These included the pH, electrical conductivity (EC), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), manganese (Mn), copper (Cu), iron (Fe), and zinc (Zn).

The pH and EC were measured using the Metrohm Swiss made 8.27 pH lab and Jenway 4510 conductivity meter, respectively, while calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), manganese (Mn), copper (Cu), iron (Fe), and zinc (Zn) contents were measured with the VARIAN AA240FS Fast Sequential Atomic Absorption Spectrometer (AAS). Table 6.2 shows the water quality parameters of rainwater.

Table 6.2: Selected chemical properties of rainwater (RW) obtained from Brackenfell, Cape Town in 2019.

Water quality parameters	Rainwater
pH	5.76
Electrical conductivity (EC), mS m^{-1}	10.60
Calcium (Ca), mg L^{-1}	7.95
Magnesium (Mg) mg L^{-1}	1.46
Potassium (K), mg L^{-1}	1.84
Sodium (Na), mg L^{-1}	7.04
SAR	1.18
Iron (Fe), µg L^{-1}	989.0
Copper (Cu) µg L^{-1}	80.00
Zinc (Zn), µg L^{-1}	3.00
Manganese (Mn), µg L^{-1}	159.0

6.3.3.2 Winter rainfall application

Soils from the repeated greywater application experiment were treated with a total quantity of 370 mm of rainwater to represent winter rainfall for the three winter months. Rainfall simulation was done similarly to repeated-greywater treatments with 18 mm rain application per rainfall incidence. This was done to see whether the effects of the greywater could be remediated by the same volume of rainwater. The greywater-treated soils were homogenized and repacked in the soil columns to prevent preferential flow along the sides, as the granite soil had shrunk and pulled away from the sides of the columns during the drying-out period. The rainwater was also applied according to series of wetting and drying events over a period of 7 weeks, where the soils were irrigated to 120% of FC to simulate rainfall leaching and then dried to 50% FC in the oven. During these rainfall events, the leachates were captured and analysed to study the removal of salts, alkalinity and DOC (EC, pH and UV-visible absorbance at 350 nm – Section 5.3.2.2). The volume of leachates was also determined.

6.3.4 Soil quality parameters

The following soil quality parameters were measured to evaluate soil changes caused by either the repeated application of the four greywater streams in comparison to tap water or the impact of rainwater soil leaching on soil properties.

6.3.4.1 Soil chemical properties

The following soil chemical properties were measured after both the summer and winter irrigation experiments.

6.3.4.1.1 Soil pH and electrical conductivity (EC)

The pH and electrical conductivity (EC) of both the granite (SP1) and chromic (BD1) soil samples were measured in deionised water at 1:2.5 soil: water ratio (The Non-affiliated Soil Analysis Work Committee, 1990; AgriLASA, 2004).

6.3.4.1.2 Exchangeable cations (Ca, Mg, Na and K), water-soluble cations and exchangeable acidity

The soil exchangeable cations and exchangeable acidity were determined for both summer irrigation and after winter rain leaching as outlined by Thomas (1982), where exchangeable cations (Ca, Mg, Na and K) were extracted with ammonium acetate (NH_4OAc, pH = 7.0) while the exchangeable acidity was extracted with 1 M KCl using and determined using 0.01 M NaOH titration method.

The water-soluble cations were extracted in a similar manner as the exchangeable cation however deionised water was used for this extraction instead of ammonium acetate. The water-soluble cations were used to correct the exchangeable cations extracted with NH_4OAc. The effective cation exchange capacity (ECEC) was calculated from exchangeable cations and acidity using Eq. 6.1 while exchangeable sodium percentage (ESP) was calculated using exchangeable Na and ECEC (see Eq. 6.2)

$$ECEC\ (cmolc\ kg^{-1}) = Exchangeable\ acidity + Exchangeable\ Ca, Mg, K\ and\ Na \qquad \text{Eq. 6.1}$$

$$ESP\ (\%) = \frac{Exchangeable\ Na(cmolc\ kg^{-1})}{ECEC(cmolc\ kg^{-1})} \times 100 \qquad \text{Eq. 6.2}$$

Where; both exchangeable cations (Ca, Mg, Na and K) and exchangeable acidity were in $cmol_c$ kg^{-1}.

6.3.4.1.3 Plant available P, Cu, Fe, Zn and Mn

The Mehlich III method as described by Reed and Martens (1996), was used to evaluate levels of plant available phosphorus (P), copper (Cu), iron (Fe), zinc (Zn) and manganese (Mn). The measured plant nutrients were extracted using a Mehlich III solution (consisting of acetic acid, 1 M nitric acid, ammonium nitrate and ammonium fluoride) on 1:10 ratio of soil to Mehlich III solution. The extracted Cu, Fe, Zn and Mn contents were measured using VARIAN AA240FS

Fast Sequential Atomic Absorption Spectrometer (AAS) while the Mehlich III extracted phosphorus was measured by the Jenway 7315 spectrophotometer, at 880 nm wavelength using the ascorbic acid colorimetric method described by Kuo (1996). The standard curve was formed using the following phosphorous concentrations 0, 0.2, 0.4, 0.6 0.8 and 1 ppm and yielded the following linear equation with R-Squared (R^2) value of 0.95.

$$y = 0.1581x + 0.0284 \tag{Eq. 6.3}$$

Where, y is the absorbance value at 880 nm and x is the concentrations of P.

6.3.4.1.4 Total Carbon and Nitrogen

Soil total C and N contents, both after the repeated greywater application experiment and after winter rainwater leaching, in each sample were determined through the dry combustion method as conversed by Nelson and Sommers (1982).

6.3.4.2 Soil physical properties

The soil physical properties were determined only after the summer irrigation experiment i.e. after the repetitive greywater irrigation period.

6.3.4.2.1 Water dispersible clay

The water dispersible clay (WDC) of the soils continuously irrigated with TW, SH, LLD, PLD and DW was determined using the IUSS Working Group WRB (2015) method also explained in Chapter 4 (**section 4.2.2.2**). In this study the WDC was expressed as the percentage of the soil total clay mass as stipulated in chapter 4, equation 4.2.

6.3.4.2.2 Saturated hydraulic conductivity

The soil saturated hydraulic conductivity (K_{sat}) was also measured after the summer tap water and greywater irrigation experiment using 70 ml (67.2 mm) of rainwater. This was done using infiltration experimental set-up described in the previous chapter (**section 5.3.1.3**) and was measured using Darcy's law where rainwater was applied at a constant head pressure of 1 cm and the leachate volumes were quantified at specific time intervals.

6.3.4.2.3 Hydrophobicity

Hydrophobicity was measured on both an undisturbed (after repetitive greywater irrigation period) and a disturbed soil samples (after repacking the soils) using the water droplet penetration time (WDPT) method as described by Bisdom *et al.* (1993). This method basically measures the time taken for a drop of water (50 µL) to infiltrate the soil surface.

6.3.4.3 Soil microbiological properties

The two replicates of soil samples were sent to Sporatec, Stellenbosch University for microbial diversity and community analysis. The soil microbial properties were determined after the summer irrigation period and were estimated by measuring soil microbial diversity and community composition. Due to the high cost of analysis, it was only performed on the granite (SP1) soil samples.

6.3.5 Statistical analysis

All statistical analyses were performed using Statistica (version 13.5.0.17). A one-way ANOVA was used to test statistically significant differences on soil properties after repetitively irrigating with tap water and the four greywater streams and also after rainwater (RW) leaching. This was done to test the effect of the repeated application of tap water and the greywater streams on soil quality and if rainwater (RW) successfully remediated the greywater-treated soils. The significant differences between soil leachates parameters resulting from rainwater leaching on soils irrigated with tap water and the greywater streams were also tested using a one-way ANOVA. A Fisher's Least Significant test was used for mean separation while Spearman Rank Correlation Test was used to determined relationships between the measured soil, water and leachates quality parameters.

6.4 RESULTS AND DISCUSSION

6.4.1 The effect of repeated application of tap water and four greywater streams on soil chemical, physical and microbiological properties

This section focuses only on soil properties after the repeated application of tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) compared to the unirrigated soil (i.e. control).

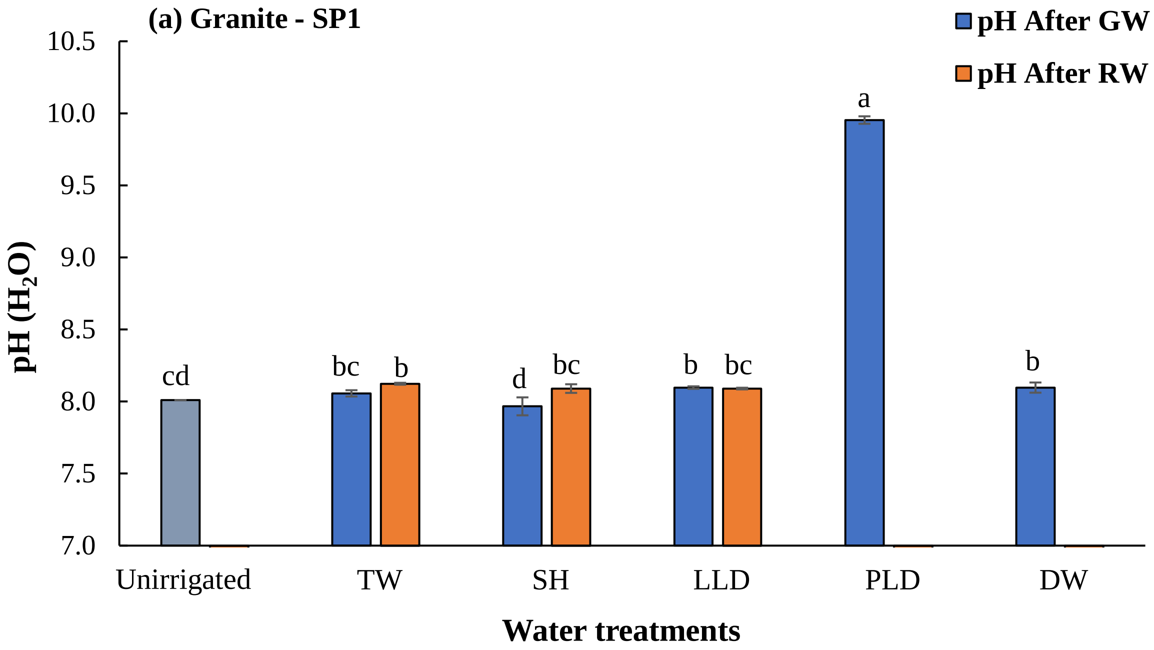
6.4.1.1 Chemical soil properties

6.4.1.1.1 Soil pH and EC

Repetitive application of tap water (TW) and shower (SH) in SP1 granite soil caused no significant effect on the soil pH when compared to the unirrigated soil while a significant pH increase was observed in the liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) greywater irrigated soil (**Figure 6.1a**). In the BD1 chromic soil, repetitive application of both TW and greywater streams significantly increased the pH of the soil (**Figure 6.1b**). PLD greywater application yielded significantly the highest pH increase on both soils (**Figure 6.1a and b**). Thus, PLD greywater added alkalinity to the soil. This could be related to the PLD greywater's addition of basic salts, carbonates and hydroxides to the soil (**Table 3.5**). Similar trends were observed by Siggins *et al.* (2016) and Mohamed *et al.* (2018). Moreover, it is important to note that the PLD greywater irrigated granite soil had the highest pH value of 9.95 while that of chromic was 9.29. This shows that the BD1 soil better buffered against the PLD pH change compared to the granite soil due to its high clay and organic matter content (see **Table 4.2**). When comparing the greywater streams, the soil pH values due to LLD and DW greywater irrigation were not significantly different from each other, yet higher than the shower greywater on both soils.

The electric conductivity (EC) results in this study revealed that all the tap water and the four greywater streams added salts to the soils (granite and chromic) (**Figure 6.2a and b**). This increase can be attributed to the salts contained in these water treatments (see **Table 6.1).** However, the amount of salts added in tap water (TW), shower (SH) and liquid laundry detergent (LLD) greywaters in the granite soil were not significantly different from the unirrigated soil (**Figure 6.2a)**. Mohamed *et al.* (2013) also reported small soil salinity contributions due to bathroom and liquid laundry detergent greywater application. A significant increase was observed in the chromic soil for all the water treatments (**Figure 6.2b**). Furthermore, continuously irrigating with powdered laundry detergent (PLD) and dishwasher

(DW) greywater significantly increased the quantity of salts in both soils (**Figure 6.2a and b**). The DW greywater irrigated soils yielded significantly the highest EC values (1858 mS m^{-1} for granite and 1982 mS m^{-1} for chromic) compared to the unirrigated soil, TW, SH, LLD and PLD water treatments. This can be attributed to the application of saline DW greywater (**Table 6.1**). Soil irrigated PLD greywater also significantly increased the EC of soils (i.e., 638 mS m^{-1} for granite and 585 mS m^{-1} for chromic) compared to the unirrigated soil, TW, SH and LLD greywater streams. Thus, irrigating with either PLD or DW greywater streams may lead to the development of saline (i.e., salt accumulated) soils also referred to as white alkali soil. Salt accumulation in soils has many soil-crop influences such as reduction of plant available water and crop yield (Ayers and Westcot, 2007).



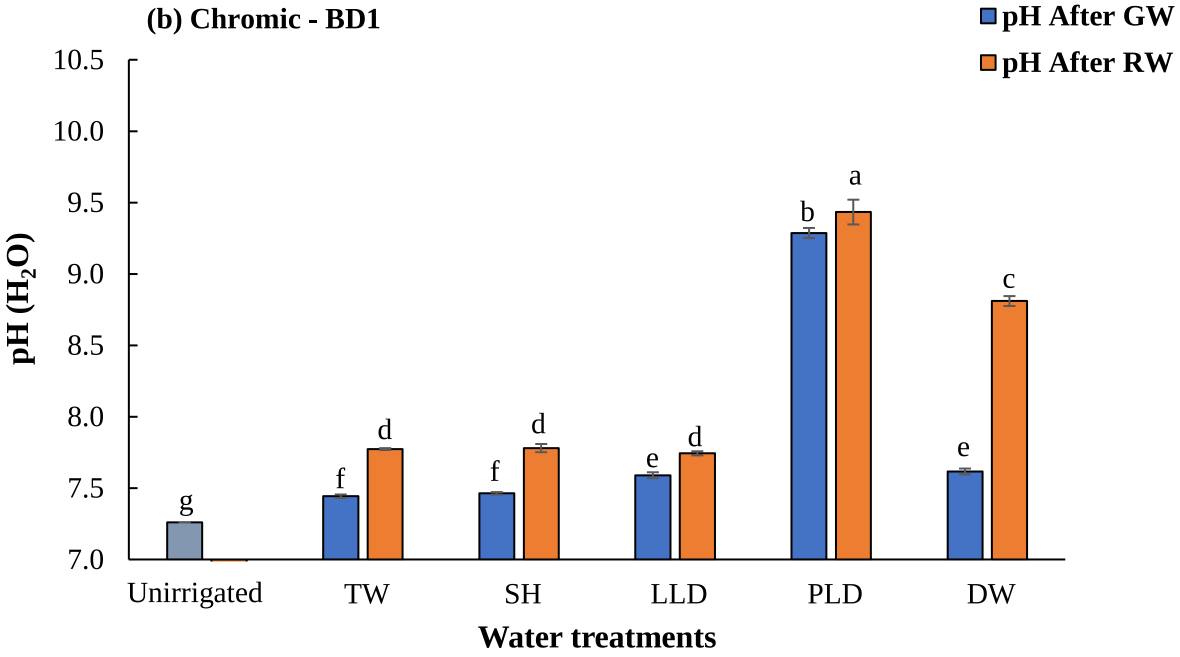
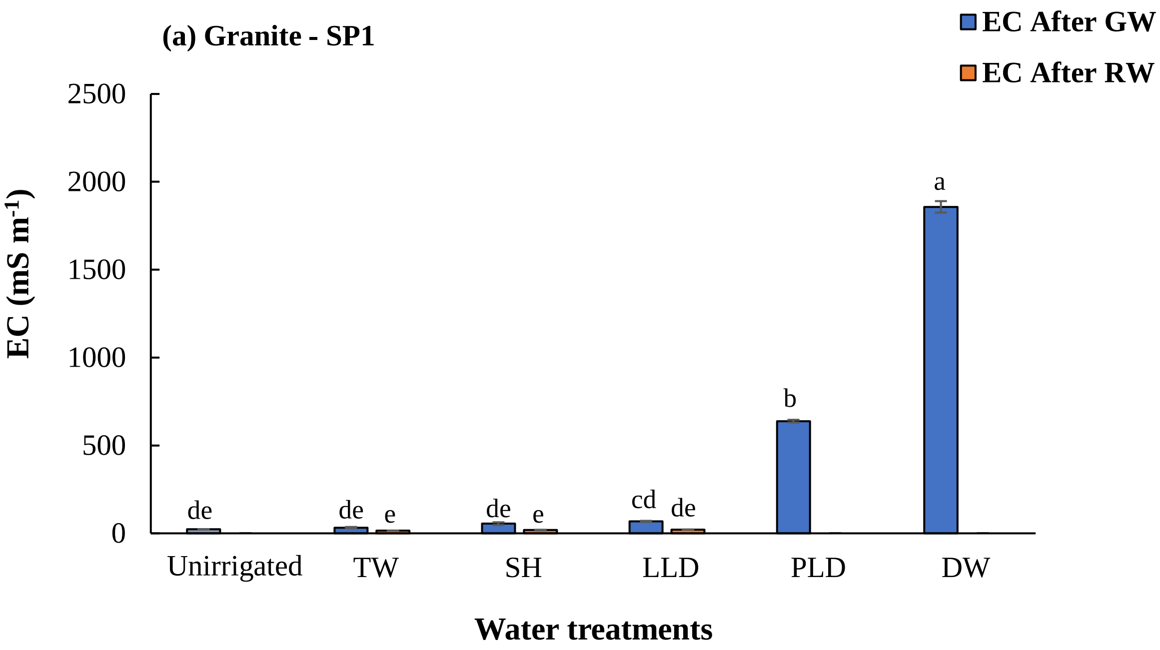


Figure 6.1: The average pH values of the unirrigated soil (control) and soil irrigated with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) after greywater irrigation and rainwater leaching experiment, (**a)** Granite- SP1 and (**b)** Chromic-BD1. GW = greywater, RW = rainwater. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05. Error bars indicates the standard error.



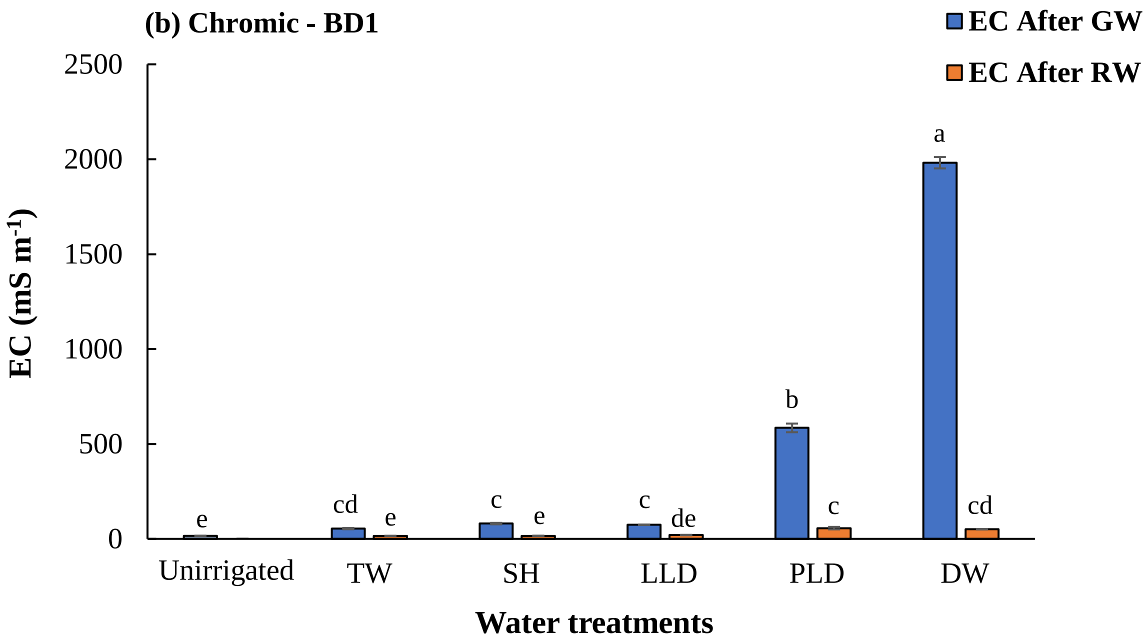


Figure 6.2: The mean EC values of unirrigated soil (control) and soil irrigated with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) after greywater irrigation and rainwater leaching experiment, (**a)** Granite- SP1 and (**b)** Chromic-BD1. GW = greywater, RW = rainwater. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05. Error bars indicate standard error.

6.4.1.1.2 Exchangeable cations (Ca, Mg, Na and K), acidity, effective cation exchange capacity (ECEC) and exchangeable sodium percentage (ESP)

The exchangeable cations and acidity, effective cation exchange capacity (ECEC) and exchangeable sodium percentage (ESP) of the unirrigated soil and soils repetitively irrigated with tap water and four greywater streams are presented Table 6.3 below. Application of PLD greywater significantly reduced the exchangeable K content in the granite (SP1) soil while in the chromic (BD1) soil the K content was significantly reduced by repeated application of all the water treatments (i.e., TW, SH, LLD, PLD and DW) when compared to the unirrigated soil (control). Irrigating with sodium (Na) rich PLD and DW greywater streams (see **Table 3.5**) significantly increased the Na content as well as the ESP of both soil types (granite and chromic) compared to the unirrigated soil, TW and other greywater streams (*i.e.*, SH and LLD). The Na content and ESP in the PLD and DW greywater irrigated granite soil were not significantly different from each other, however chromic PLD greywater irrigated soil had significantly the highest Na and ESP values compared to DW greywater irrigated soils. Moreover, continuously irrigating with TW, SH, LLD and PLD water treatments significantly increased the exchangeable Ca content in the granite soil when compared to the unirrigated soil while a significant reduction was observed due to DW greywater application. In chromic soil only the application of TW, SH and LLD increased Ca while that of DW greywater streams significantly reduced when compared to the unirrigated soil. This was mainly influenced by the Na content and ESP (significant correlations; $r = -0.71$ and -0.75, $p<0.05$) on the chromic soil. The Ca content of the PLD greywater irrigated chromic soil was not statistically different from the unirrigated soil. Exchangeable Mg content was reduced by TW, PLD and DW water application in the granite while on the chromic soil all water treatments caused a significant Mg decrease. The exchangeable acidity of PLD and DW irrigated soil significantly increased in the granite compared to unirrigated soil, TW and other greywater streams while a significant increase in chromic soil was only observed on PLD greywater irrigated soils. Furthermore, as mentioned in section 6.3.4.1.2, the exchangeable cations were corrected with the water-soluble cations, so that the ECEC is a true reflection of cation exchange capacity. Therefore, results from this study showed that both the application of TW, SH, PLD and DW greywater significantly elevated the ECEC in the granite soil, while in the chromic soil significant increases were observed in SH, LLD and PLD when compared to the unirrigated soil. The ECEC of the PLD greywater irrigated soils was significantly the highest in both soils. A similar trend was observed by Mohamed *et al.* (2018). A possible reason could be increased PLD greywater soil pH (see **Figure 6.1a and b**), which leads to deprotonation of reactions on soil mineral edges and organic matter.

Table 6.3: Exchangeable bases, acidity, ECEC and ESP of two soil types (*i.e.*, granite- SP1 and chromic- BD1), (a) after the repeated application of tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) and (b) after leaching greywater-treated soil with rainwater.

				a) After greywater application					**b) After rainwater leaching**				
Soil types	**Soil parameters**		**Unirrigated**	**TW**	**SH**	**LLD**	**PLD**	**DW**	**TW**	**SH**	**LLD**	**PLD**	**DW**
Granite (SP1)	K		0.75a	0.55ab	0.40bc	0.50ab	0.10c	0.70ab	0.62ab	0.60ab	0.61ab	-	-
	Na		0.45b	0.42b	0.37b	0.94b	11.92a	11.37a	0.67b	0.60b	0.62b	-	-
	Ca		14.11c	20.35a	19.96a	17.24b	18.18ab	9.24d	13.14c	14.38c	12.78c	-	-
	Mg	cmolc kg^{-1}	2.25a	1.97bc	2.03abc	2.08ab	0.18e	1.26d	1.90c	1.97bc	1.96bc	-	-
	Exch. acidity		0.01c	0.01c	0.00c	0.02c	0.09b	0.17a	0.05c	0.03c	0.03c	-	-
	ECEC		17.57cd	23.30b	22.76b	20.76bc	30.47a	22.82b	16.38d	17.58cd	15.99d	-	-
	ESP (%)		2.54b	1.79b	1.61b	4.53b	38.47a	45.49a	4.08b	3.42b	3.82b	-	-
Chromic (BD1)	K		0.99a	0.42e	0.52cde	0.44de	0.44de	0.62bcde	0.85ab	0.66bcd	0.72bc	0.64bcde	0.75abc
	Na		0.26c	0.06c	0.16c	0.31c	21.91a	5.92b	0.75c	0.53c	0.66c	2.55c	2.69bc
	Ca		19.96b	26.37a	29.14a	31.42a	18.43bc	14.48c	18.81bc	18.93bc	18.13bc	15.07bc	15.20bc
	Mg	cmolc kg^{-1}	2.31a	1.56d	1.80b	1.77bc	1.29e	1.81b	1.87b	1.90b	1.86b	1.24e	1.57cd
	Exch. acidity		0.12bc	0.05d	0.06d	0.07cd	0.15b	0.08cd	0.07cd	0.07cd	0.03d	0.03d	0.23a
	ECEC		23.63cd	28.44bc	31.67b	34.01b	42.21a	22.98cd	22.36cd	22.09cd	21.40d	19.53d	20.43d
	ESP (%)		1.08d	0.20d	0.52d	0.92d	51.85a	24.53b	3.27d	2.39d	3.02d	13.07c	12.97c

6.4.1.1.3 Soil salinity and sodicity classification after repeated greywater application

This section focusses on classifying the soils affected by the salts induced by the repeatedly irrigated with TW and the four greywater streams. Based on the pH, EC and ESP results presented in the previous sections, soil conditions induced by the alkalinity (high pH), salinity (high EC) and sodicity (high ESP) of irrigation water are presented in table 6.4 below. However, it is important to note that the thresholds for the electrical conductivity (EC) were established under the use of water-saturated soil paste extraction method. In this study, the EC was measured in 1:2.5 soil-water mixture. Therefore, the EC values were converted to approximate the EC of saturated paste (EC_e). This conversion was implemented using a regression equation (with correlation coefficient (r) of 0.99) stipulated in a study conducted by Sonmez et al. (2008) which was based on evaluating different EC soil-water extraction ratio relationships to the saturated paste EC. According to general soil texture classes, both the granite and chromic soils are loamy soils (see **Table 4.1**). Therefore, the following linear loamy soil's equation was for the EC conversion (Sonmez *et al.*, 2008).

$$EC_e = 3.84EC_{(1:2.5)} + 0.35 \qquad \text{Eq. 6.3}$$

The pH, converted EC and ESP results are shown in table 6.5 below. The pH, EC and ESP results revealed that, unirrigated soils, and soils repetitively irrigated with TW, SH, and LLD water treatments had normal soil conditions (both the granite and chromic soil types) (refer to **Table 6.4**). Conversely, soil irrigated with PLD greywater (granite and chromic) show both characteristics of a saline and sodic soils (see **Table 6.4**) with pH > 8.5, EC > 400 mS m^{-1} and ESP >15 (**Table 6.5**). This means that PLD greywater added alkalinity, salinity and sodicity to the soils. Thus, resulting in alkaline saline-sodic soils. This yielded both black and white alkali soil. Moreover, soils irrigated with dishwasher (both granite and chromic) also show characteristics of both saline and sodic soils. However, in contrast to the PLD greywater results, these soils had a pH < 8.5 while the EC and ESP were greater than 400 mS m^{-1} and 15% (**Table 6.5**). This means that DW greywater added salinity and sodicity to the soils. These soils were then classified as saline-sodic soil (**Table 6.4**).

Table 6.4: Legend of soil conditions induced by alkalinity, salinity and sodicity of irrigation water (Adapted from Halvin *et al.*, 1999; Brady and Weil, 2017).

Soil conditions	**pH**	**EC (mS m^{-1})**	**ESP (%)**
Normal	<8.5	< 400	<15
Saline	<8.5	> 400	<15
Sodic	>8.5	< 400	>15
Saline-sodic	<8.5	> 400	>15

Table 6.5: The pH, converted EC and ESP of the two representative soil types (granite- SP1 and chromic- BD1) after the repeated greywater application.

			Water treatments				
Soil Types	**Parameters**	**Unirrigated**	**Tap water**	**Shower**	**LLD**	**PLD**	**DW**
Granite SP1	**pH**	8.0	8.1	8.0	8.1	**10.0**	8.1
	EC (mS m^{-1})	90.2	125.5	211.9	261.5	**2450.3**	**7134.7**
	ESP (%)	2.5	1.7	1.6	4.5	**38.5**	**45.6**
Chromic BD1	**pH**	7.3	7.4	7.5	7.6	**9.3**	7.6
	EC (mS m^{-1})	61.0	207.7	307.6	284.5	**2242.9**	**7607.4**
	ESP (%)	1.1	0.2	0.5	0.9	**51.8**	**24.6**

6.4.1.1.4 Carbon, Nitrogen and Carbon: Nitrogen Ratio (C:N ratio)

The carbon content of both soil types (granite and chromic) was significantly reduced by the continuous application of the water treatments (**Table 6.6a**). These reductions could be related to the decomposition of organic material by the soil microbes over the 10 weeks period. On the granite soil the % C decrease ranged from 8.9-14.1% while in the chromic soil it varied from 7.6-14.7%. The nitrogen content of both soils (granite and chromic) was significantly reduced by TW and PLD greywater application. The C:N ratios also decreased due to the water application irrespective of source.

Table 6.6: The carbon (C), nitrogen (N) and carbon to nitrogen ratios (C: N) of two soil types (a) after the repeated greywater irrigation period and (b) after leaching greywater-treated soil with rainwater.

			a) After greywater application					**b) After rainwater leaching**				
Soil types	**Soil parameters**	**Unirrigated**	**TW**	**SH**	**LLD**	**PLD**	**DW**	**TW**	**SH**	**LLD**	**PLD**	**DW**
Granite (SP1)	**N (%)**	0.147a	0.137b	0.143ab	0.140ab	0.137bc	0.142ab	0.128c	0.128c	0.138b	-	-
	C (%)	2.379a	2.060bc	2.056bc	2.044bc	2.056bc	2.168b	2.007bc	1.942c	2.040bc	-	-
	C: N	16.137a	15.016bcd	14.389d	14.641cd	15.025bcd	15.264bc	15.729ab	15.18bcd	14.783cd	-	-
Chromic (BD1)	**N (%)**	0.286a	0.270bcd	0.281ab	0.276abc	0.255e	0.275abc	0.258de	0.263cde	0.268bcde	0.226f	0.258de
	C (%)	4.377a	3.924bc	3.995b	4.008b	3.734c	4.045b	3.841bc	3.870bc	3.955bc	3.419d	3.981b
	C: N	15.315a	14.516d	14.198e	14.537d	14.627cd	14.732cd	14.914bc	14.699cd	14.781cd	15.153ab	15.421a

6.4.1.1.5 Plant available P content

The granite (SP1) soil had a lower starting plant available phosphorus (P) content of 53 mg kg^{-1} compared to the chromic (BD1) soil which contained 153 mg kg^{-1} (**Figures 6.3a and b**). There was a significant increase in plant available P in the SP1 soil in the TW (+44%), PLD (+50%) and DW (+162%) treatments compared to unirrigated soil, while for the chromic soil a significant increase was only observed in the PLD (+80%) and DW (+110%) treatments (**Figure 6.3a and b**). The P increments were partially attributed to the P contained in these greywaters (see **Table 3.5)**, while increases from TW application could be related to mineralisation of organic P that was promoted by the wet soil under favourable temperatures. Similar to the granite soil results, Negahban-Azar *et al.* (2013) observed no significant differences in P contents between sandy loam soils irrigated with surfactant rich greywater and potable water. Additionally, Mohamed *et al.* (2013) and Turner *et al.* (2013) also observed a significant soil P increase when irrigating with combined greywater sources. The plant available P of DW greywater irrigated soils were significantly higher than other water treatments due to high P content in DW greywater (**Table 3.5**). The chromic soil showed a larger P increment due to PLD (+79.7 mg kg^{-1}) and DW (+168.8 mg kg^{-1}) treatments compared to the granite treated with PLD (+26.7 mg kg^{-1}) and DW (+85.1 mg kg^{-1}) likely because of the lower soil pH values of chromic (pH 9.3 and 7.6) compared to granite (pH 10.0 and 8.1) (**Table 6.4**). The solubility of mineral P is greatest between pH 5 to 8 due to greatest solubility of Fe, Al and Ca phosphates (Brady and Weil, 2017). Under alkaline conditions, the phosphate ions combine with calcium or calcium carbonate to form insoluble Ca-phosphate compounds which precipitate out of soil solution (Halvin *et al.*, 1999; Tan, 2010). This fixes and reduces solubility the phosphorus, making it unavailable in the soil solution (Brady and Weil, 2017). Repeated application of SH and LLD greywater streams had no significant influence on the soil P content (**Figure 6.3a and b)**.

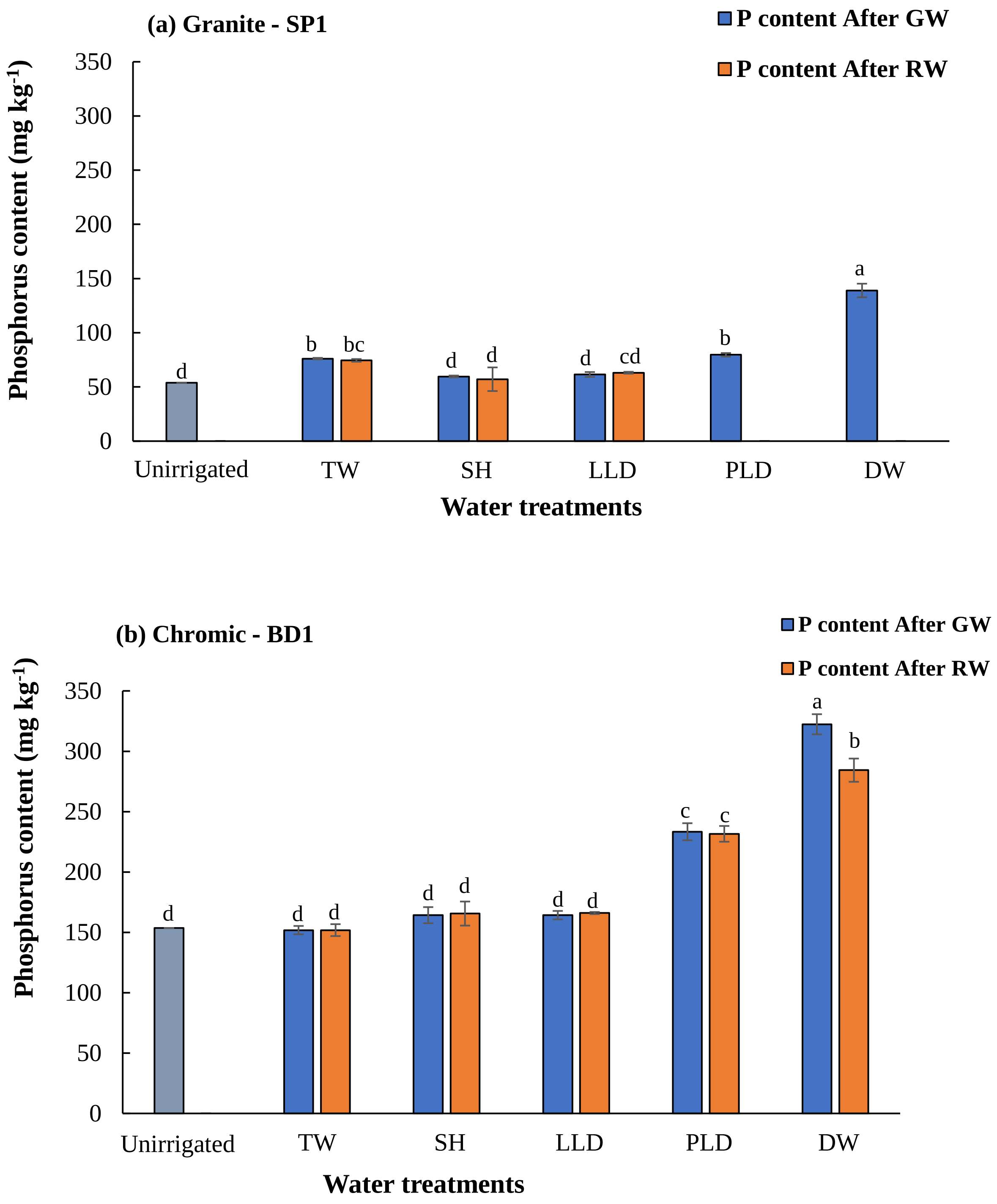


Figure 6.3: The mean Mehlich 3 P contents (mg kg^{-1}) of the control (unirrigated soil), tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) irrigated representative soil types (**a)** Granite- SP1 and (**b)** Chromic- BD1. GW = greywater, RW = rainwater. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$. Error bars indicate standard error.

6.4.1.1.6 Plant available trace metal (Cu, Fe, Zn and Mn) contents

The trace metal contents were found in very low or undetectable quantities in all the tap water and greywater solutions (**Table 3.5**). The availability of trace metals is generally low in soils with high pH (Halvin *et al.*, 1999). Results for the plant available copper (Cu), iron (Fe), zinc (Zn) and manganese (Mn) contents after the repeated greywater application are presented in table 6.7a below. All the heavy metals were in sufficient quantities. DW greywater significantly increased plant available Cu in granite soil, while the Cu content of other treatments were not significantly different from the unirrigated soil (**Table 6.7a**). Conversely, all the treatments significantly decreased Cu availability in chromic soil compared to the unirrigated soil (**Table 6.7a**). The Fe contents of the granite soil were significantly reduced by TW, SH, PLD and DW greywater compared to the unirrigated soil, while in the chromic soil a significant reduction was only observed for the TW irrigated soil. Application of TW, SH, LLD and PLD treatments significantly reduce plant available Mn in chromic soil, while a significant Mn reduction was only observed in DW granite greywater-irrigated soil. Furthermore, repeated TW application significantly increased Zn availability in granite soil while a significant increase was observed in DW greywater irrigated soil.

Table 6.7: Mehlich 3 trace metal contents of two soil types (a) after the repeated greywater irrigation period and (b) after leaching greywater-treated soil with rainwater.

			a) After greywater application					**b) After rainwater leaching**				
Soil types	**Trace metals (mg kg^{-1})**	**Unirrigated**	**TW**	**SH**	**LLD**	**PLD**	**DW**	**TW**	**SH**	**LLD**	**PLD**	**DW**
Granite (SP1)	Cu	9.17c	15.26bc	12.56c	15.71bc	16.14bc	22.99ab	22.14ab	25.91a	31.24a	-	-
	Fe	245.06a	194.46cd	204.47bcd	228.40ab	211.06bcd	186.18d	206.61bcd	188.86cd	220.92abc	-	-
	Mn	22.57a	15.20ab	16.86ab	19.25ab	21.39a	12.77b	17.16ab	20.93ab	23.35a	-	-
	Zn	67.8b	90.73a	83.53ab	79.20ab	77.30ab	83.43ab	81.21ab	79.12ab	81.84ab	-	-
Chromic (BD1)	Cu	86.08a	24.75bc	21.89c	25.08bc	27.03bc	28.46bc	33.18b	33.16b	31.37bc	34.06bc	28.15bc
	Fe	173.09cd	140.78e	153.16de	166.02cde	171.99cd	164.86cde	185.47bc	189.53bc	205.61ab	200.21ab	224.30a
	Mn	104.03ab	60.33f	70.17ef	78.25de	87.73bcd	102.77ab	81.36cde	79.97cde	93.73bcd	95.30bc	118.06a
	Zn	45.9cde	46.30cde	49.37bcd	47.67cd	52.13abc	56.00ab	43.53de	42.24de	45.73cde	39.11e	58.06a

6.4.1.2 Soil physical properties

6.4.1.2.1 Water dispersible clay (WDC) of the soil clay mass

The SP1 soil generally had higher %WDC of the soil clay mass compared to the chromic (BD1) soil (**Table 4.1**). This can be attributed to its high pH (**Table 4.2**) and the lack of Fe oxide minerals (**Table 4.2)** which makes it more susceptible to clay dispersion (Suarez *et al.*, 1984). Results from this study revealed that continuously irrigating with liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) greywater streams significantly increased %WDC of the soil clay mass compared to tap water (TW) in both the SP1 and BD1 soil types (**Figure 6.4a and b**). The %WDC of TW and SH irrigated soils were not significantly different from each other on both soils, however, in the BD1 the %WDC of SH irrigated soils was also not significantly different from the LLD soils (**Figure 6.4b)**. The %WDC of these soils was mainly influenced by the Na content and/or the sodium adsorption ratio (SAR) of the water treatments which showed significant positive correlations ($r = 0.91$, at $p < 0.05$ on both soils). TW and SH greywater had quite similar Na and SAR values (**Table 3.5**), hence the %WDC of the soil clay mass of these water treatments were not significant different from each other either. Nevertheless, application of both 370 mm powdered laundry detergent (PLD) and dishwasher (DW) greywater streams induced significantly the highest soil clay dispersion capacity compared to other water treatments (**Figure 6.4a and b**). However, it should be noted that even though the dishwasher greywater had significantly lower SAR (50.5) compared to the PLD greywater (147) (**Table 3.5**), the %WDC of these water treatments were not significantly different from each other. A possible reason could be the fact that both PLD and DW greywater streams had relatively high pH values of 10.67 and 9.51 (**Table 6.1**), which resulted in increasing the net negative charge of the clays, and consequently, strongly elevating clay dispersion (Chorom *et al.*, 1994). Comparable results were also observed in a study conducted by Suarez *et al.* (1984) where high pH was the main influencer of clay dispersion when using solutions of the same SAR. Granite PLD and DW greywater irrigated soils dispersed an average of 95.5% and 88.2% of the soil total clay while on chromic soil, PLD and DW dispersed on average 36.7% and 34.3% of the soil clay. Additionally, water dispersible clay of the LLD greywater irrigated chromic soils were not significantly different to that of shower greywater (**Figure 6.4b**) even though the LLD greywater had higher Na content and SAR compared to the SH greywater (**Table 3.5**). This could be related to greywaters having similar pH and the ability of the chromic soil to resist clay dispersion compared to the granite, thus more stability.

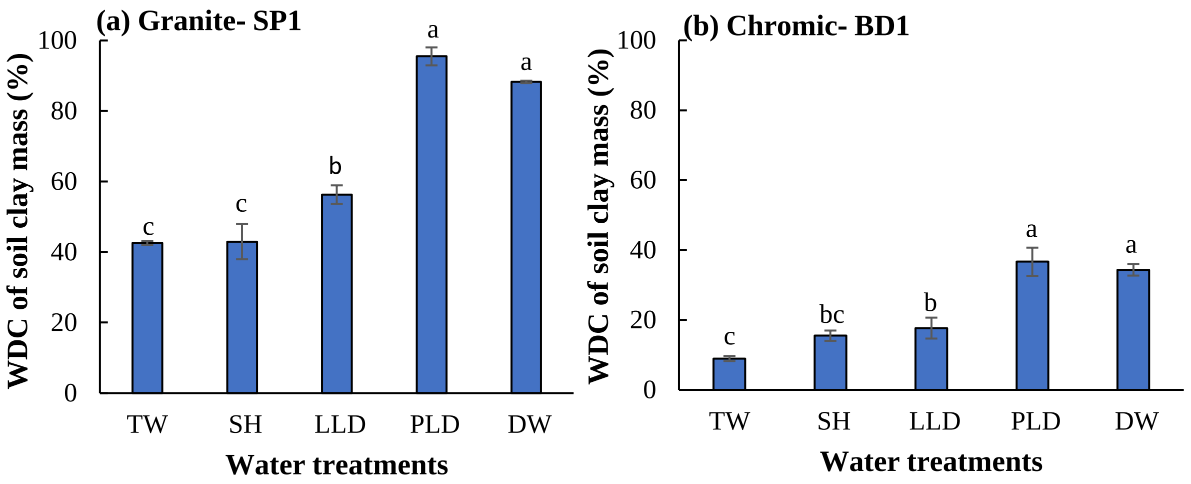


Figure 6.4: The average percentage of the water dispersible clay of the soil clay mass of two representative soil types (**a**) Granite- SP1 and (**b**) Chromic- BD1 that were continuously irrigated with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW). Statistically significant differences at p<0.05 between the water treatments are indicated by the letter of significances. Standard error indicated by error bars.

6.4.1.1.2 Saturated hydraulic conductivity (K_{sat})

The soil saturated hydraulic conductivity (K_{sat}) of tap water and four greywater streams follow a similar pattern on both the SP1 and BD1 soil types (**Figure 6.5a and b**). This basically means that the water treatments have the same effect on both soils, however, in different intensities due the varying soil properties (**Table 4.1**). When comparing the greywater streams to tap water (TW), repeated application of LLD, PLD and DW greywater streams significantly decreased water percolation on granite soil as indicated by significant K_{sat} reduction, while shower greywater's K_{sat} was not significantly different from TW (**Figures 6.5a**). On the chromic soil, all the greywater streams significantly reduced the soil K_{sat} compared to tap water (**Figures 6.5b**). These K_{sat} declines were mainly influenced by the soil %WDC and the water treatment's sodium content/SAR, confirmed by significant negative correlations (r = -0.86 and -0.91 for granite and r = -0.88 and -0.89 for chromic, at p <0.05). Water infiltration of both PLD and DW greywater irrigated soils were significantly the lowest (**Figure 6.5a and b**) due to high %WDC (**Figure 6.4a and b**). The percentage decrease in infiltration rate of the SP1 PLD and DW treatments were 99.9 and 100%, respectively, while the PLD and DW treatments on chromic soil were decreased by 85.0 and 93.3%, respectively. (**Figure 6.6**). No water could pass through the DW granite irrigated soil on all the replicates, therefore the soil K_{sat} for this treatment (SP1 DW) was quantified to be zero and water was observed floating at the surface.

In this soil all the soil pores were completely sealed by the dispersed clay, thus inhibiting water movement. Apart from clay dispersion, salt crystals which might have resulted from partially leaching or the downward movement of salts were also observed blocking holes at bottom of the soil column tubes (**Figure 6.7**). Thus, also attributed in limiting water movement and leaching. Similar to DW greywater, the K_{sat} of granite PLD irrigated soils on one replicate was zero due to pore sealing while only small water volumes (<5 ml) could passed through on other two replicates. However, after 8 hours of irrigation all the pore spaces were completely blocked, thus no passage of water. Hence very low K_{sat} were also observed. Additionally, since clay dispersion disaggregated the soil particles, the structure of the granite PLD and DW greywater irrigated soils were completely destroyed due to maximal clay dispersion, thus, not allowing the passage of water. Consequently, no further soil or leachate quality analysis were done on both granite PLD and DW soils. In the chromic soils, even though PLD and DW greywater irrigation significantly reduced water infiltration, these soils were still leachable or could allow the passage of water. This show their resistance to degradation by PLD and DW greywater compared to granite soil.

Additionally, SH and LLD treatments reduced the granite infiltration by 24.7 and 48.1%, respectively, while the chromic soil infiltration was reduced by 41.7 and 53.8%, respectively. The use of low salinity water *i.e.*, in this case rainwater (**Table 6.2**) to irrigate saline sodic soils also reduces soil permeability due to salt removal which promotes dispersion of clay (Ayers and Westcot, 2007).

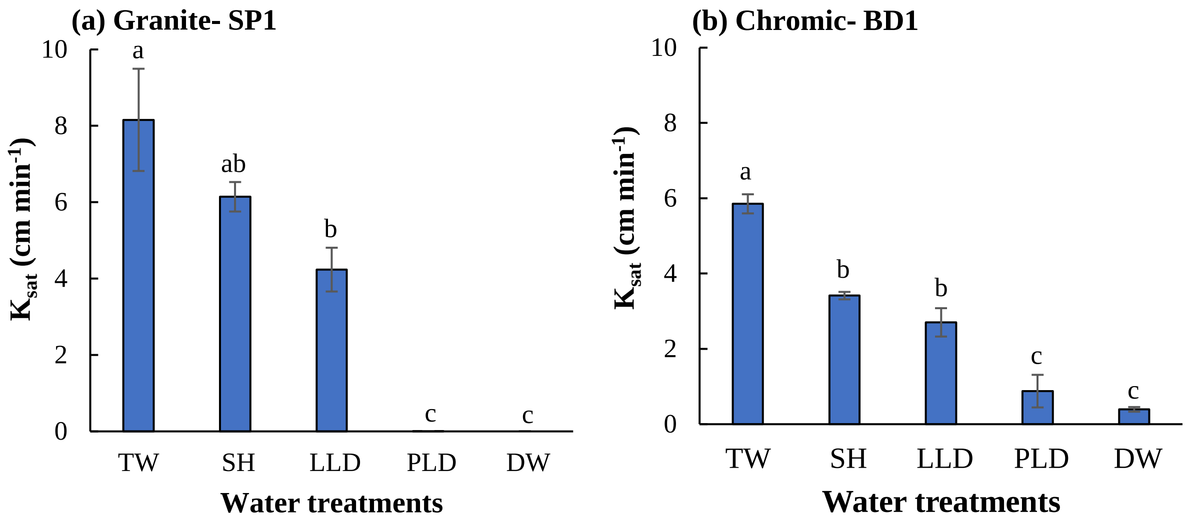


Figure 6.5: The average saturated hydraulic conductivity (K_{sat}) of two representative soils (**a)** Granite-SP1 and (**b) Chromic-** BD1 after the repeated application of tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher. (DW). Letters of significances show statistically significant differences between the water treatments at $p<0.05$. standard error indicated by the error bars.

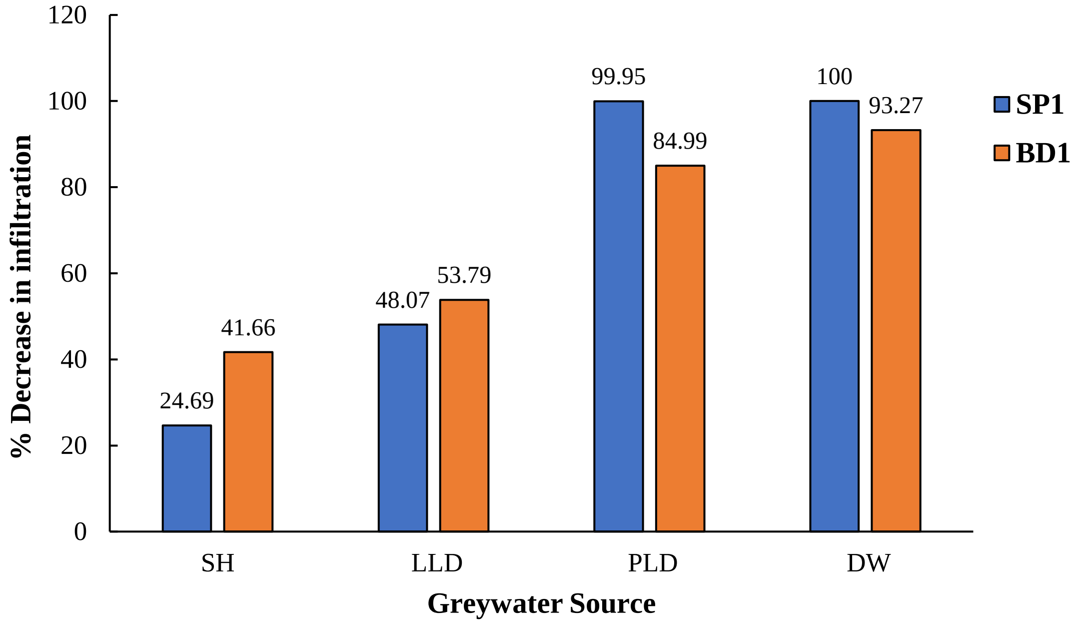


Figure 6.6: The percentages decrease in granite (SP1) and chromic (BD1) soil infiltration rate due to repetitive application of tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) greywater streams compared to tap water (TW).

Figure 6.7: The bottom of the granite (SP1) dishwasher greywater irrigated soil when leached with rainwater.

6.4.1.2.3 Surface changes

Apart from the change in water dispersible clay of soils (%WDC of the soil clay mass) and the soil saturated hydraulic conductivity (K_{sat}) several surface changes in the soils were also physical observed.

6.4.1.2.3.1 Black alkali and salt accumulated soils

Black surface layers were observed on both the granite and chromic soils due to continuous irrigation with powdered laundry detergent (PLD) greywater. As discussed in the previous chapter (**section 5.4.2.2.2**) that application of PLD greywater disperses organic matter and makes it more soluble due to its high pH, when these soils were subjected to warm incubation temperatures (30 ^{o}C), the dissolved organic matter tend to move upwards with water by capillary rise and evaporates at the soil surface which then result in black soil surface colours (see **Figure 6.8**). Therefore, leading to the development of black alkali soils (Brady and Weil, 2017). Furthermore, as discussed in the section 6.4.1.1.1, PLD greywater irrigated soils had high salt content and therefore underneath the black layer of dried of organic matter, white surfaces were observed which showed deposition of these salts (Halvin *et al.*, 1999) (**Figure 6.8**). White surface layers were also observed in dry dishwasher irrigated soils which show salt accumulation at the surface and thus referred as white alkali in saline soils (Brady and Weil, 2017). It should be noted that only small quantities of salt accumulation could be observed in shower and liquid laundry detergent (LLD) greywater irrigated soils especially in the chromic soil. No signs of salt accumulation were observed on TW irrigated soils **(Figure 6.8**). Additionally, it is important to note that surface crusts were observed for SH, PLD and DW irrigated soils (circled in red; **Figure 6.8**).

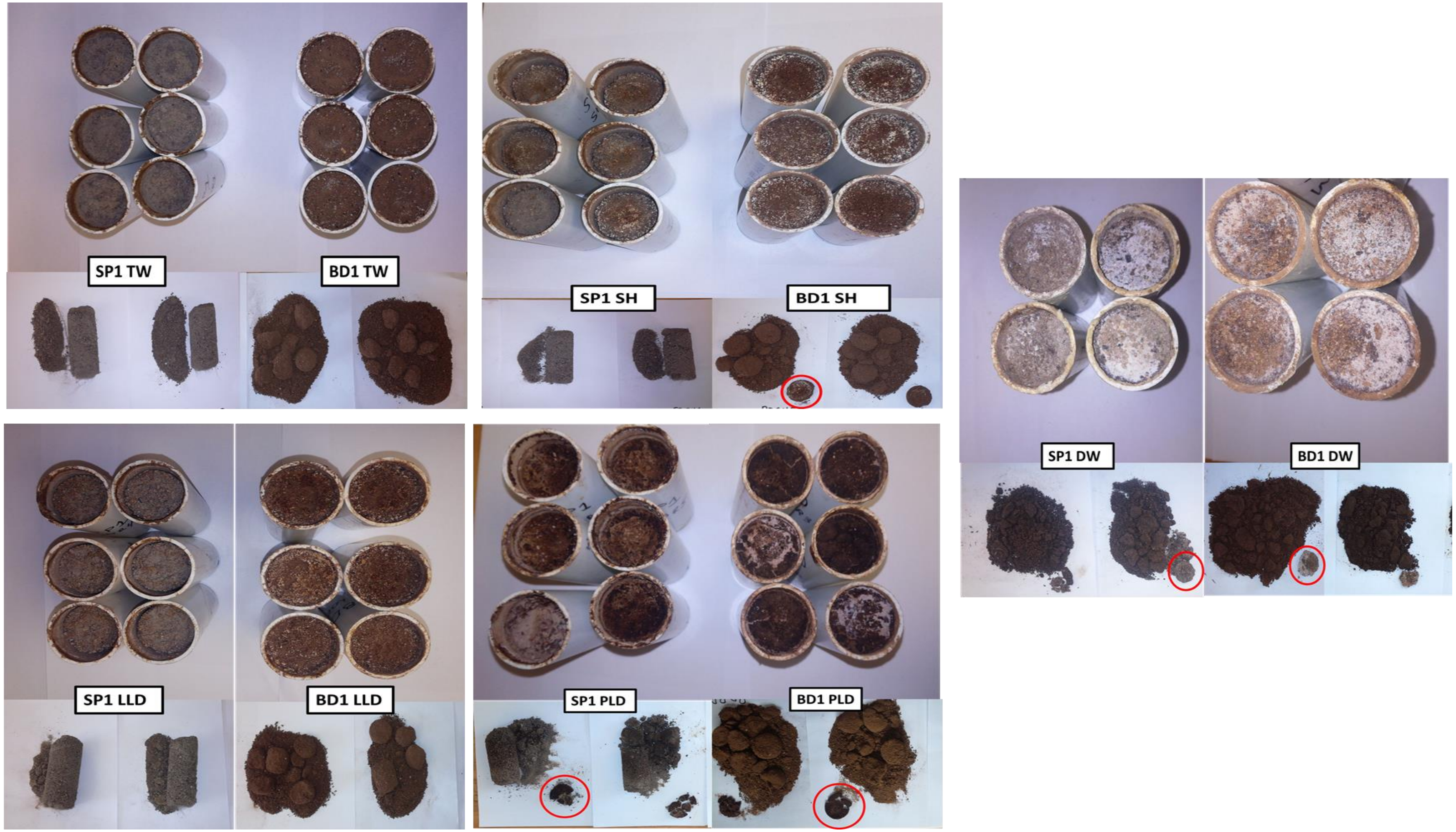


Figure 6.8: Visual display of dry granite (SP1) and chromic (BD1) soil samples after the summer irrigation period i.e. after 370 mm application of tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW). The red circles show surface crust layers.

6.4.1.2.3.2 Hydrophobicity

The water droplet penetration time (WDPT) results were interpreted using the WPDT classes stipulated in Table 6.8. Results revealed that soils repetitively irrigated with TW, LLD, PLD and DW greywater streams showed no signs of hydrophobicity on undisturbed soil samples while shower (SH) greywater irrigated soils developed a hydrophobic layer (**Table 6.9**). The hydrophobic nature of these soils could be related to the formation of the hard crust at the top of the soil column as shown in Figure 6.8. This hard layer might be a protection layer created by fats and oils resulting from the soaps and hair products used in shower greywater (**Table 6.9**). For example, in solid soaps, fats and oils are added to give the soap hardness and prevent them from dissolving easily when left in water, thus helping them last long while other shower oil products act as moisturizers protecting the skin from water loss. Therefore, these might function in the same manner when added to the soil, thus leading to hydrophobic soils. The granite shower greywater irrigated soil samples were categorised as being strongly hydrophobic whereas the chromic SH soils were slightly hydrophobic (**Table 6.9**). Hydrophobicity studies conducted on sand and loam soils show that application of surfactant-rich laundry greywater induced soil-water repellence (Travis *et al.*, 2010; Maimon *et al.*, 2017).

All the disturbed (gently crushed and homogenized) soil samples were not hydrophobic, even the shower greywater irrigated soil samples (**Table 6.9**). This could be related to the fact that disturbing and repacking the SH greywater irrigated soils in the soil column tubes mixed them thoroughly, thus diluting them. Moreover, from both undisturbed and disturbed soil sample hydrophobicity results, a conclusion can be drawn that repetitive application of TW, LLD, PLD and DW did not cause hydrophobicity of soils while shower greywater can lead to periodic water repellence.

Table 6.8 : Allocation of the water droplet penetration time (WDPT) into different classes (Bisdom *et al.*, 1993; Dekker and Ritsema, 1996)

WDPT Time in seconds	WDPT class
< 5	Non-repellent
5-60	Slightly repellent
60-600	Strongly repellent
600-3600	Severely repellent
>3600	Extremely repellent

Table 6.9: The mean water droplet penetration time (WDPT) in seconds (mean ± standard error) of two representative soils *viz.* granite- SP1 and chromic- BD1 continuously irrigated with tap water and the greywater streams under undisturbed and disturbed soil conditions.

	UNDISTURBED		**DISTURBED**	
Water treatments	**Granite- SP1**	**Chromic- BD1**	**Granite- SP1**	**Chromic- BD1**
Tap water (TW)	0.60 (± 0.04)	0.94 (± 0.02)	0.57 (± 0.02)	0.92 (± 0.01)
Shower (SH)	70.00 (±10.41)	32.67 (± 8.69)	0.69 (± 0.06)	0.54 (± 0.03)
Liquid laundry detergent (LLD)	1.15 (± 0.08)	1.04 (± 0.07)	0.46 (± 0.02)	0.54 (± 0.02)
Powdered laundry detergent (PLD)	0.73 (± 0.14)	0.51 (± 0.01)	0.87 (± 0.11)	0.85 (± 0.06)
Dishwasher (DW)	1.41 (± 0.64)	2.13 (± 0.64)	0.85 (± 0.07)	0.81 (± 0.11)

6.4.3 Soil microbiology

Bacterial and Fungal diversity and community in the granite (SP1) soils were estimated using the Shannon and Simpson diversity Indexes as well as Species richness. The Shannon diversity Index was used to measure the abundance of bacteria and fungi in the soil community whereas Simpsons diversity Index measured the number of different species present. Individual or similar species found in these soils were estimated by Species richness.

6.4.3.1 Bacterial community

Simpson diversity Index and Species richness positively correlated significantly with the Shannon diversity (r = 0.99 and 0.93) which means that an increasing number of different or individual species will significantly increase the bacterial community. Application of all water treatments *i.e.*, tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) significantly reduced bacterial community and richness of individual species in SP1 soil (**Figure 9 and 11**). Comparing the water treatments, soil irrigated with the DW greywater had significantly the highest bacterial population compared to TW, SH and PLD, however, not significantly different from those irrigated with LLD greywater. This was influenced by amount of Ca and Zn of these soils. High nitrogen and carbon contents elevated the bacterial community (both show significant positive correlation, r = 0.65, at $p<0.05$). Generally increasing calcium and pH increases bacterial diversity (Brady and Weil, 2017). Reduced calcium and zinc contents significantly increased the bacterial community and the number of species (significant negatively correlated, r = -0.73 and -0.64, at $p<0.05$). Similar results were for Zn reported by (Hiroki, 1992)

Additionally, repeated TW, SH, LLD and PLD water irrigation also significantly reduces diversity of bacterial species in the SP1 soil as indicated by Simpson Index while no significant alteration was observed in DW greywater irrigated soils when compared to the control (**Figure 10).** Similar to the Shannon Index, the Simpson index was also significantly influenced by Ca and Zn (r = -0.77 and -0.68, at $p<0.05$). However, in addition to the Ca and Zn, population of individual species were reduced by high phosphorus, low Mg and Fe contents (correlated at $p<0.05$, r = -0.66, 0.66 and 0.59 resp.). Therefore, the DW greywater did not degrade microbes as compared to the other water treatments followed by the LLD greywater.

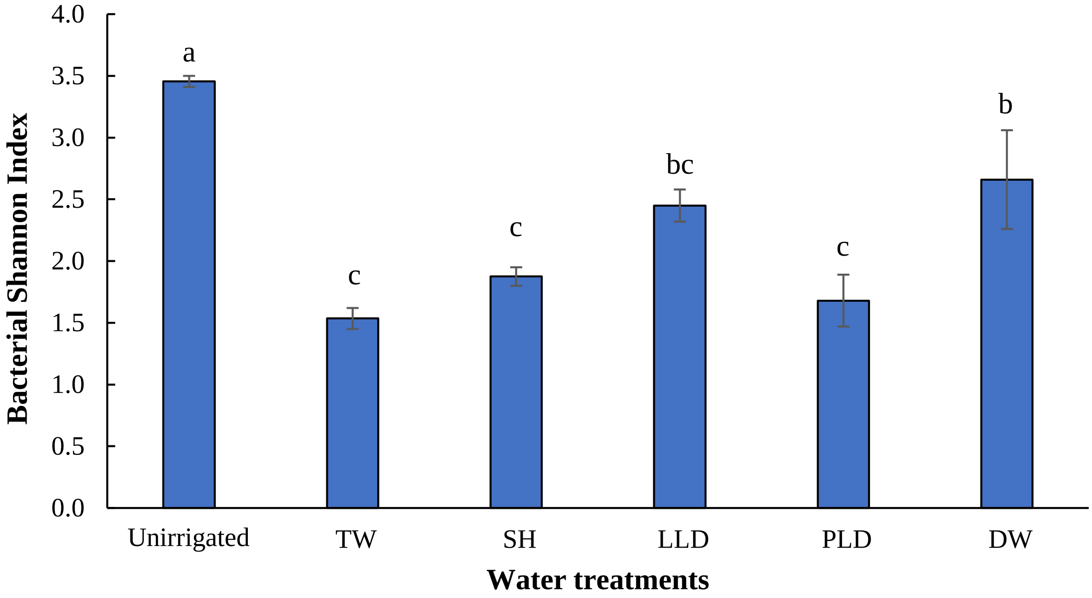


Figure 6.9: The mean Bacterial Shannon Diversity Index of the granite (SP1) soil before (control) and after irrigating with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) water treatments. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p< 0.05$. Error bars indicate standard error.

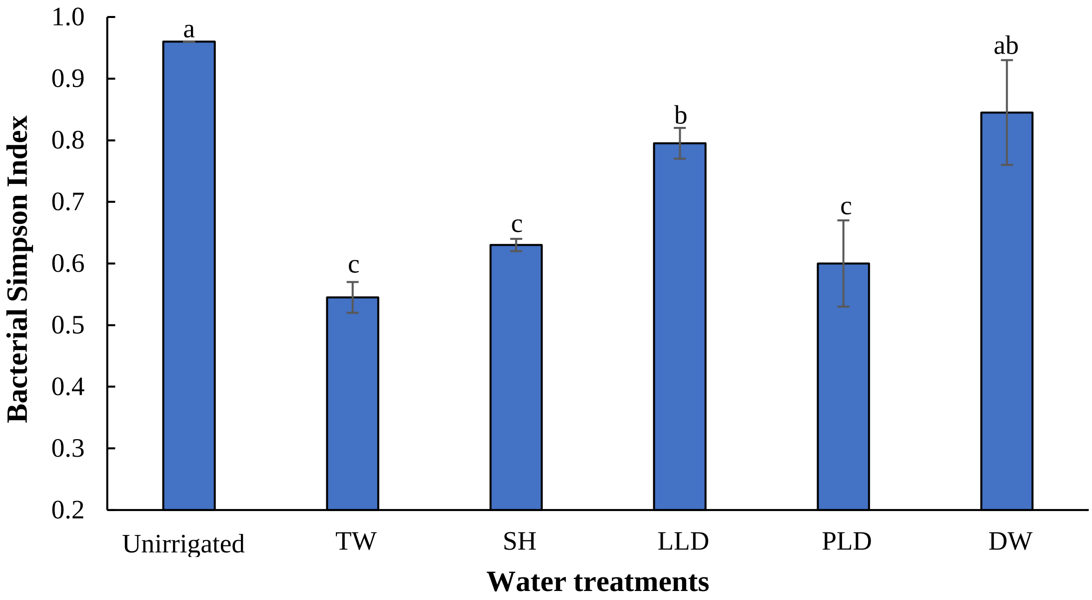


Figure 6.10: The mean Bacterial Simpson Diversity Index of the granite (SP1) soil before (control) and after irrigating with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) water treatments. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at $p < 0.05$. Error bars indicate standard error.

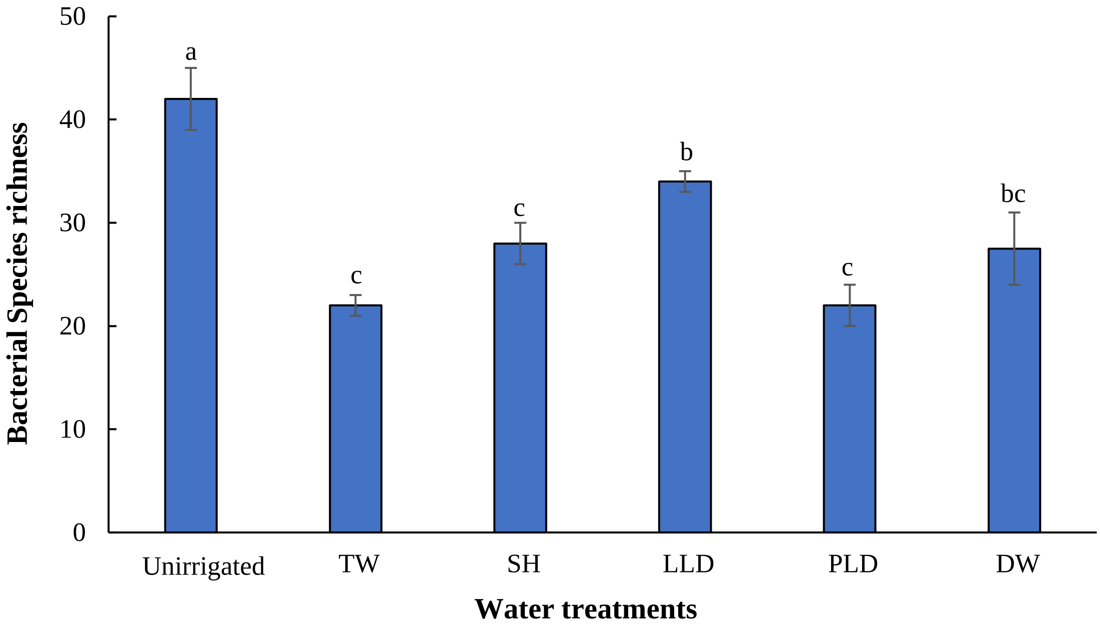


Figure 6.11: The mean Bacterial Species richness of the granite (SP1) soil before (control) and after irrigating with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) water treatments. Statistically significant differences are

illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05. Error bars indicate standard error.

6.4.1.3.2 Fungal community

There were no significant differences in the soil Fungal Shannon and Simpson diversity Index, and Richness of species in unirrigated soil and soils irrigated with the water treatments (i.e., TW, SH, LLD, PLD and DW) (**Figures 12, 13 and 14**). This could be mainly due to the fact that fungi can occur under a wide range of environments. In contrast to the bacterial community and diversity, there were no significant correlations between fungal community and diversity trace metals. These findings are similar to those reported by Hiroki, (1992). Negative significant correlations between Simpson Index and EC, Na and ESP of soil (r = -0.71, -0.71 and -0.60, p<0.05) were observed, which indicated an increase in these soil parameters will likely decrease fungal species diversity. On average a slight decrease (not significant) in the fungal species were observed in PLD soil while the DW was high as the control. However, the Na, EC and ESP of the DW soil was as high as the PLD. This decrease might have been affected by the type of salts used in these detergents.

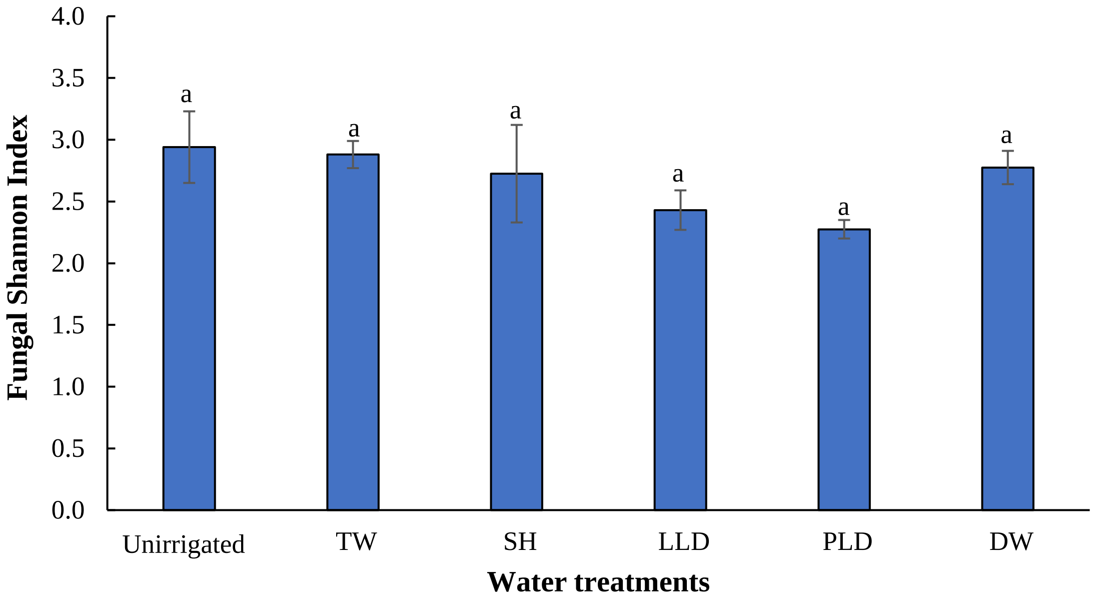


Figure 6.12: The mean Fungal Shannon Diversity Index of the granite (SP1) soil before (control) and after irrigating with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) water treatments. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05. Error bars indicate standard error.

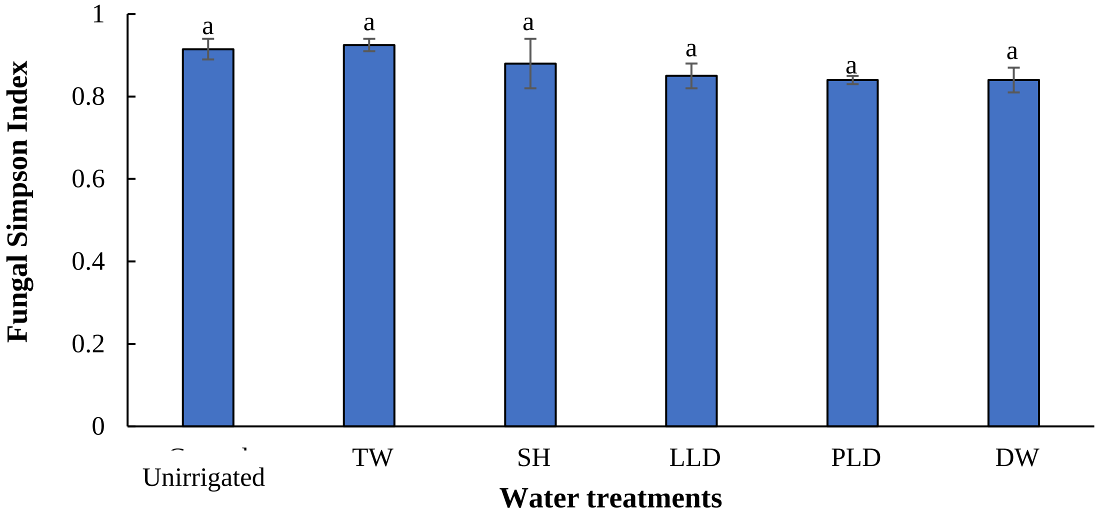


Figure 6.13: The mean Fungal Simpson Diversity Index of the granite (SP1) soil before (control) and after irrigating with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) water treatments. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05. Error bars indicate standard error.

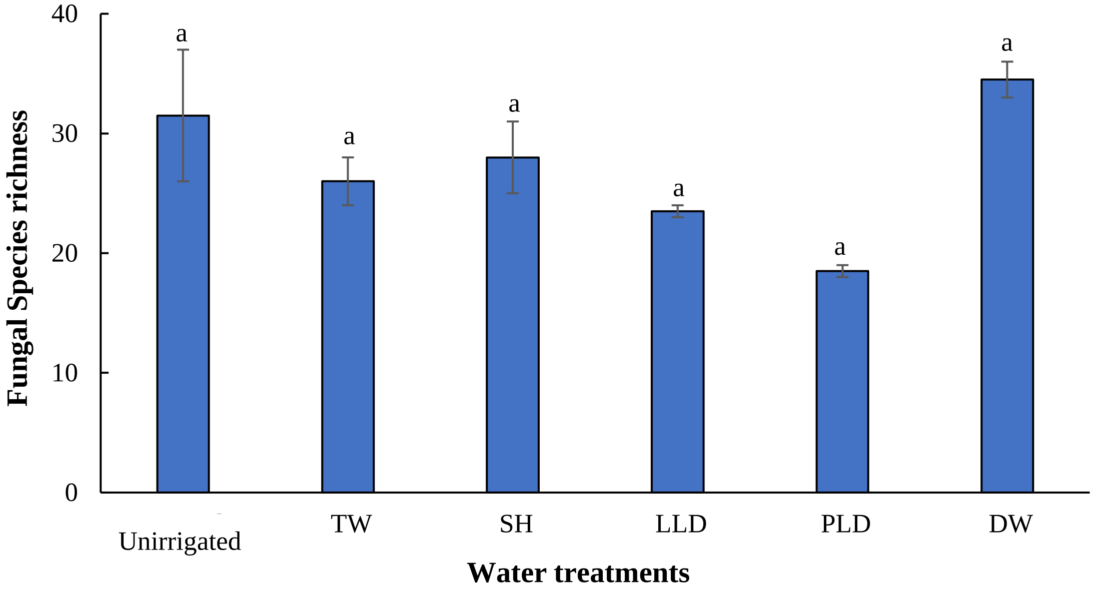


Figure 6.14: The mean Fungal Species richness of the granite (SP1) soil before (control) and after irrigating with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) water treatments. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05. Error bars indicate standard error.

6.4.2 The effect of winter rainfall leaching on soil irrigated with tap water (TW) and the four greywater streams (SH, LLD, PLD and DW)

This section presents the leachates and soil quality results of granite (SP1) and chromic (BD1) soils after leaching with rainwater. This was performed in order to examine the influence of winter rainfall on soil repeatedly irrigated with the greywater streams compared to tap water. It is important to note that the leachates and soil quality results for granite soil in this section were discussed and conclusions were only drawn for soils irrigated with TW, SH and LLD greywater since the rainwater was unable to pass through the PLD and DW greywater irrigated soils, thus no leachates were obtained.

6.4.2.1 Leachate quality

The quality of leachates was assessed to determine potential risk resulting from winter rainfall leaching of greywater irrigated soils.

6.4.2.1.1 Leachate pH and electrical conductivity (EC)

Rainwater had an acidic pH (5.76) with low electrical conductivity of 10.6 mS m^{-1} (**Table 6.2**). Rainwater leaching of soils repeatedly irrigated with TW and greywater streams increased both the pH and EC of the soil leachates (**Figures 6.15 and 6.16).** Soils irrigated with SH and LLD greywater streams had significantly higher leachate pH increases compared to TW on SP1 soils (**Figure 6.15a**). The granite soil leachate pH and EC were influenced by the pH and EC of these soils confirmed by significant negative correlations ($r = -0.59$ and -0.61, $p<0.05$). On the other hand, soil irrigated with PLD greywater contributed to highest leachate pH increase compared to other water treatments (TW, SH, LLD and DW) in BD1 soil while LLD had the lowest increase though not significantly different to that of TW and SH (**Figure 6.15b**). This can be attributed to pH and EC of soils confirmed by significant positively correlations ($r = 0.56$ and 0.68, $p<0.05$).

Additionally, the amount of salt leached in LLD greywater irrigated granite soils were higher than those leached on TW and SH greywater irrigated soils (**Figure 6.16a**). This was influenced by the pH and EC of soils confirmed by significant correlations ($r = -0.60$ and -0.58, $p<0.05$). The chromic DW soil leachate EC was significantly the highest compared to TW, SH, LLD and PLD, followed by the PLD (**Figure 6.16b**). This was also mainly due pH and EC of soils confirmed by significant positively correlations ($r = 0.68$ and 0.85, $p<0.05$). Leaching significant amounts of salts below the water table could add more salts to groundwater thus, increasing the salinity of the groundwater source.

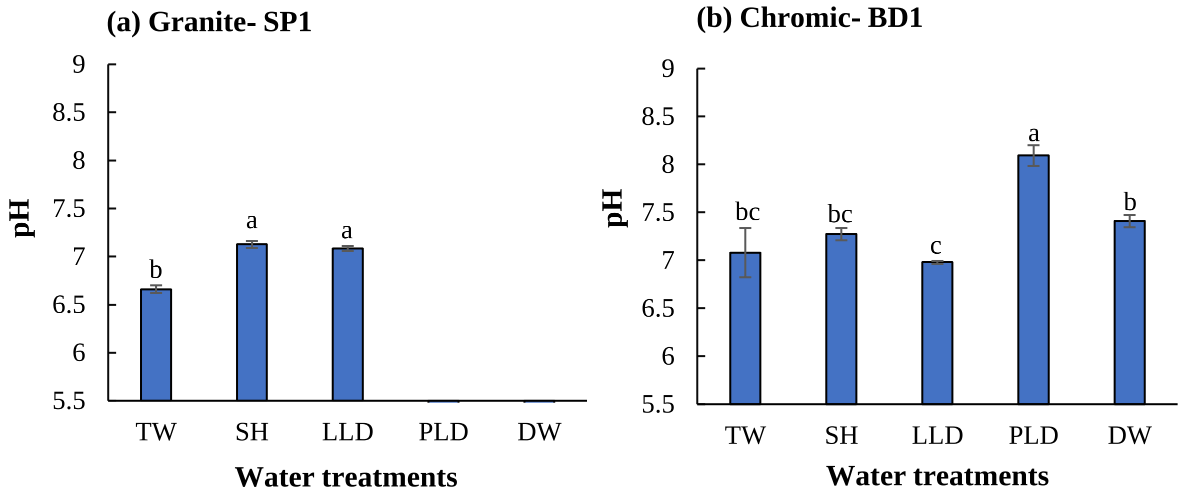


Figure 6.15: The mean soil leachate pH values of the tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) irrigated soils (**a) Granite-** SP1 and (**b)** Chromic- BD1. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05.

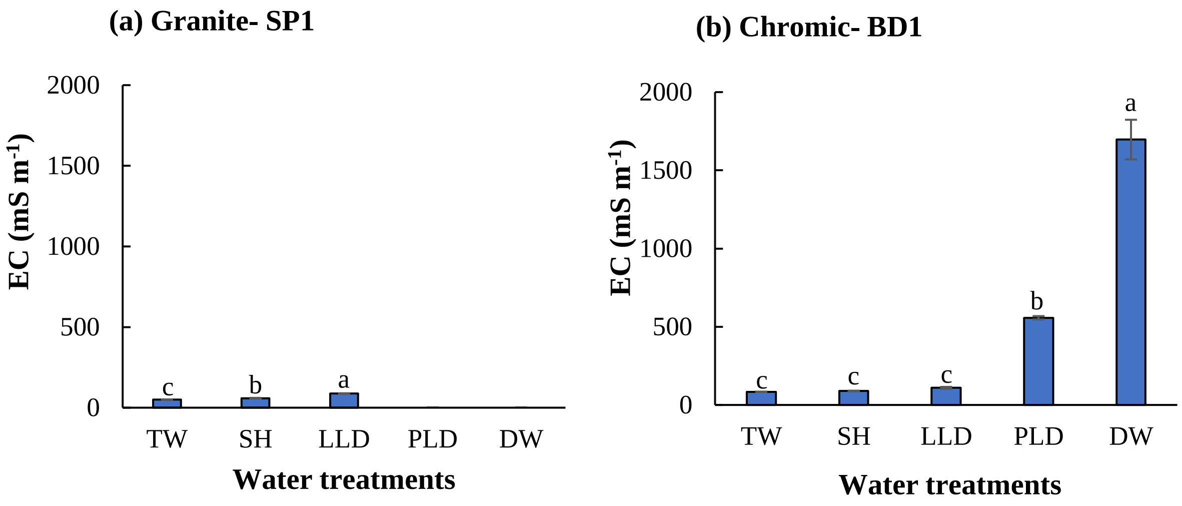


Figure 6.16: The mean soil leachate EC values of the tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) irrigated soils (**a)** Granite- SP1 and (**b)** Chromic- BD1. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05.

6.4.2.1.2 Leachate absorbance (at 350 nm)

Soil leachate absorbance of LLD on granite soils were significantly higher than the leachate absorbance of TW and SH greywater (**Figure 6.17a**). In chromic soil the amount of DOC leached by TW, SH, and LLD greywater streams were not significantly different from each

(**Figure 6.17b**). However, chromic soil continuously irrigated with PLD greywater significantly increased DOC removal followed by DW irrigated soil. The PLD results were similar to those found in chapter 5. The amount of DOC removed in DW irrigated soils was also higher than the TW, SH and LLD which is in contrast to the single application study results in the previous chapter. Thus, repeated application of both PLD and DW on the chromic soil (BD1) caused solubilisation of DOC, which was leached out with application of rainwater. Furthermore, it is also important to note that the chromic leachate absorbance values (**Figure 6.17b**) were significantly higher than the chromic group soils leachate values presented in the previous chapter (**Figure 5.4**), indicating increased organic matter dispersion with repeated GW application, even in the chromic soil. The chromic leachate absorbance significantly correlated with %WDC of the clay mass (r = 0.92, p<0.05) and K_{sat} (r = -0.88, p<0.05), indicating that organic matter dispersion in these soils increased with increasing clay dispersion, which results in lower K_{sat} values meaning longer contact time with high pH and Na-rich soil solution. Clay dispersion would also lead to disruption of bonds with organic matter leading to increased DOC dispersion and removal. These results concur with the PLD greywater results observed for alluvium soil in the previous chapter (**section 5.4.1.1.2**) that the longer the water solution stays in the soil the more organic matter will dissolve and leach from the soil (also see **Figure 5.8**).

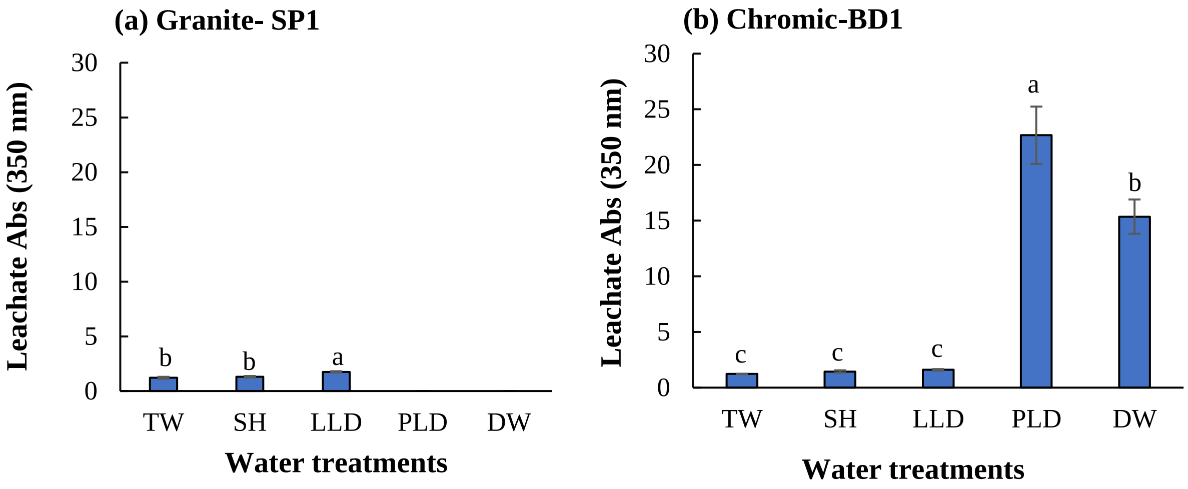


Figure 6.17: The mean soil leachate absorbance (Abs) values (at 350 nm) of the tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) irrigated soils (**a**) Granite- SP1 and (**b**) Chromic- BD1. Statistically significant differences are illustrated by letters of significance tested using Fisher's Least Significant Difference test at p< 0.05.

6.4.2.2 Soil properties

6.4.2.2.1 Soil pH and EC after rainwater application

The pH of the granite TW and LLD treatments showed no significant changes after the rainwater leaching experiment however a significant pH increase was observed on SH greywater treated soil (**Figure 6.1a**). When compared to the unirrigated granite soil the pH of both SH and LLD treatments after rainwater leaching were not significantly different. This means winter rainfall leaching will not greatly influence the pH of these soils in the short term. In contrast to this, the pH of TW irrigated soils significantly increased after rainwater leaching when compared to the unirrigated soil. A possible explanation for the increased pH could be related to the ammonification of organic N or generation of weak organic acids during decomposition (Xu *et al.*, 2006). When leaching soils with acidic rainwater, you could expect a pH decrease due to the leaching of basic cations however, significant pH increments were also observed in the chromic soil after rainwater leaching in all the water treatments especially in those irrigated with DW (**Figure 6.1b**). This could result from hydrolytic exchange phenomenon as explained by McBride (1994). The sodium ions (Na^+ ions) in the cation exchange sites or on organic functional groups are being replaced by H^+ from carbonic acid (H_2CO_3) in rainwater. However, it should be noted the displaced Na remains in the solution instead of reacting with HCO_3^- group in the solution (see **Eq. 6.4**). Thus, resulting in the formation of acidity in the soil colloid (i.e., either silicate clays or organic matter) while forming alkalinity in the soil solution, leading to an increased soil pH. Furthermore, after rainwater leaching, high pH in PLD greywater irrigated soils could also be related to the deposition of carbonates which resist from dissolving in the soil solution, thus the pH remains high. Therefore, rainwater leaching deteriorated the chromic soil pH especially in PLD and DW greywater-treated soils.

$$\text{Soil colloid-}Na^+ + H_2CO_3 \rightarrow \text{Soil colloid-}H^+ + HCO_3^- + Na^+ \text{ (Modified from McBride, 1994)} \quad \text{Eq. 6.4}$$

There was a significant change in the EC after soil continuously irrigated with TW and greywater streams were leached with rainwater. Application of rainwater significantly leached salts out of the soil as indicated by reduced electrical conductivity (EC) on both soils (**Figure 6.2a and b**) and increased soil leachate EC (**Figure 6.16a and b**). Similar observations were reported by Albalawneh *et al.* (2016). The PLD and DW greywater irrigated soils contained significant quantities of soluble salts and therefore high quantities of these salts were leached out from these soils (**Figure 6.2b**). Furthermore, it is important to note that after rainwater leaching the EC of TW, SH and LLD greywater irrigated granite and chromic soils were not significantly different from the initial soil state (unirrigated soil) which means rainwater leaching rehabilitated the soil EC especially the chromic soil (**Figure 6.2b**). However, even though reduced, the EC of both rainwater leached PLD and DW greywater irrigated chromic soils were still significantly higher than the unirrigated soil. This means that winter rainfall will not fully improve the salt content of these soil. However, further leaching might recover the salt content of these soils.

6.4.2.2.2 Exchangeable basic cations and acidity, ECEC and ESP after rainwater application

The exchangeable cations and acidity, ECEC and ESP results of greywater irrigated soils after rainwater leaching are presented in Table 6.3b. Rainwater leaching caused no significant change in the K content of the TW and LLD irrigated SP1 soils while a significantly increase was observed on SH greywater irrigated soil (**Table 6.3a and b**). However, all these treatments (TW, SH and LLD) were not significantly different from the unirrigated soil. In chromic rainwater leached soils an increase was observed in the K content, however, only K contents of TW and DW leached greywater irrigated were statistically not different from the unirrigated soil. The leaching of SH, LLD and PLD greywater irrigated soil significantly decreased the K content in BD1 soils. There was also no significant change in the Na, exchangeable acidity and ESP of TW, SH and LLD treated greywater granite soil and these parameters were not different from the control (unirrigated soil). In the chromic soil the Na of both PLD and DW greywater was significantly reduced by the rainwater and like other treatments was statistically not different from the control. This means that rain leaching improved the Na contents of these soils. Furthermore, exchangeable acidity of chromic LLD and PLD greywater treated soil was significantly reduced by the rainwater while a significant increase was observed on DW greywater treated soil. This might have resulted from the application of acid rainwater. The Ca and Mg contents were reduced by rainwater leaching on both soils (granite and chromic) when compared to after greywater irrigation. The Mg contents after rainwater leaching were significantly lower than that of unirrigated soil on both soils (granite and chromic), while the Ca contents were not statistically different from the unirrigated soil. Conversely, rainwater leaching significantly reduced the ECEC of the granite soil effective cation exchange capacity due to leaching of the exchangeable cations (Ca, Mg, Na and K), back to values similar to that of unirrigated soil. The ECEC of all the treatments in chromic soil after rainwater leaching were not statistically different from the unirrigated soil.

6.4.2.2.3 Soil salinity and sodicity classification after rainwater application

The converted EC, pH and ESP values of granite and chromic treatments after leaching with rainwater are presented in Table 6.10. Leaching with rainwater resulted in substantial improvement of the chromic PLD and DW treatments (previously classified as saline-sodic – Table 6.5) in terms of EC (< 400 mS m^{-1}) and ESP (<15%) so that they are no longer classified as such. However, as previously discussed in Section 6.4.2.2.1, the pH of these treatments remained unacceptably high due to likely accumulation of carbonates and Na, and black surface colours were still observed (**Figure 6.18**).

Table 6.10: pH, converted EC and ESP of the granite (SP1) and chromic (BD1) soils irrigated with tap water (TW), shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) after rainwater leaching.

			Water treatments				
Soil types	**Parameters**	**Unirrigated**	**Tap water**	**Shower**	**LLD**	**PLD**	**DW**
Granite (SP1)	**pH**	8.0	8.12	8.09	8.09	-	-
	EC (mS m^{-1})	90.2	61.06	71.28	83.03	-	-
	ESP (%)	2.5	4.08	3.42	3.82	-	-
Chromic (BD1)	**pH**	7.3	7.77	7.78	7.74	**9.43**	**8.81**
	EC (mS m^{-1})	61.0	60.56	61.71	78.07	217.96	195.69
	ESP (%)	1.1	3.27	2.39	3.02	13.07	12.97

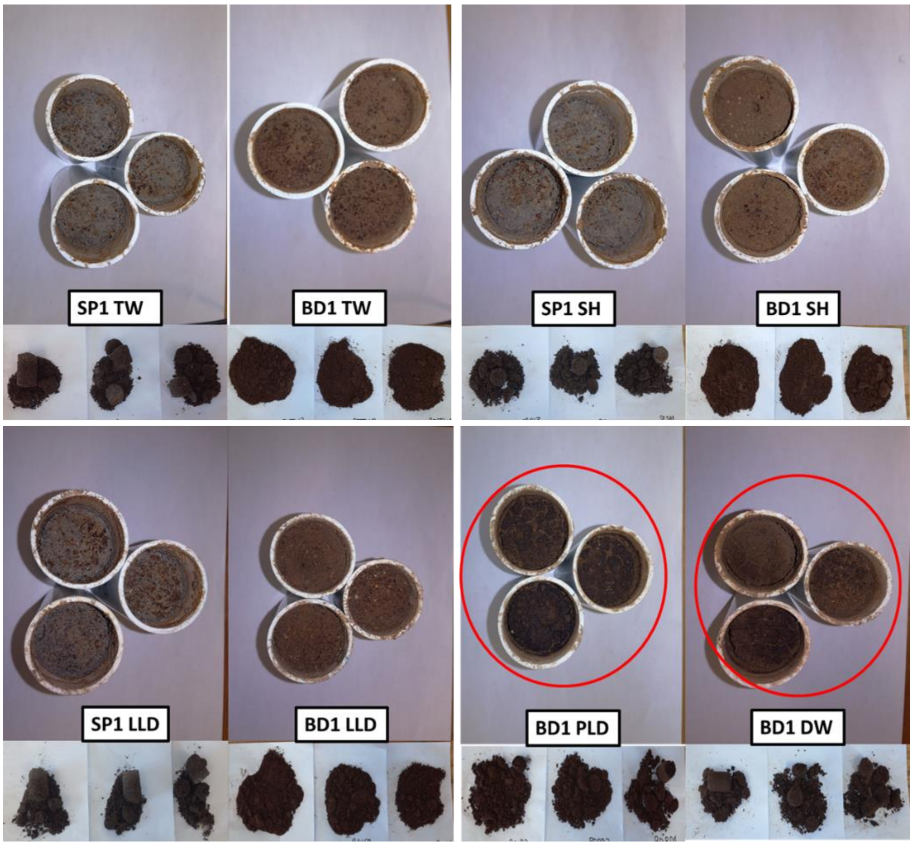


Figure 6.18: Visual display of the soil from summer greywater irrigation after leaching with rainwater; red circle show soils with black surface colours

6.4.2.2.4 Total C and N after rainwater application

The total C and N contents of TW, SH and LLD greywater irrigated SP1 and BD1 soils after rainwater leaching were significantly lower than the unirrigated soils (**Table 6.6b**). However, the carbon contents of these not statistically different from TW, SH and LLD after greywater irrigation (**Table 6.6a**), so as their C: N ratio. Leaching of PLD greywater treated soil significantly reduced the carbon content of the chromic soil by 8.4% when compared to after greywater irrigation experiment (**Table 6.6a and b**) and was also significantly lower than that of the unirrigated soil (reduced by 21.9%). These results are in agreement with the leachate absorbance results in section 6.4.2.1.2 (**Figure 6.17b**) which showed that some organic matter was leached by rainwater from these soils (PLD greywater treated soils). Therefore, PLD greywater solubilized organic matter, helping to remove it due its high pH. The carbon content of the DW was also significantly lower than unirrigated soil, however, not statistically different from that the DW soil C after repeated greywater application. Furthermore, the N content of both PLD and DW leached soils was significantly reduced while a significant increase was observed on the C:N ratio which was no statistically significant to that of the unirrigated soil.

6.4.2.2.6 Plant available P after rainwater application

There were no significant changes in the phosphorus (P) content of TW, SH and LLD greywater irrigated granite soils both before and after rainwater leaching (**Figure 6.3a**). In most soils P is immobile (Brady and Weil, 2017) due to the fact that it is readily adsorbed by the soil colloids/mineral surfaces. Therefore, the P content of rainwater leached TW treated was still significantly higher than the control. Similar observations were obtained by Negahban-Azar *et al.* (2013). Additionally, there were no significant changes in the P content TW, SH, LLD and PLD greywater treated chromic soil both before and after rainwater leaching (**Figure 6.3b**). Therefore, plant available P content of leached PLD greywater treated was still significantly higher than unirrigated soils. However, a significant decrease was observed on chromic DW greywater irrigated soils after rainwater leaching. This is due to the elevated soil pH (**Figure 6.1b**). In soil with alkaline pH (normally > 8.5), phosphates precipitate out of the soil solution by binding with calcium (Brady and Weil, 2017). This results in the P fixation making unavailable in the soil for plants (Halvin *et al.*, 1999; Tan, 2010). Additionally, high pH also results in more negative surface (Tan, 2010), which promotes repulsion of the negatively charged phosphate ion (PO_4^{3-}). This might lead to potential leaching of phosphorus. If P is leached to ground water, problems such as eutrophication (i.e. process of microbial growth due to high phosphorus in water) could be yielded.

6.4.2.2.7 Plant available trace metals after rainwater application

Trace metal contents before and after rainwater leaching is presented in Table 6.7a and b. Rainwater leaching significantly increased the Cu content in TW, SH and LLD treatments on the granite and was now statistically not significant to that of unirrigated granite soil. The Cu contents of the chromic soil after rainwater leaching, of all the water treatments (*i.e.*, TW, SH, LLD, PLD and PLD were still significantly lower than the unirrigated soil. However, there was a significant increase in the SH treatment Cu content after rainwater, when compared to SH chromic greywater irrigated soils. Contrarily, no change was observed in the Cu content of the chromic soils before and after rainwater leaching in other water treatments (*i.e.*, TW, LLD, PLD and PLD). The Fe contents of the granite TW, SH and LLD treated soils before and after rainwater leaching were not statistically different and were significantly lower than the unirrigated soil. However, in the chromic soil, rainwater leaching significantly increased the Fe content of LLD, PLD and DW treated soils and these values were significantly higher than the unirrigated soil. This means that rainwater increased the solubility of Fe in these soils. Both TW and SH leached chromic soil treatments show no significant change compared to the unirrigated soil, however, had higher values than before rainwater leaching. The Zn and Mn contents of the granite TW, SH and LLD treated soils were not significant different from before and after rainwater leaching and from the control. In chromic soils, leaching TW and SH treated soil significantly increased the Mn content, however, this was still significantly lower than the control. DW leached soil were the only ones that were statistically not significantly different to unirrigated soil. The Zn content of PLD treated soils was significantly reduced by rainwater leaching but was now not statistically different from that of unirrigated soil. There was no change observed in the Zn content of DW treated soils before and after rainwater but was still statistically higher than other treatments and that of unirrigated chromic soil.

6.5 CONCLUSIONS

Repeated application of PLD and DW greywater streams had the most harmful effect on soil properties while the effect of the other water treatments (*i.e*., TW, SH and LLD were less harmful on soils and not that different from each other and to the unirrigated soils regarding most of the measured parameters. PLD greywater added alkalinity (high pH), salinity (high EC) and sodicity (high Na or ESP) on both granite and chromic soils, thus yielding alkaline, saline sodic soils while continuous application of the DW greywater significantly increased salinity and sodicity thus leading to saline-sodic soils. Due to their high pH and SAR, PLD and DW greywater irrigation significantly increased clay dispersion, that damaged soil structure and significantly reduced the soil infiltration. The granite soil was more prone to structural degradation with the PLD and DW greywater irrigated soils having highest clay dispersion resulting in no rainwater infiltration, while the chromic PLD and DW soil infiltration rate was significantly reduced by 84.99 and 93.27%, respectively. Plant available P was increased by TW on the granite soil due to P mineralisation while PLD and DW greywaters added significant amounts of P, thus increasing plant available P on both soils. The undisturbed soil surface of SH treatment showed signs of periodic hydrophobicity (both (the granite and chromic soils) while no hydrophobic properties were observed in soils irrigated with other water treatments. Mixing of the soils removed the hydrophobicity. Application of all the water treatments did not influence the soil fungal community and diversity while reducing the soil bacterial community and diversity. Furthermore, the laundry greywater streams (LLD and PLD) did not have much influence on the trace metal content compared to TW, SH and DW which caused variability.

Soil leaching with rainwater significantly increased the pH of all the chromic soils due to either ammonification of organic N (especially in TW, SH and LLD treated soils) and Na hydrolytic exchange (in PLD and DW greywater treated soils). Leaching the soil with rainwater improve most of the soil properties such as reduction of salts, cation accumulation and ESP especially in PLD and DW greywater treated soils. Rainwater significantly decreased soil total C content of PLD greywater treated chromic soils by 21.9% compared to the unirrigated soil. Rainwater leaching did not change P and C contents. Additionally, the N content was also reduced. Solubility of trace metals i.e. Cu, Fe, Mn and Zn was increased by the application of rainwater.

Therefore, from these results, it was concluded that PLD and DW should not be applied on dispersive granite-derived soils due to the formation of completely impermeable soils, which would be extremely difficult to remediate. Rainwater leaching reduces salts while increasing alkalinity of soils especially in PLD and DW soils. The SH and LLD greywater streams had less negative effects on soil quality, however, should be carefully monitored. Further, longer term field studies would be beneficial to show these effects under fluctuating wetting and drying cycles.

CHAPTER SEVEN

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The main aim of this study was to investigate the effects of the major streams of domestic greywater on a variety of representative urban soils found in the Cape Town and Stellenbosch urban areas, and to establish which soil types are most susceptible to degradation due to greywater application.

In **Chapter Three**, greywater characteristics were assessed and showed variability within and between greywater sources depending on the type of detergents used. Based on greywater quantity and quality, four greywater streams, namely; shower (SH), liquid laundry detergent (LLD), powdered laundry detergent (PLD) and dishwasher (DW) were selected. SH and LLD had better irrigation water quality because most of their water quality parameters were within the target quality range and not significantly different from TW. However, water generated from PLD and DW were characterised as poor-quality streams because their water quality parameters were above the target quality and significantly higher than tap water, except for trace metal contents.

In **Chapter Four**, 20 soil samples from five major soil groups namely; aeolian sand, alluvium, granite, shale and chromic, occurring in Cape Town and Stellenbosch urban areas were characterised for physical and chemical soil properties. The chromic soils had significantly higher CBD Fe (> 2%) compared to all the soil groups. The clay contents of shale and chromic derived soils was significantly higher than other soil groups. The clay fraction of the granite and shale soil groups was more easily dispersed by water compared to other soil groups.

In **Chapter Five**, the vulnerability of the soil groups to degradation in terms of soil permeability, DOC and clay removal, by 200 mm liquid and powdered detergent laundry (LLD and PLD) greywater applications in comparison to tap water was determined. Both laundry greywater streams were observed to significantly reduce soil saturated hydraulic conductivity (especially PLD) due to high clay dispersion compared to TW. The granite and shale soils were more prone to K_{sat} reduction due to pore sealing by the dispersed clay while the chromic soils were more resistant due to high clay in combination with Fe oxides which promote soil aggregates. PLD greywater removed significant amounts of DOC compared to LLD and TW due its high pH. The aeolian sands lost significantly more DOC (7.5 %C) of the soil total carbon compared to other soil groups, likely due to the low clay content and weak bonds between organic matter and sandy soil particles. In contrast, 200 mm PLD greywater application on chromic soils resulted in the lowest DOC losses likely due to strongest chemical stabilization with sesquioxides. Furthermore, application of the laundry greywater streams significantly increases leachate turbidity and ash content compared to tap water on aeolian sands. This meant that finer soil particles (silt and clay) were leached out of the soil. Therefore, application of PLD greywater degraded soil quality.

Comparison of the effects of SH and DW greywater streams to the laundry greywaters and tap water on 11 selected soils was also assessed. The soil K_{sat} and DOC loss due to the application SH and DW greywater streams were not significantly different from the TW and LLD greywater. However, the PLD greywater significantly reduced K_{sat} and increased DOC loss in all the soils compared to all the greywater streams and tap water. The SH and DW greywater leached out salts from the soils like TW and LLD greywater while PLD greywater added salts to the soils. Therefore SH, LLD and DW greywater effects were not different from TW while the PLD greywater had negative impacts.

In **Chapter Six**, the effect of repeated greywater application (370 mm applied over 10 weeks) of the four greywater streams (i.e., SH, LLD, PLD and DW) and TW was determined on a representative dispersive (SP1- granite group) and stable (BD1 - chromic group) soil. As expected, repeated application of PLD and DW had the most detrimental effects on soil quality parameters. PLD greywater induced alkalinity (high pH), salinity (high EC) and sodicity (high ESP) on both the granite and chromic thus leading to the formation of alkaline saline sodic soils while DW greywater added salinity and sodicity resulting in saline-sodic soils. Both PLD and DW greywater significantly increased clay dispersion on both soil types with the granite having the highest clay dispersion capacity (95 and 88% for granite, 37 and 34% for chromic, resp.). This led to significant K_{sat} reduction of both soils. The K_{sat} of granite DW greywater irrigated soils was zero while that of the PLD was almost zero. PLD and DW significantly increased plant available P on both soil types, especially in DW irrigated soils. Plant available P of the chromic were higher than the granite soil sample. Continuous application of all the water treatments significantly reduced the total C of both granite (-8.9 to -14.1%) and BD1 (-7.6 to -14.7%) soils. Most soil effects caused by both the application of SH and LLD greywater streams were not significant from those caused by TW except an increased pH in chromic soil, and periodic hydrophobicity caused by shower greywater. Application of all the greywater streams and TW in the SP1 soil on average reduced soil bacterial community, diversity and species richness, especially PLD greywater-irrigated soils. However, no effect was observed on fungal population.

The subsequent effect of winter rainfall leaching on greywater-irrigated soils was also studied, to determine whether rainfall was successful at remediating the soils. The leachate pH and EC of all the water treatments applied increased while PLD and DW greywater leached significant quantities of DOC from the soil which further reduced the soil total C by 21.9% for PLD and 9% for DW when compared to the unirrigated soil. Application of rainwater leached out salts on the permeable granite and chromic soils. This resulted from leaching of exchangeable cations, thus decreasing the effective cation exchange capacity and exchangeable sodium percentage. A significant soil pH increase was observed on chromic soil due to the hydrolytic exchange of Na in saline-sodic soils (i.e., those irrigated with PLD and DW) while on normal soil it might be due to the ammonification while no pH change was observed in the granite TW, SH and LLD irrigated soils. The solubility of trace metals (Cu, Fe, Mn and Zn) was increased by rainwater.

Therefore, we can conclude that even though the SH and LLD greywater were of better irrigation water quality, their use for continuous irrigation should be monitored due to impact on hydraulic conductivity, and eventual Na accumulation. PLD greywater is not suitable for irrigation because it had the most harmful effects on soil quality. The application of a single 200 mm DW greywater application show minimal signs of soil degradation when compared to TW, however, repeatedly applied it resulted in significant clay dispersion which caused massive hydraulic changes. Repetitive DW greywater application also elevated SOC removal when compared to the once off application. This indicates that the longer the use of DW greywater, the greater the negative impact. This study is the first study that quantifies DOC leaching losses due to greywater application. Solubilisation and removal of soil organic carbon via PLD and DW application will have a detrimental impact on soil health and quality, including limiting microbial activity, degradation of soil aggregation, reducing CEC and water holding capacity. Thus, both PLD and DW greywater is not fit for irrigation. Even though rainwater leaching reduced salinity in the saline-sodic soils, increased alkalinity (high pH) can affect many soil-plant properties. Hence, further remediation is needed.

RECOMMENDATIONS AND FUTURE RESEARCH

Existing methods can be used to remediate or restore salt and Na-affected soils. For example, saline soils can be leached with good quality water while sodicity of soils is normally corrected by adding gypsum. Saline-sodic soils can be amended by first adding gypsum then leaching with good irrigation water. Gypsum ($CaSO_4$) promotes soil aggregation by flocculating the dispersed clay due to sodicity. Thus, resulting in improving soil aeration and water infiltration. However, further studies need to be conducted to ensure if these soils will fully recover.

At present, South Africa wastewater reuse national standards do not distinguish between greywater and blackwater and require greywater to be treated to the standards of potable water. However, there are many households in the Western Cape Province that use untreated greywater, especially laundry greywater for home irrigation. For example, Cape Town residents have been recommended to use laundry greywater for garden irrigation (City of Cape Town, 2019) and they do not differentiate between greywater generated from liquid and powdered laundry detergents which have been found to degrade the soils at different intensities. Therefore, findings from this study will assist government and municipalities to develop greywater reuse guidelines that take into consideration different domestic greywater streams incorporation with soil type at which greywater is applied. This information will then help the public to use greywater effectively and prevent soil degradation.

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