Effect of ABR effluent irrigation on Swiss chard (*Beta vulgaris* subsp. *cicla*) growth and nutrient leaching

By

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DEDICATION

A special dedication to my late father, mother and the Musazura family.

SUMMARY

The Decentralised Waste Water Treatment System (DEWATS) is used in countries such as India and Indonesia for the treatment of human waste. The waste is passed through a series of baffles where it is anaerobically degraded, resulting in the production of the Anaerobic Baffled Reactor (ABR) effluent. Disposal of the effluent can still pose a challenge if not done properly and lead to environmental pollution. The effluent has been shown to contain high concentrations of mineral elements such as nitrogen and phosphorus, which are important for plant growth. There is little information on the use of effluent for agriculture particularly under the South African climatic and edaphic conditions. This study investigated the effect of using ABR effluent on the nutrient uptake, growth and yield of Swiss chard (*Beta vulgaris* subsp. *cicla*) on selected soil types. Field and tunnel experiments were carried out at Newlands Mashu Permaculture Centre in Durban (longitude of 30°57'E and latitude of 29°58'S). The initial experiment planted in the summer season of 2012 was designed to collect baseline data on growth and yield of Swiss chard and other selected crops under rain-fed vs. irrigated conditions using tap water. The treatments were laid out using a randomised complete block design (RCBD) with three replications. The treatments included: tap water irrigation without fertiliser application (TW); tap water irrigation with fertiliser application (TWF) and rain-fed with fertiliser application (RFF). The second experiment was conducted in winter 2012 with the aim of investigating growth and yield of Swiss chard irrigated with ABR effluent during the dry season. In the second study, the treatment "tap water irrigation without fertiliser application" was substituted with irrigation with ABR effluent while the other treatments were maintained. The third experiment was conducted in the summer season of 2013. The treatments remained similar to those of the winter 2012. Soil samples were collected from the top 30 cm before planting and after harvesting for chemical analyses. A neutron probe access tube was also installed in the middle of each plot in order to monitor soil water status and irrigate plots according to the root zone soil water deficit. Wetting Front Detectors (WFDs) were installed at 30 cm and 50 cm depths to monitor nutrient leaching. The leachates collected by WFDs were analysed for nitrates and phosphates using Merck Reflectoquant test kit. Similarly, the ABR was analysed for its chemical composition before each irrigation event. Treatment effect on Swiss chard and soil was tested by analysing fresh crop biomass, dry biomass, chlorophyll content, crop nutrient uptake and soil chemical properties. Parallel studies were conducted in a tunnel to investigate growth and yield response of Swiss chard grown on different soils (acidic, clayey loam and sandy loam soil) treated with varying fertiliser rates. The experiment was laid out as a factorial treatment structure with the following factors: Irrigation source (2 levels); soil type (acidic, clayey loam and sandy loam soil) and fertiliser application rate (No fertiliser, half-optimum recommended rate and optimum recommended rate based on soil analyses) replicated four times. The Swiss chard was grown in the tunnel in pots for 11 weeks. Crop growth and chlorophyll data, similar to that collected from the field was also collected from the pot trials. Data analysis was done using GenStat® 14th Edition (VSN International, Hemel Hempstead, UK). The results from the baseline study (experiment 1) did not reveal significant differences between treatments (TW, TWF and RFF) thus suggesting that the inherent soil fertility was high and could support Swiss chard growth. There were significant differences ($P<0.05$) between the treatments (ABR, TWF and RFF) during the winter season (experiment 2) with respect to Swiss chard biomass. Swiss chard plants produced under rain-fed conditions had lower dry mass compared with those that were irrigated using ABR effluent and tap water with fertiliser. However, the effect of using ABR effluent on Swiss chard biomass was comparable to tap water with fertiliser because these did not differ significantly. The results from the third experiment showed a lack of significant differences with respect to N and P leaching between the irrigation sources (ABR, TWF and RFF). Controlled experiments in the tunnel revealed a significant interaction between soil type and irrigation source. Swiss chard pots containing acidic soil and irrigated using the effluent showed significantly higher dry mass ($P < 0.01$), fresh mass ($P< 0.05$) and leaf area index ($P < 0.001$) compared to those irrigated with tap water. In conclusion the ABR effluent may have a liming effect which could have possibly increased Swiss chard growth in acidic soil. ABR effluent was more useful as an irrigation source in winter than in summer; however in summer the effluent could be more useful as a fertiliser source in areas where water is not limiting for crop production. N and P leaching and uptake could not be associated with irrigation using ABR effluent.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

CHAPTER 1

GENERAL INTRODUCTION

Low agricultural productivity, water scarcity and poor sanitation are key challenges in developing countries such as South Africa. These coupled with increasing population can cause tremendous pressure on production resources. For example, in recent years there has been a considerable expansion of densely populated informal settlements around the towns where there are little or no capacities to formalize them (Hudson, 2010). Most of the residents in these informal settlements are generally poor and unskilled and are confronted with considerable challenges with regards to food insecurity and proper sanitation facilities. Some of them practice urban and peri-urban agriculture; however, their productivity is limited by the prohibitive costs of inorganic fertilisers and water shortage for irrigation (Scott *et al.*, 2004; Thebe, 2012).

In recent years, several innovative technologies have been proposed that could provide solutions to the problems associated with lack of sanitation and food shortage among the urban and peri-urban poor communities. For example, the eThekwini municipality is assessing the use of alternative sanitation technologies such as the Ventilated Improved Pit (VIP) latrines, Urine Diversion (UD) toilets and the Decentralised Wastewater Treatment System (DEWATS) in South Africa (Hudson, 2010). Studies done on the DEWATS to assess its appropriateness for on-site sanitation in densely populated areas demonstrate that the technology may have a positive potential within these communities due to its low running costs (Foxon *et al.*, 2005).

The DEWATS system uses the principle of anaerobic digestion and the system consists of alternating hanging and standing baffles which treats sewage water under anaerobic conditions to produce effluent and biogas (Morel and Diener, 2006). Anaerobic Baffled Reactor (ABR) effluent contains mineral nutrients such as N and P which can promote the growth of algae when disposed into water bodies so its disposal into rivers can cause eutrophication. Moreover, standard characteristics required for disposal into water bodies are highly prohibitive to developing countries such as South Africa. Since the effluent meets the Department of Water, Forestry and Fisheries (DWAF) standards required for irrigation it has a potential use in agriculture as irrigation water and its use can reduce the need for inorganic fertilisers due to the presence of mineral nutrients (Foxon *et al.*, 2005).

During the recent years wastewater management has been orientated towards recycling rather than disposal in a way that will protect the environment and benefit human beings (Murray and Buckley, 2010). Such practices have already been implemented in many developing countries including Ghana to produce leafy vegetables (Scott *et al.*, 2004); Senegal to grow forage plants and Zimbabwe in agroforestry (Thebe, 2012). There are concerns and dilemmas about the use of wastewater for irrigation purposes due to the possible negative effects on soil properties, microbial contamination of food and water resources, and heavy metals. The above mentioned concerns, however, depend on the source of wastewater and the treatment process which the sludge went through. For instance previous studies by Cameron *et al.* (1997) have shown that ABR effluent has potential to improve plant productivity without affecting soil properties. The authors further stated that there are no risks associated with heavy metal toxicity since it contains insignificant amounts.

Large fraction of the N in most wastewater is in organic form but plants utilise N in inorganic forms (NO_3 and NH_4^+). Therefore, the organic N has to be transformed into inorganic form before it can be utilised by plants (Tesfamariam *et al.*, 2009). The mineralisation of organic N is affected by different factors such as soil type, soil water, soil temperature, soil pH and composition of the organic matter (Bar-Tal, 2011).

Although N is an important plant growth nutrient, excessive amounts can also have negative effects such as delayed maturity in flowering plants or loss of quality due to the accumulation of nitrates in leaf vegetables (Pescod, 1992). The presence of excess nitrate above what plants can use could, however, lead to leaching below the active root zone under poor irrigation management practices and/or high rainfall (Tesfamariam *et al.*, 2009). Unlike N, P is less mobile hence it can accumulate in the soil and impede the uptake of other micronutrients such as manganese (Mn) (Jiménez, 2006). In addition, irrigation using treated wastewater can lead to phytotoxicity due to excess chloride and sodium (Jiménez and Asano, 2008). The sensitivity of plants to salinity and other elements is crop and species dependent. Some vegetables, such as Swiss chard, which is commonly grown on the backyard of most urban and peri-urban home gardens, are moderately sensitive to salinity (Pescod, 1992).

Nevertheless, there is little information on a) Swiss chard response to ABR effluent irrigation, and b) the effect of ABR irrigation on selected soil chemical properties. This study investigated the effect of irrigation with ABR effluent on Swiss chard crop grown on different soils both in the laboratory and under field conditions. Information generated from this study can inform policy makers and allow them to develop policies that integrate agriculture into urban planning.

Thesis structure

This thesis comprises of six chapters:

CHAPTER 1 provides the background and justification for the research. The chapter highlights the key issues with regards to waste water reuse in agriculture with particular reference to the current understanding of ABR effluent use for irrigation.

CHAPTER 2 reviews in detail the challenges to sanitation provision, waste and wastewater management and potential solutions including reuse. The section reviews the current understanding of wastewater use and more specifically ABR effluent in agriculture both nationally and internationally. This section is concluded by the problem statement, hypothesis and objectives of the study.

CHAPTER 3 is an experimental chapter which reports on baseline studies on nutrient uptake, growth and yield of Swiss chard, maize and dry bean. The purpose of the baseline study was to characterize the experimental conditions before the application of ABR effluent and assess the impact on crop growth.

CHAPTER 4 discusses the effect of ABR effluent irrigation on nutrient leaching, uptake, growth and yield of Swiss chard (*Beta vulgaris* subsp. *cicla*). ABR effluent was used for irrigating Swiss chard during two seasons (winter and summer). The results across all the three seasons on the response of Swiss chard growth and nutrient uptake after irrigation with ABR effluent are presented.

CHAPTER 5 reports on the findings of a tunnel experiment investigating Swiss chard growth after irrigation with ABR effluent on three contrasting soils (acidic, clay loam and sandy loam soil).

CHAPTER 6 is the general discussion linking the three experimental chapters and concludes the thesis. The chapter offers recommendations and suggestions for future work.

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CHAPTER 2

LITERATURE REVIEW

2.0 INTRODUCTION

The increase in global population which is estimated to reach nearly nine billion by 2050, resource depletion and environmental pollution are issues of main concern (UNDP, 2007). According to the United Nations Development Fund, over 70% of the population in developing countries will be living in urban settlements by the year 2030 and beyond UNDP (2007). This is likely to add to the significant challenges that governments in many developing countries face with regards to the provision of essential services. In addition, water scarcity and climate change have also been identified as major issues that are likely to impact humanity in future (Drechsel *et al*., 2010). South Africa is one of the countries likely to face significant water scarcity due to the absence of strategic water management system (Mjoli, 2010). These will most likely result into potential conflicts between water requirements for domestic use, agriculture and industry and will add to the considerable challenges that most urban municipalities are currently facing in their efforts to waterborne sanitation facilities and water (Mjoli, 2010).

Waterborne sanitation systems connected to main sewerage systems are common in developing cities; however these centralised sanitation systems may not be sustainable in the long-term. This is mainly because many of the migrants to urban cities are often poor and will often reside in informal settlements far away from the main sewer systems. Connecting the centralised wastewater treatment systems to these settlements would require major infrastructural investment and may not by financially sustainable because of the inability of these communities to afford to pay for the services (Hudson, 2010). Furthermore the costs of installing and maintaining sanitation infrastructure and water provision are also likely to rise in future.

Therefore there is need to develop innovative and sustainable alternatives to the problems of sanitation particularly for communities living outside the boundaries of municipal water borne systems. For example, less than 50% of the residents of eThekwini municipality are connected to the main sewer systems. About 20% of the residents living in informal settlements do not have any form of sanitation (Foxon *et al*., 2005). The decentralised waste water treatment system (DEWATS) provides a potential alternative to the provision of sanitation facilities to these communities. The DEWATS reduces Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) at high treatment rates; however, the system produces nutrient rich Anaerobic Baffled Reactor (ABR) effluent, whose disposal into the water resources can cause pollution (Foxon *et al.*, 2005). ABR effluent has been characterised and meets the standard requirements for irrigation water despite its microbial load (Foxon *et al.*, 2005). Therefore there is potential to use the effluent of agricultural production. This chapter reviews the potential of ABR effluent use for agriculture. In the first section of this review, the current status of wastewater use in agriculture and the potential of ABR effluent use for crop production are reviewed. This is followed by a discussion on the effect of wastewater irrigation on soil chemical and physical properties and crop growth. The review also discusses the risk of microbial contamination and safety guidelines after irrigation with treated wastewater. Policies regarding the use of treated wastewater are also discussed. The review highlights potential gaps in knowledge about the use of ABR effluent for agriculture and the need for research.

2.1 Wastewater use in agriculture

Wastewater is generally described as water that has been altered in quality due to human activities. It can further be categorised into urban wastewater that is generally from domestic wastewater (blackwater and greywater), storm water (surface runoff water) and industrial effluent. Blackwater is the water that has been contaminated with faecal matter and urine (Levy *et al.*, 2011). Greywater originates from kitchen and bathroom activities such as bathing, dishwashing and laundry and this water can be high in phosphorus especially when P rich detergents are used (Lusk *et al.*, 2012).

The use of wastewater and biosolids in agriculture has been practiced for many years (Jiménez and Asano, 2008). In most developing countries unplanned use of untreated wastewater is a predominant practice since there are no proper guidelines for wastewater use and proper resources for wastewater treatment (Scott *et al.*, 2004; Drechsel *et al.*, 2010). The direct use of wastewater for agriculture is mainly being done in towns; in rural areas people are indirectly using it as polluted downstream water (Jiménez and Asano, 2008; Drechsel *et al.*, 2010). Sewage sludge is deemed noxious but is being used for agricultural crop production in many countries such as Vietnam (Jensen *et al.*, 2005) and China (UNHSP, 2008).In South Africa sewage sludge is being treated and is being used according to the guidelines developed (Snyman, 2007).

Untreated wastewater is concentrated with important plant growth mineral nutrients such as N, P and K as compared to treated wastewater. Wastewater (treated and untreated) is being used to irrigate crops even those that can be eaten raw (lettuce, onion, tomatoes and cabbages). This is due to ignorance on the impacts such microbial contamination and health risks (Scott *et al.*, 2004). When raw wastewater is being used the fertiliser value may be compromised by the extent of nutrient loading, leading to delayed maturity and rank growth resulting from excessive N especially in flowering plants such as rice (Kumamoto Municipal Government, 1983; Jiménez, 2006; Qadir *et al.*, 2010).

Domestic wastes and wastewater must be treated before being disposed into the environment and the treatment process includes several steps that aim to remove solids, nutrients and microorganisms (Ianelli and Giraldi, 2011). Wastewater Treatment Plants (WWTP) can be divided into decentralised and centralised wastewater treatment systems. The decentralised wastewater treatment system has been found to be more sustainable due to lower maintenance cost especially in developing countries as compared to the latter (Qadir *et al.*, 2010). An example of a decentralised wastewater treatment system is an Anaerobic Baffled Reactor (ABR), which is defined as an improved septic tank that anaerobically degrades wastewater (greywater, blackwater and brown water) and generates a nutrient rich effluent while settling down sludge (Morel and Diener, 2006). It consists of different treatment methods, involving the anaerobic treatment of organic matter. Other aerobic treatments of the effluent can be done through constructed wetlands prior to disposal (WHO, 2010; Figure 2.1).

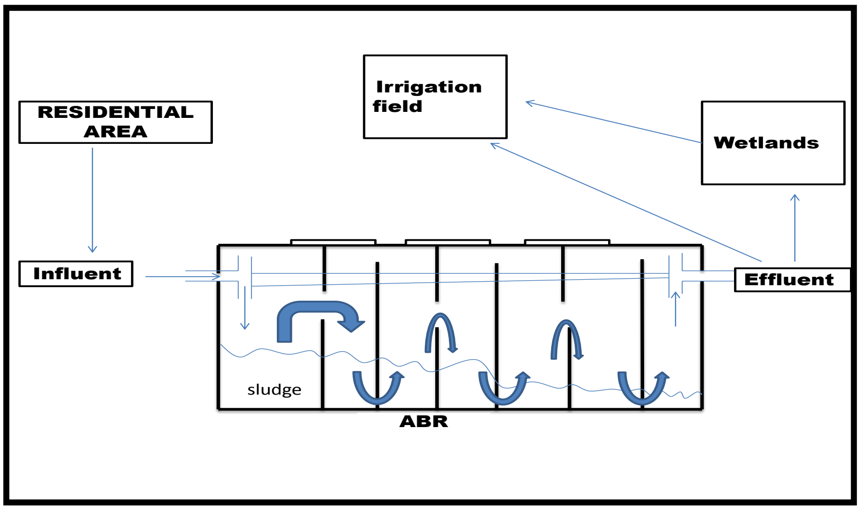

Figure 2.1. A schematic diagram showing raw wastewater from households passing through an ABR and disposal of effluent onto agricultural fields or wetlands.

The ABR was first designed by McCarty and co-workers (Bachman *et al.*, 1983) and was later modified to retain solids while treating other difficult compounds e.g. dyes at a low cost (Booparthy and Tilche, 1991). The system is cheap to maintain since it does not use electricity to function once it is established. The treatment process depends on the microorganisms, which can be inoculated to speed up the anaerobic treatment process especially in the first chamber as compared to other centralised wastewater treatments (Nasr *et al.*, 2009). The ABR forms part of the Decentralised Water Treatment System (DEWATS) and has a capability of treating a wide range of influents, ranging from industrial influent to household influent (Morel and Diener, 2006) even under acidic conditions (Bayrakdar, 2009). It consists of an inlet pipe, which allows the entrance of raw wastewater and an outlet that allows the outflow of biogas and effluent rich in orthophosphate and ammonium nitrogen with fewer nitrates due to the anaerobic degradation of sewage water (Foxon *et al.*, 2005; Morel and Diener, 2006; She *et al.*, 2006). Due to short compartments, the entering liquid can be equally distributed within the chambers (SASSE, 1998) and a series of vertical baffles force wastewater to flow through compartments in an up and down manner (Figure 2.1). The compartments contain anaerobic bacteria responsible for the anaerobic degradation of wastewater solids (Nasr *et al.*, 2009) and the most efficient wastewater treatment occurs within chambers four and five due to low organic matter (Booparthy, 1988). It has got a two phase operation (methanogenesis and acidogenesis), which are separated to allow the development of different bacterial groups under optimum conditions such as neutral pH (Langenhoff *et al.*, 2000).

Post-treatments of the resulting effluent can be done in wetlands to remove nitrogen and phosphorus. Studies by Nasr *et al.* (2009) have shown that duckweed ponds could remove 73.5% N and 65% P at 15 day hydraulic retention time (HRT). Nasr *et al.* (2009) further concluded that the resulting duckweed can be used to produce protein rich stock feed while the treated effluent is used for unrestricted irrigation due to its ability to remove three to four logs of faecal coliforms (Figure 2.1).

Although the ABR system is cheap and simple to maintain the effluent released still needs further treatments especially if it is to be used for irrigation due to high microbial load (Foxon *et al.*, 2005). Treated wastewater comprises of 99.9% water and 0.01% solids, which can either be dissolved or suspended solids and the nature of the solids affect water quality (Pescod, 1992). Water quality is defined as the suitability of certain water for a certain purpose, for example potable or agricultural use and this can be characterised by factors such as biological, physical and chemical components (Pescod, 1992). Major physical and chemical components include Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), nutrients, Electrical conductivity (EC), alkalinity ($CaCO_3$) while biological component include pathogens (coliforms, protozoa and viruses) (Pescod, 1992). Biological, physical and chemical characterisation of wastewater can enable us to monitor the water quality. This allows us to decide if it meets requirements for certain use such as irrigation or disposal into rivers.

Therefore there is a need to develop guidelines that will integrate urban wastewater management with agriculture. Such guidelines must assess and consider the impacts of treated wastewater irrigation on soils, crops, water bodies and human health. The main driver for the establishment of wastewater use guidelines would be to achieve sustainable wastewater recycling to prevent environmental pollution through discharge into rivers. International guidelines were made by FAO (1985), however these are not applicable internationally but they are just used as reference by many countries.

Many countries have developed their own wastewater use guidelines which take into consideration political, economic and social issues. For example, the first wastewater use guidelines were established in California (1918) and these have been revised by different organizations (WHO and IRDC) in different countries (USA, Australia and Spain) (Scott *et al.*, 2004). Other countries, for example Jordan and Tunisia are using wastewater legally for irrigation according to their own guidelines (Scott *et al.*, 2004). Tunisia established its first treated wastewater irrigation guideline in 1989, currently the intensity of irrigation is increasing at a tremendous rate and some of the irrigated crops are citrus, olives, cotton and some golf courses (Bahri and Brissaud, 1996). In Zimbabwe attempts have been made to establish wastewater irrigation farms, for example Aisleby Farm in Bulawayo where some of the wastewater is used to irrigate social amenities such as parks, cereals (wheat and maize) and in Gweru where it is being used in agroforestry to irrigate eucalyptus trees. In 1970 the Harare city council promoted the irrigation of pasture crops using wastewater as a way of minimizing the pollution of Lake Chivero and this proved to be a success (Thebe, 2012). In South Africa, wastewater irrigation was also implemented in Mnini area of the eThekwini district, where fruit trees (bananas and mangoes) and vegetables were grown as a way of acting against the pollution of Ngane River. However the feasibility of the programme was jeopardised by technical and structural issues such as proper trade permits, lack of consultation from the community, lack of operational permits in certain farming areas and lack of permission from the forestry department to use virgin land (Murray and Buckley, 2010). Clearly the failure of the initiative in Mnini area can be attributed to lack of proper guidelines that govern wastewater use (Drechsel *et al.*, 2010; Qadir *et al.*, 2010; Thebe, 2012). Other potential problems that may arise could include the amount of land area available for irrigation and the volume of wastewater generated, which might consequently lead to the need to manage extra effluent (Thebe, 2012).

In South Africa wastewater and biosolids use guidelines have been published by the Department of Water, Agriculture, Forestry and Fisheries (DWAF) in 1996. However, there are no clear guidelines on the use of treated wastewater for agricultural production. The applicability of water quality and more specifically the use of ABR effluent in agriculture are dependent on soil type, crop type, irrigation type and weather conditions of a certain area. The guidelines for the use of ABR effluent should also consider the effluent quality, volumes discharged, N and P recovery for plant use and leaching into water bodies and the risk of microbial contamination.

2.2 The potential use of ABR effluent for agriculture

This section will review the current understanding with respect to treated effluent and in particular the use of ABR effluent for agriculture. The use of treated effluent in agriculture has its own merits and demerits, which include effects on the soil chemical and physical properties, environmental pollution, effects on plants, irrigation structures, heavy metals and microbial contamination (Drechsel *et al.*, 2010; Mateo-Sagasta *et al.*, 2013). Different countries in the world are using municipal wastewater for agriculture in both treated and untreated forms and this is driven by factors such as management of wastewater volumes generated and water scarcity, nutrient (N and P) recovery, water scarcity and effects of disposing nutrient rich effluents into water bodies (Scott *et al.*, 2004; Mateo-Sagasta *et al.*, 2013). The major drivers towards wastewater reuse in agriculture are dependent on the country. Developed countries are generally focused on wastewater volumes generated while for most developing countries the focus is on nutrient recovery for sustainable agriculture (Mateo-Sagasta *et al.*, 2013).

2.3 Characterisation of ABR effluent

Table 2.1 shows the physical, chemical and biological properties of ABR effluent as compared to the irrigation and the disposal standards. The ABR effluent does not meet the minimum standards for the disposal of wastewater into the environment and water bodies in terms of the COD, total N, Total suspended solids (TSS) and the Total coliforms but in most cases it meets the standard requirements for irrigation water, although the total N content might have impact on flowering crops such as maize. These characteristics can clearly indicate the importance of using ABR effluent for irrigation (Foxon *et al.*, 2001).

Table 2.1 Physical, chemical and biological properties of the ABR effluent showing standards required for discharge and irrigation (DWAF, 1996)

	Unit	**Inlet**	**Outlet**	**Discharge standards**	**Irrigation standard**
****COD**	mg COD L^{-1}	716	192	75	400
***pH**		6.9	6.5	5.5 – 9.5	6.5-8.4***
***Kjeldahl N**	mg N L^{-1}	44.6	37.1	<5	5 -30***
***P**	mS m^{-1}	4.9	5.5	10	-
****TSS**	Mg L^{-1}	480	225	25	-
****VSS**	mg L^{-1}	306	127	-	-
Alkalinity:					
(CaCO3)	mg L^{-1}	256	246		-
****Total coliforms**	Colony	1.3×10^8	5×10^7	1 000	10 000

N.B.

* (Hudson, 2010)

** (Foxon *et al.*, 2005)

***DWAF (1996)

2.3.1 COD and BOD in ABR effluent

Chemical oxygen demand (COD) is the amount of organic matter within water and this can indicate the ability of water to deplete oxygen and reduce other compounds such as nitrates. However the ABR is capable of reducing the COD by 86 % (Foxon *et al.*, 2005) and the BOD by 70% to 95% (SASSE, 1998). So the ABR exhibits a better treatment as compared to conventional septic tanks which can treat influent by 30 to 50 % (UNEP, 2002). The removal of COD in the ABR system is due to high sulphate concentration resulting from sulphate reducing bacteria (Vossoughi *et al.*, 2003).

2.3.2 ABR effluent pH

Average pH in the ABR is 6.5 and this allows the activity of the methanogenesis bacteria to act on the degradation of the organic waste. The minimum requirement for the irrigation water pH is 6.5 – 8.4 (DWAF, 1996), meaning that the ABR effluent has a potential for use as irrigation water. The alkalinity in wastewater is affected by the presence of chemicals such as $CaCO_3$, contents originating from soaps and detergents. High alkalinity originates from poor buffering within the treatment system and in the ABR treatment; it is buffered by the methanogenesis and acidogenesis methods (Tawfik *et al.*, 2010). The pH in irrigation water is important and it affects nutrient availability, corrosion of irrigation pipes and crop quality especially in sensitive species (DWAF, 1996).

2.3.3 Total solids in ABR effluent

Total solids within a water sample refers to all solids (Suspended and dissolved) and they are an indication of water that has been reduced in quality (Pescod, 1992). Suspended solids include solids which are not dissolved and these can be plant debris and soil particles. Soluble solids exist in solution and they can be obtained after evaporation. The ABR is capable of reducing about 50% of total solids in the first sedimentation chamber (Tilley *et al.*, 2008) and the removal efficiency is dependent on the retention period (Singh *et al.*, 2009). Suspended solids and dissolved solids can affect soil physical properties, clogging of the drip pipes and salinity problems; hence an EC of 40 mS m^{-1} is recommended and <100 mg L^{-1} of suspended solids (DWAF, 1996). Most of the treated wastewaters have total suspended solids of between 100 mg L^{-1} and 350 mg L^{-1} depending on the strength (diluted or concentrated) wastewater (Pescod, 1992).

2.4 Effects of treated wastewater on soil chemical and physical properties

Some benefits of irrigation with treated wastewater include improved soil physical structure and nutrient retention although some other negative effects arise. Irrigation with treated wastewater affects soil chemical and physical properties, which consequently have effects on crop growth and environmental pollution.

Treated wastewater can affect soil properties such as organic C, Cation Exchange Capacity (CEC), pH, microbial activity, porosity, hydraulic conductivity and bulk density (Leal *et al.*, 2009; Al-Omron *et al.*, 2011; Adrover, 2012). Irrigation with wastewater decreases the soil hydraulic conductivity due to the accumulation of suspended solids, which alter the soil structure and reduce the soil pore size (Abedi-Coupai *et al.*, 2006; Begum *et al.*, 2011). Suspended solids incorporate organic C in the soil and this depends on the type of wastewater used, treated wastewater has lesser suspended solids compared to raw wastewater and lagoon wastewater (Levy *et al.*, 2011). Organic C affects soil pH, CEC, mineralisation of nutrients and microbial activity (Jüeschke *et al.*, 2008). Wastewater can increase soil organic matter and the nature of organic matter in treated wastewater is different from biosolids. Wastewater undergoes treatment process which leaves highly biodegradable dissolved organic matter (DOM) as compared to biosolids (Chen *et al.*, 2011). The incorporation of DOM in the soil after irrigating with treated wastewater can increase soil microbial activity, which is associated with nutrient mineralisation through improved aeration resulting from the effect of organic C on soil porosity (Kuzyakov *et al.*, 2000; Ngole, 2010).

Wastewater irrigation can affect soil aggregate stability, water retention and hydraulic conductivity, which might consequently lead to surface runoff and soil erosion (Levy *et al.*, 2011). Several studies have confirmed a reduction in soil hydraulic conductivity and bulk density with wastewater irrigation due to the clogging of soil pores caused by organic matter and microbial activity (Xantholagis and Wallender, 1991; Tarenitzky *et al.*, 1999). However, the effects are more pronounced in clay soils than in sandy soils (Reza and Ameneh, 2011). Wastewaters have variability in Sodium Adsorption Ratio (SAR) and suspended solids, which is an indication that its effects on soil physical properties vary. Sodium Adsorption Ratio refers to the proportion of Na in relation to divalent cations (Mg^{2+} and Ca^{2+}) (Pescod, 1992) (Eq. 2.1). Sodicity is affected by the concentration of Na from wastewater, and according to Eq. 2.1 an increase in Na increases SAR, which can be ameliorated through addition of Ca and Mg. The application of fresh water can render the soil solution more dilute and eventually leach Na since it is less adsorbed by soil colloids as compared to divalent cations. Wastewater rich in Ca and Mg is less likely to cause soil sodicity (Reza and Ameneh, 2011).

$$\text{SAR} = \text{Na} / [(\text{Ca} + \text{Mg})/2]^{1/2} \qquad \text{Eq. 2. 1}$$

Changes in soil structure are affected by the agglutination of soil peds in the presence of organic matter, leading to improved soil structure when irrigating with wastewater (Bresson *et al.*, 2001) but this depends on the quantity of organic matter. Disaggregation of soil particles can be caused by large amounts of organic matter from wastewater (Piccolo *et al.*, 1992). This is because dissolved organic C can adsorb large amounts of Na on the soil particles (Xantholagis and Wallender, 1991). However, this is more significant in less disturbed soils such as citrus plantations as compared to constantly ploughed fields (Levy *et* *al.*, 2011). Highly sodic clays can also be affected as compared to calcareous clays (Chen *et al.*, 2011). The effects of wastewater on soil physical properties is dependent on the extent of the wastewater treatment, being more pronounced in untreated compared to treated wastewater. Information pertaining to the response of soil properties to irrigation with wastewater is inconsistent; however it is very crucial to monitor long term changes in soil properties to avoid possible negative effects (Levy *et al.*, 2011).

Organic C increases binding sites on the soil colloids thereby contributing to increased cation and anion exchange capacity due to their ability to sorb dissolved substances from the soil solution, retaining them within the plant rooting zone (Chen *et al.*, 2011). The decomposition of organic matter is associated with the formation of organic acids that lowers soil pH contributing to lower pH after irrigation with treated wastewater (Brar *et al.*, 2000; Al-Omron *et al.*, 2011; Mojiri, 2011). Studies by Shahalam *et al.* (1997) have revealed that low pH is attributed to the formation of weak carbonic acids from the CO_2 liberated during the decomposition of organic matter and this has a buffering action through the formation Ca $(HCO_3)_2$. Studies by Rousan *et al.* (2007) showed an insignificant change in soil pH after long term irrigation using treated wastewater. Lower pH in the soil can increase the solubility of basic cations such as Ca^{2+}, Mg^{2+} and K^+, which are eventually leached into the lower levels of the soil, leaving Al^{3+} dominating the soil exchange sites.

$$Al^{3+} + 3H_2O \rightleftharpoons (AlOH)_3 + 3H^+ \qquad \text{Eq 2.2}$$

The effect of Al induced acidity can be reduced by the presence organic matter from the wastewater. Organic matter reduces the amount of Al^{3+} in soil solution by complexing with it, implying that irrigation with wastewater creates a soil pH the buffering system (Levy *et al.*, 2011).

The effect of organic C on soil properties is dependent on factors such as soil type (Ngole, 2010), the nature of the organic C (dissolved vs. suspended) and weather conditions (Chen *et al.*, 2011). Studies by Ngole (2010) showed a reduction in pH with application of sludge and this was less pronounced in arenosol (sandy) soil as compared to vertisol (clay) soil due to better aeration within the former. Soils with high organic matter, especially clay soils are highly acidic due to slow decomposition which is caused by the formation of complexes (organominerals) between clay particles and organic matter (Samuel *et al.*, 1993). Studies by

Singh *et al.* (2012) have shown a slight increase in clay soil alkalinity irrigated with sewage wastewater due to the presence of alkali metals in treated wastewater. A buffering effect of irrigating alkaline soils with municipal wastewater was observed by Mojiri (2011) and Bame *et al.* (2013). On the contrary, Leal *et al.* (2009) observed a little increase in soil pH from wastewater irrigation and related it to the presence of alkaline compounds ($CaCO_3$) in wastewater and soil processes such as denitrification which liberate OH^- ions. Information on the effects of treated wastewater on soil pH is not clear and the effect of ABR effluent irrigation on Swiss chard nutrient uptake in different soils (acidic, sand and clay) is not documented.

2.5 Effects of treated wastewater on growth and yield of plants

Several studies have demonstrated that treated effluents can increase plant growth and yield of crops such as sorghum (Day and Tucker, 1977), forage crops (Bole and Bell, 1978), maize (Marten *et al.*, 1980), wheat (Aziz *et al.*, 1995), vegetable crops (Shahalam *et al.*,1997; Zavadil, 2009; Adewoye *et al.*, 2010) and cotton (Alikhasi *et al.*, 2012). Moreover, treated wastewater and biosolids can increase the yield and quality of crops when applied at the right time and concentration. Some nutrients such as N may exceed crop requirements and reduce yields in crops such as rice (Singh and Mishra, 1987) while high amounts of nitrogen can be beneficial to leaf vegetables (Mateo-Sagasta *et al.*, 2013). Some wastewater may affect plant growth for example undiluted textile wastewater could inhibit germination and seedling growth of kidney bean and lady fingers (Ajmal and Khan, 1985). The response of crops to irrigation using wastewater can be crop specific. Some crops yield better when irrigated with the effluent alone while others yield better when irrigated with effluent and a supplementary fertiliser (Pescod, 1992). There is no consistent information on the crop response to wastewater irrigation. Moreover the effect of ABR effluent irrigation on Swiss chard yield has not been investigated.

2.6 Effects of treated wastewater on nutrient uptake and leaching

Wastewater management aims to prevent pollution through disposal of nutrient rich effluent into rivers; however nutrient removal through plant production is effective way wastewater nutrient management. Studies by Bame *et al.* (2013) have shown an increase of nitrates in the soil after irrigation with ABR effluent; however the recovery of nutrients through plant uptake such as by Swiss chard is little understood. This section, reviews nutrient (N and P) transformations in the soil after irrigation with treated wastewater and, how these can be taken up or be rendered unavailable for plant uptake. We further review on how irrigation with wastewater leads to nutrient leaching and contaminate underground water resources.

Nutrient uptake is a very complex process and the roots do not necessarily grow towards the nutrient source. This process occurs following three different mechanism namely mass flow (dissolved in water), root interception and through diffusion. For nutrients to be taken up from the soil they must be in high concentrations and soluble in solution. Different factors within the soil ecology can affect nutrient uptake and these include pH, CEC, biological activity and the availability of nutrients in soluble forms (Samuel *et al.*, 1993). Several studies report an increase in nutrient uptake after irrigation with treated wastewater (Mohammad and Ayadi, 2005; Kiziloglu *et al.*, 2007; Rousan *et al.*, 2007; Leal *et al.*, 2009; Adewoye *et al.*, 2010). However, Kiziloglu *et al.* (2007) showed that irrigation method affects nutrient uptake; submerged drip irrigation being more effective since it supplies nutrients directly near plant roots.

2.6.1 N transformations and uptake by plants

Nitrogen is the major growth driving nutrient, which is important for structural and metabolic activities such as the synthesis of chlorophyll, proteins, enzymes and nucleotides. It is required by plants in larger quantities compared to other nutrients and its deficiency is evidenced with factors such as retarded growth, chlorosis and reduced yield (Bar-Tal, 2011). Most of the treated wastewaters have total N concentrations of between 20 and 85 mg L^{-1} (Pescod, 1992), meaning that they are good source of N fertiliser. Soil nitrogen is available for uptake in the form of NH_4^+ and NO_3^-which are inorganic forms (Tesfamariam *et al.*, 2009; Marschner, 1995). ABR effluent contains nitrogen in the form of NH_4^+ due to the anaerobic conditions during wastewater treatment (Foxon *et al.*,.2005; Hudson, 2010), which when applied in soil can be adsorbed by negatively charged soil colloids due to differences in charges and this process is called fixation. The fixation of NH_4^+ is affected by the presence of polyvalent cations such as Al^{3+}, Ca^{2+}, Mg^{2+} and Fe^{3+}, which are preferentially adsorbed at the expense of monovalent cations especially under dryer conditions due to ionic strength in the soil solution. Organic C can enhance the fixation of NH_4^+ through the introduction of new binding sites (monodentates and polydentates) but the effect of treated wastewater in promoting this process is still not well understood (Bar-Tal, 2011) . Soil nitrogen can be made available for plants through the process of mineralisation, which is the conversion of organic nitrogen (Microbial biomass and soil organic matter) to inorganic forms. Mineralisation of nitrogen involves ammonification and nitrification. Ammonification is the conversion of organic N to ammonia (Levy *et al.*, 2011; Bar-Tal, 2011) (Eq. 2.3) and this process is followed by the nitrification process, which is the conversion of NH_3 to NO_3^- (Eq. 2.4-5).

$$NH_4^+ \longrightarrow NH_3 + H^+ \qquad \text{(Eq. 2.3)}$$

$$NH_3 + O_2 + 2H^{+}\ 2e^- \longrightarrow NH_2OH + 2H^+ + 2e^- \longrightarrow NO_2^- + 5H^+ + 4e^- \qquad \text{(Eq. 2.4)}$$

$$NO_2 + H_2O \longrightarrow NO_3^- + 2H^+ + 2e^- \qquad \text{(Eq. 2.5)}$$

The nitrification process is facilitated by two main groups of microbes including ammonia oxidizing bacteria *Nitrosomonas* (Eq. 2.2) and the nitrite oxidizing bacteria *Nitrobacter* (Eq. 2.3). The former bacterium is less sensitive to cold temperature than the latter so under cold conditions nitrite accumulation could take place to levels that can be toxic to plants (Russel *et al.*, 2002).

Mineralisation is affected by C: N ratio, the nature of the organic matter (dissolved organic matter and solid organic matter), temperature and pH. Treated wastewater with C: N ratio of more than 25 can lead to net immobilisation, most treated wastewater have a C: N ratio of less than five and the mineralisation rate is high (Bar-Tal, 2011). Since the ABR effluent has low BOD and COD due to high treatment efficiency of the DEWATS (Hudson, 2010), it is expected to have a lower C:N ratio hence mineralisation in the soil should be easy. Furthermore, dissolved organic C is mineralised faster than solid organic C and this is a major reason why the response to the use of biosolids is slower than irrigation using treated wastewater (Bar-Tal, 2011). The process is rapid in neutral to basic pH so high acidity and anaerobic conditions especially in poorly drained clay soils can reduce mineralisation (Bar-Tal *et al.*, 2011).

The loss of nitrogen in the form of N_2O and NO is termed denitrification and is facilitated by *Pseudomonas s.*, *Bacillus s.*, *Micrococcus s.* and *Achromoonbacter* under water logged conditions (Eq. 2.6).

$$NO_3 \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2 \qquad \text{Eq. 2.6}$$

During waterlogging these bacteria use oxygen from NO_3^- under anaerobic conditions in the presence of organic matter and optimum conditions to transform NO_3 to N_2O, and N_2 (Coryne, 2008). As compared to use of biosolids, irrigation with treated wastewater is less likely to cause denitrification. This is because treated wastewater has lower C: N ratio due to lower amounts of organic C. Denitrification can be hastened by climatic conditions that promote waterlogging (Bar-Tal, 2011).

The nitrogen recovery after irrigation is an important aspect when considering the practicability of irrigating using sewage wastewater. Feigin *et al.* (1981) studied the effects of the treated wastewater effluent on the mineralisation of nitrogen and concluded that higher nitrogen losses were due to organic C which promoted denitrification. Several studies have shown that wastewater irrigation can increase N uptake and this depends on the ability of wastewater to meet the crop N requirements (Bieloray *et al.*, 1984; Adeli *et al.*, 2005). On the other hand the presence of other nutrients might indirectly affect N uptake by plants. Begum *et al.* (2011) concluded that even Cu have an antagonistic effect on N uptake in rice by reducing its uptake and quality.

The value of treated wastewater as a source of N that can substitute other inorganic fertilisers is well documented. Different responses have been observed with different wastewaters (raw wastewater, lagoon wastewater, industrial wastewater and wetlands wastewater), soils and plants. However, there is no information in literature on nitrogen uptake and growth response of Swiss chard after irrigation with ABR effluent.

2.6.2 P transformations and uptake by plants

Phosphorus is the second most important nutrient that is responsible for structural and metabolic functions such as the formation of energy carriers (ATP). Phosphorus fertilisers are derived from phosphate rocks which are finite and expensive (Jiménez, 2006; Cordell *et al.*, 2009; Lusk *et al.*, 2012). P in treated wastewater exists in inorganic forms such as orthophosphates and pyrophosphate (Bar-Yosef, 2011; Lusk *et al.*, 2012) which are derived from human excreta and detergents (White and Hammond, 2008). In most treated wastewaters the amount of P is between 6 and 20 mg L^{-1}. P is generally scarce in most agricultural soils and exists as organic P (20 to 80%), mineral P and phosphates. Plants require P in the form of phosphates, which are generally very low in the soil. Inorganic P can be available to plants through desorption and solubilisation (Schachtman *et al.*, 1998). It is a very stable mineral nutrient which accumulates in soil with long term wastewater irrigation and excessive levels lead to unavailability of other nutrients (Zn, Cu and Fe) under alkaline conditions (Jiménez, 2006). Wastewater treatment does not remove P unless some other removal mechanisms are employed for example the addition of Al^{3+} and Fe^{3+} by the process of flocculation, which is a method similar to the production of struvite from urine through the addition of MgO (Burns *et al.*, 2003). Studies by Hudson (2010) and Foxon *et al.* (2005) have shown a negligible reduction of P from the ABR. Therefore ABR effluent is potentially a good source of phosphorus fertiliser.

Phosphorus in the soil can exist in the inorganic forms ($H_2PO_4^-$, HPO_4^{2-}, $CaH_2PO_4^+$, $CaHPO_3$ and $CaPO_4^-$) and it is taken up by plant roots in the form of a monovalent anion $H_2PO_4^-$. This form is available under slightly acidic pH. Complexing agents such as citrate can increase soil inorganic P in solution by complexing with Al^{3+} and Fe^{3+} to produce soluble complexes such as Ferric hydroxyphosphate polymer ($Fe|O|OH|H_2PO_4$) (Bar-Yosef, 2011). This is the reason why irrigation with treated wastewater increases P uptake in plants (Bar-Yosef, 2011). However the availability of inorganic P in the soil is affected by soil type. Previous studies by Bame *et al.* (2013) have found that soils with high organic matter can adsorb P making it unavailable for plant uptake. Furthermore pH can play a crucial role in the precipitation of P and it can be precipitated as Al and Fe compounds under acidic conditions and as Ca and Mg compounds under alkaline conditions (Lusk *et al.*, 2012).

Previous sections have reviewed the importance of ABR effluent in supplying nutrients (N and P) within the plant root zone and plant nutrient uptake can be a solution for their utilisation. However leaching of these nutrients can be a factor of consideration which might lead to the contamination of underground water resources. Nutrient leaching is affected by rainfall regimes, irrigation management practices (Tesfamariam *et al.*, 2009) and soil type (Levy *et al.*, 2011). Irrigation with ABR effluent can increase NO_3^- concentrations through nitrification (Bame *et al.*, 2013) and since it cannot be adsorbed by soil colloids leaching is most likely to occur. On the other side Bame *et al.* (2013) observed that P is less mobile as compared to nitrate so its possibility for leaching is less. Therefore it is important to investigate the uptake of N and P as affected by immobilisation or leaching, in a way that will assess either the benefit through reduced leaching, increased adsorption and uptake.

2.7 Miscellaneous effects of treated effluents on soil and plants

In spite of the advantages associated with irrigation using treated effluents, some negative effects may arise and these are of great importance as they determine the net benefits associated with the reuse of wastewater. For example, factors such as specific ion toxicity, salinity, environmental pollution, microbial contamination and health aspects and heavy metals are some of the negative effects that may possibly arise from the use of ABR effluent for irrigation. This section aims at reviewing potential miscellaneous effects after irrigation with ABR effluent as evidenced by several studies on different treated wastewaters. The assessment of potential harmful effects is very important in effecting the decision making process by policy makers and regulatory bodies.

2.7.1 Salinity and specific ion toxicity

Salinity refers to the amount of dissolved salts in a water solution. It is an indication of the presence of salts such as NaCl, $CaCl_2$, $MgSO_4$, Na_2SO_4, $CaSO_4$ and $NaHCO_3^-$. Salinity in the soil can have negative effects on plant water uptake, leading to reduced uptake of essential macronutrients via mass flow. The end results include premature aging and nutrient deficiency (Maksimovic and Illin, 2012). Salinity problems can be controlled in several ways such as the use of tolerant crops, application of fresh water and the removal of crops during dry season. Previous studies by El-Hamouri *et al.* (1995) have shown little effect of domestic wastewater on soil salinity in arid areas in the short term. However, long term irrigation with wastewater lead to significant accumulation of salts in the soil (Pescod, 1992; Al-Omron, 2010). Some crops such as Bermuda grass, however, could tolerate salinity to a certain level, due to their ability to uptake Na in cell vacuoles, leading to reduced intercellular space and increased leaf area (Delfine *et al.*, 1998). Other crops withstand high salinity levels by forming osmolytes such as amino acids (proline and glycine), which increase solute potential that maintains osmotic equilibrium for water uptake (Ashraf and Foolad, 2007). One of the ways to minimize salt accumulation within the rooting zone is leaching using fresh water and this depends on soil texture and vegetation (Pescod, 1992). In hot and dry periods accumulation of salts in the root zone could be minimised by vegetation removal during those periods (Maksimovic and Ilin, 2012).

2.7.2 Effect of treated wastewater on heavy metals

Heavy metals are of great food safety concern when irrigating with wastewater as their accumulation in soil and uptake by plants can lead to phytotoxic levels and animal poisoning (Tiller, 1986; Behbahaninia *et al.*, 2009). The effects on phytotoxicity are dependent on crop type; some crops can tolerate heavy metals while others cannot (Rattan *et al.*, 2005). Noxious heavy metals include Al, Cd, Pb, Se, Hg, Ar, Ni and Cr (Tiller, 1986). Among these Cd is not essential for both animal and plant physiology (Levy *et al.*, 2011). Other heavy metals such as Co are of little concern since plants cannot take them up at toxic quantities (Chang *et al.*, 2002). Cr is found in wastewater as a hexavalent ion, an unstable form which when in soil changes to a trivalent ion an insoluble form that is unavailable for plant uptake (Jiménez, 2006).

There are certain limits of heavy metals that are perceived safe for crops before they reach phytotoxic levels and these are: 2000 mg L^{-1} (Zn), 200 mg L^{-1} (Cu), 5000 mg L^{-1} (Fe), 200 mg L^{-1} (Mn), 200 mg L^{-1}(Ni), 5000 mg L^{-1} (Pb) and 10 mg L^{-1} (Cd) (Pescod, 1992). Faecal sludge contains quantities of heavy metals, which are within the acceptable limits for agriculture as compared to sewage treatment plant sludge because faecal matter comes from animals, which rarely consume heavy metals as compared to sewage treatment plants where municipal sewage might be contaminated with industrial wastewater (Levy *et al.*, 2011). Treated wastewater contains lower concentrations of heavy metals as compared to biosolids and the use of biosolids must comply with the DWAF sludge use standards (Herselman and Snyman, 2009). Heavy metals in treated effluents can be affected by the level of treatment, being high in raw wastewater and sewage sludge as compared to treated effluents (Behbahaninia *et al.*, 2009). This is because they are sorbed onto the organic solids except for a few soluble forms, which might be found in the effluent (Levy *et al.*, 2011). This implies that treated wastewaters contain lower concentrations of heavy metals whose accumulation in the soil can be due to prolonged irrigation with wastewater (Brar *et al.*, 2000; Rattan *et al.*, 2002). Moreover, most of the heavy metals are soluble in acidic conditions and they can be precipitated through liming so the presence of basic compounds in wastewater ($CaCO_3$ and Mg^{2+}) might reduce their solubility and uptake by plants (Ma and Lindsay, 1993). Studies show that ABR effluent is within the neutral and alkaline range (pH 6.5 to 8.4) so it is less likely to cause heavy metal toxicity in the soil. The accumulation of heavy metals can be affected by the irrigation type; drip irrigation will have localised build-up of heavy metals in the soil as compared to furrow irrigation (Mojiri and Aziz, 2011).

Several studies have shown that the uptake of certain heavy metals by specific crops is variable. Heavy metal toxicity risks are dependent on the use of the crop and edible part of the crop (Maksimovic and Ilin, 2012). According to Gharbi *et al.* (2005), heavy metals accumulate in lettuce roots as compared to edible parts (leaves). On contrary, Naaz and Pandey (2010) found some heavy metals lettuce shoot and roots although there were mostly concentrated within plant roots. Akbari *et al.* (2012) found that irrigation of dry beans with urban wastewater leads to the accumulation of heavy metals in bean roots and leaves as compared to the pods. On the other hand Harati *et al.* (2012) found the accumulation of Pb in maize leaves and, Cd and Ni in maize ear after irrigation with urban wastewater. Antoli´n *et al.* (2005) observed an increase in grain heavy metals in sewage sludge fertilised barley.

2.7.3 Effect on environmental pollution

A key objective of wastewater irrigation is to maximise mineral nutrient uptake and concurrently counteract water discharge problem in an environmental friendly way (Jiménez, 2006). Irrigation with treated wastewater can introduce nitrogen which can be nitrified to nitrates (NO_3^-) and this cannot be adsorbed by negatively charged soil colloids (Levy *et al.*, 2011) hence they can be easily leached down to underground water resources especially in sandy soils. The rate of leaching can be reduced by the action of microorganisms on organic matter to produce compounds such as polysaccharides. These can increase soil aggregation as well as the anion exchange capacity and retention of NO_3^- (Barton *et al.*, 2005). NO_3^- can contaminate the groundwater, exposing people to risks of diseases such as methaemoglobinaemia and stomach cancer (Hussain *et al.*, 2002). The presence of phosphorus can exacerbate algal blooms leading to considerable pollution of rivers (Kivaisi, 2001). Other factors which might increase pollution of rivers is reduced infiltration rate, leading to increased surface runoff, soil erosion and the deposition of P rich soil into the rivers causing eutrophication (Nhapi and Tirivarombo, 2005; Levy *et al.* 2011). Eutrophication results have multiplier effects such as mosquito breeding and outbreak of other vectors such as *Schistosomiasis* (Kivaisi, 2001). Groundwater contamination and eutrophication risks can be prevented by proper planning. Factors such as the level of the water table, slope, soil physical characteristics (texture, hydraulic conductivity, bulk density and matric potentials) and the proximity to water bodies (rivers) must be considered (Pescod, 1992; Helmar and Hespanhol, 1997).

2.7.4 Microbial contamination and health risks

Wastewater contains considerable pathogens and microorganisms that are of health concern (Pescod, 1992) hence its use must neither affect consumers nor human resources working with wastewater (WHO, 1989; DWAF, 1996; Strauss, 2000). To ensure that best quality of wastewater for irrigating crops is met expensive wastewater post treatments such as chlorination are required and they are hardly afforded in most developing countries (Blumenthal *et al.*, 1998). Some protozoan cysts such as Giardia and Cryptosporidium, nematode eggs and helminths eggs have been found to be major causes of crop contamination (DWAF, 1996; Strauss, 2000; Bouhoum *et al.*, 2002; Madyiwa *et al.*, 2002).

Several studies have confirmed that the microbial loads in most sewage wastewater is above the maximum recommended limit for agriculture use (Foxon *et al.*, 2005; Gumbo *et al.*, 2010) but some of the studies have shown low contamination level of crops irrigated with wastewater (Shahalam *et al.*, 1997; Aiello, 2007; Forslund *et al.*, 2010; Gumbo *et al.*, 2010). Forslund *et al.* (2010) found that potatoes irrigated with wastewater using drip irrigation experienced insignificant contamination, which indicate that microbial contamination of crops is dependent on the irrigation method and water quality. Shahalam *et al.* (1997) reported coliform free tomato skin irrigated with wastewater after 24 hours. Some factors contributing to the survival of pathogens include optimum conditions (neutral pH, moisture and temperature) and continuous use of wastewater (Mañas *et al.*, 2009). The most persistent and resistant pathogens are helminthic eggs (parasitic worms) which commonly affect children under the age of 15 in many developing countries and the risks have been found to be very common among families working with wastewater (Jiménez, 2006).

Most of the gastric diseases associated with wastewater are cholera, typhoid, shigellosis and ulcers, which are mostly spread by poor sanitation (Pescod, 1992 cited Sanchez-Duron, 1988; Weldesilassie *et al.*, 2010). Furthermore, women are the major players in agricultural labour source hence they can easily spread pathogens when handling food after work due to poor sanitation (Van der Hoek *et al.*, 2002).

Wastewater use guidelines have been developed to ensure that wastewater is handled in a safe manner that will protect the public, consumers and the workers exposed (WHO, 1989; Pescod, 1992; Scott *et al.*, 2004). World Health Organization (WHO), through several researches (epidemiological data, risk assessments and relevant information) came up with an international wastewater health guideline. These guidelines are not applicable internationally due to differences in social, economic and political practices; however they act as international standards. The guidelines consider factors such as crop restriction (eaten raw vs. cooked), method of irrigation (sprinkler vs. drip), worker safety (vaccination and sanitation education) and the quality of wastewater used (Thresholds of pathogens) (Pescod, 1992).

Crops that are eaten raw such as lettuce are at more risk to *E. coli* contamination and irrigation methods that exclude crop contamination should be considered. Drip irrigation and subsurface irrigation are recommended methods of irrigation. Some crops such as maize, dry bean and fruit trees are less likely to encounter contamination since the edible part is not in direct contact with effluent. Depending on the use of wastewater there are limitations to the population of certain pathogens in wastewater, for example in public areas such as parks where many people are exposed the wastewater must have faecal coliforms of <200/100 ml. Sanitation measures such as avoiding picking up fruits dropping from the ground during fruit harvesting are important (Drechsel *et al.*, 2010).

2.7.5 Cultural barriers and social perceptions

The implementation of a wastewater reuse program must consider social acceptance by communities since the use of excreta in agriculture may be culturally acceptable by some communities (UNHSP, 2008). Studies have shown that there is little acceptance in the handling of faecal matter amongst the communities in KwaZulu-Natal. However, education programs on the use of wastewater and excreta must be implemented to raise public awareness on issues such as proper handling of the sewage system (Foxon *et al.*, 2005). Urban planners and policy makers must consider wastewater treatment infrastructure that will link sanitation and food security issues. This can be very expensive to establish but it is a long term investment that may resolve urban waste management since several issues such as the disposal of urban sludge and wastewater due to ever increasing population are of concern (Drechsel *et al.*, 2010).

2.8 Problem statement

The decentralised waste water treatment system (DEWATS) provides a potential alternative to the provision of sanitation facilities to urban and peri-urban communities living in areas not connected to the main sewer systems. However, a key challenge posed by the DEWATS system is the disposal of the treated effluent which can cause pollution in water bodies. The treated effluent has been shown to contain high concentrations of nitrogen and phosphorus which are important mineral nutrients for plant growth. Recent studies have demonstrated the capacity of different soils to retain these nutrients from the effluent. However, there is inadequate information on the effect of using the ABR effluent on nutrient uptake, crop growth on different soils and leaching.

2.9 Aims and objectives

The aim of this study was to investigate the effect of ABR effluent irrigation on nutrient uptake and leaching, and growth of Swiss chard (*Beta vulgaris* subsp. *cicla*). The specific objectives were:

1. To conducts baseline studies on the effect of soil residual fertility on Swiss chard, dry bean and maize growth before irrigation with ABR effluent
2. To investigate leaching, nutrient uptake and growth of Swiss chard irrigated with ABR effluent under field conditions.
3. To investigate the effect of soil type (Acidic, Clay and Sand soils) and fertiliser combinations (Full, half and zero) on growth and yield of Swiss chard irrigated with ABR effluent under controlled conditions (Tunnel).

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CHAPTER 3

BASELINE STUDIES ON NUTRIENT UPTAKE, GROWTH AND YIELD OF SWISS CHARD, MAIZE AND DRY BEAN

Abstract

The Decentralised Wastewater Treatment System (DEWATS) is an alternative sanitation technology which has been assessed for low cost on-site sanitation by the Pollution Research Group of the University of KwaZulu-Natal. Its applicability is disadvantaged by the management of the effluent produced, which cannot be disposed into water bodies due to its effects on eutrophication. Baseline information on the site characteristics is important in wastewater use planning. A baseline study was done under field conditions aiming to investigate soil physical and chemical characteristics, nutrient uptake, crop growth and yield at Newlands Mashu. A factorial experiment was conducted in a split plot design with three blocks. The experimental treatments were three crops (maize, Swiss chard and dry bean) and three irrigation water sources namely tap water (TW), tap water with fertiliser (TWF) and rain-fed with fertiliser (RFF). Data collected included plant biomass, nutrient uptake, soil chemical properties (N, P, K, Ca, Mg, Zn, Mn, pH, organic C, total cations and acid saturation) and crop yield. Data was analysed using GenStat® 14th Edition (VSN International, Hemel Hempstead, UK). Significant differences ($P<0.05$) were observed with regard to soil pH between the three treatments. Significant increases were observed with respect to soil N, organic C ($P<0.01$) and Mn ($P<0.001$). There were no significant differences in Swiss chard biomass (fresh and dry mass) and dry bean 100 seed mass. TWF had a highest biomass with respect to Maize and dry bean. No significant differences were observed in chlorophyll content between the treatments in all the crops ($P>0.05$). In Swiss chard TWF treatment significant uptake of K ($P<0.05$) was observed. A significant uptake of Na by Swiss chard was observed in RFF treatment ($P>0.05$). In maize a significant uptake of K ($P>0.05$) was observed in TW treatment. The soil physical and chemical properties at Newlands Mashu were characterised. The residual soil fertility could support plant growth and did not have any significant effects on nutrient uptake by plants.

Keywords: Baseline studies, soil chemical properties, nutrient uptake.

3.0 INTRODUCTION

Alternatives to the provision of sanitation facilities to communities not connected to main sewer systems in urban municipalities include the use of decentralised wastewater management systems (DEWATS). The DEWATS system comprises of a series of compartments and human waste is subjected to anaerobic conditions which results into the decomposition of organic compounds. The system has been found to reduce the chemical oxygen demand (COD) and biological oxygen demand (BOD) at high treatment rate; however it produces treated effluent which may pose challenges with regards to disposal. The effluent also from the Anaerobic Baffled Reactor (ABR) contains mineral elements such as nitrogen and phosphorus which can cause pollution of rivers when disposed. However, these nutrients can be recovered and are potentially beneficial for agricultural use. ABR effluent use for crop production has been reported to improve dry matter yields compared with similar treatments irrigated with water (Bame, *et al.*, 2010; Odindo *et al.*, 2013). Therefore the effluent could supplement N and P fertiliser use for crop production thus reducing costs for small-scale peri-urban farmers.

The beneficial re-use of wastewater and biosolids in agriculture is widely recognised for improving soil properties, providing nutrients for crop uptake and growth and reduced leaching aimed at preventing contamination of surface and underground water. Leaching could be affected by several factors including soil physical properties (hydraulic conductivity and texture) and topography (Helmar and Hespanhol, 1997). Knowledge of soil physical properties could give an indication of the possibility of underground and surface water contamination.

The application of ABR effluent for irrigation requires knowledge of crop and soil types, as well as weather conditions. Therefore it would be important to characterize and assess soil types and monitor crop growth at locations before application of the ABR effluent. The determination of soil, crop and weather conditions for each specific location and the effect of ABR effluent through experimentation can be very laborious, time consuming and expensive. Therefore it is important to characterize initial conditions (soil properties, weather conditions, crop nutrient uptake and growth) at locations representative of a wide range of soils and weather variables that could be used as baseline data for studies on the effect of using ABR effluent as a nutrient and water source for crop production. Such baseline data could be applied to future modelling studies. In addition studies on the use of ABR effluent for irrigation should be cognisant of the potential effects of the residual soil fertility at such sites; and possibility of separating the effect of residual fertility and ABR effluent irrigation on mineral nutrient uptake, crop growth and yield performance. The aim of this study was to characterize the soil properties of the study site at Newland Mashu and generate base line information on the effect of residual soil fertility on mineral uptake, crop growth and yield of selected crops.

The specific objectives were:

1. To describe the physical and chemical properties of soils at the experimental site.
2. To determine the effect of residual soil fertility on biomass production of dry bean, maize and Swiss chard crops grown on these soils.
3. To determine nutrient uptake by Swiss chard and maize plants grown on soils at the Newlands Mashu Permaculture Centre.

3.1 MATERIALS AND METHODS

3.1.1 Experimental Site

Field experiments were carried out at the Newlands Mashu Permaculture Centre in Durban (Figure 3.1). The site is located at a longitude of 30°57'E and latitude of 29°58'S. It has a mean annual rainfall of 1000 mm and daily average temperatures of 20.5°C (www.durban.climatemps.com).

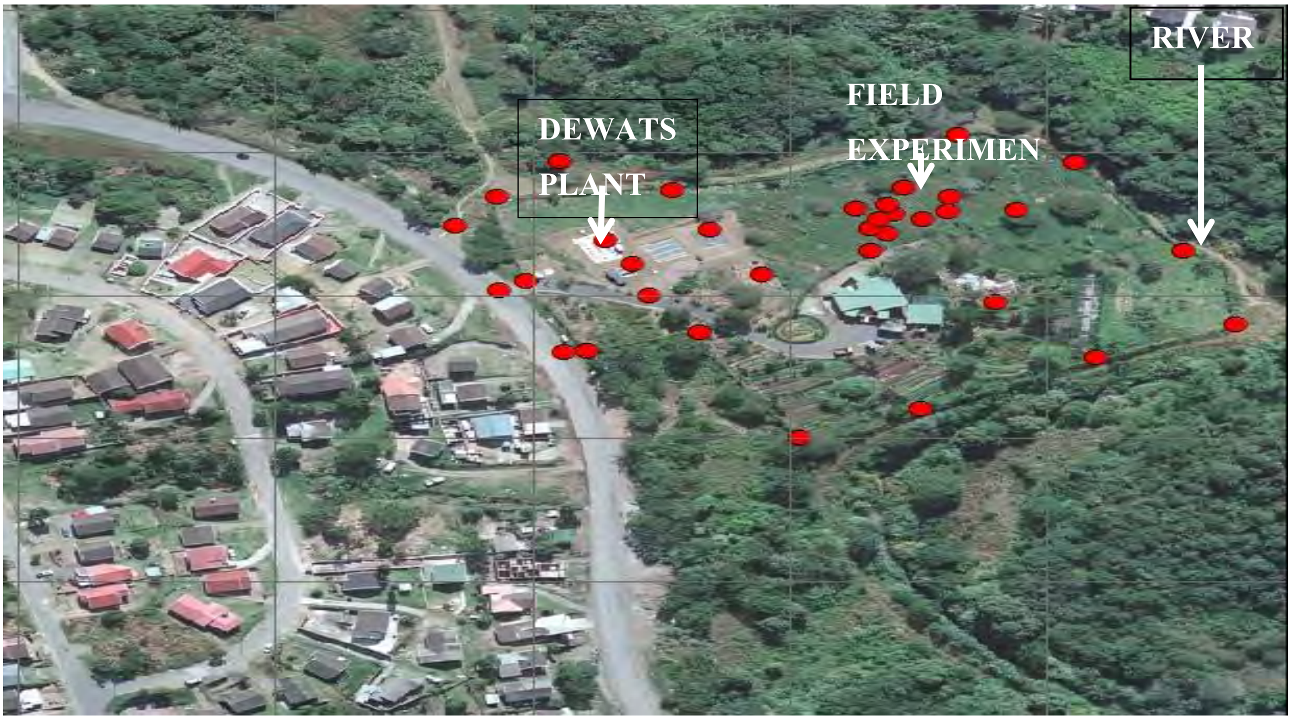

Figure 3.1 A map showing an aerial view of the experimental site, physical features (River) and the surrounding households

3.1.2 Experimental material

Seeds of the Swiss chard cultivar Ford Hook Giant variety, maize (Mac pearl mid-season variety) and PAN 116 dry bean cultivar (medium season variety) were used in the trials.

3.1.3 Experimental methodology

3.1.3.1 The characterisation of soil physical properties

The experimental site was divided into three blocks measuring 10 x 23 m^2 and each block containing three plots totalling to nine experimental plots. The experimental plots varied in size with the Swiss chard and maize plots measuring 4 x 4 m^2 and the bean plot size measuring 2 x 5 m^2. Three pits were dug at the edges of each block and undisturbed cores collected at four different depths (10, 30, 50 and 100 cm) to determine soil physical properties (saturated hydraulic conductivity, soil texture, bulk density and water retention). The choice of choosing these depths was based on Wetting Front Detectors (WFD) locations, which were placed at 30 cm and 50 cm depths.

3.1.3.2 The determination of water retention

Soil volumetric water content was determined at two matric potential of -33 kPa (field capacity) and -1 500 kPa (permanent wilting point). Undisturbed soil cores were collected from the three blocks and four depths and they were saturated in the laboratory. The soil water retention curve was developed by exposing the core samples to various tensions and concurrently measuring the soil water content at each corresponding matric potential. For the higher water potential ranges of up to -100 kPa a hanging column of water was used as prescribed by Avery and Bascomb (1974). At lower water potentials up to -1 500 kPa, a pressure plate apparatus (Soil Moisture Equipment Corp., Santa Barbara, California) was used to generate the water content at a gradient of soil water matric suctions. The plates for the pressure plate apparatus were initially soaked in distilled water overnight. The core samples were then placed on top of a filter paper on the pressure plate and the sample was allowed to get saturated from the bottom under suction in an air tight chamber as described by Klute (1986). The retention curve was developed using Retention Curve (RETC) model. The matric potentials at field capacity and wilting point for the soil were determined according to Schulze *et al.* (1985).

3.1.3.3 Particle size analysis

Soil texture was determined at each layer and block according to the United States Department of Agriculture (USDA) classification system (Samuel *et al.*, 1993). Soil samples collected were ground and passed through various diameters of sieves; 2.0-0.05 mm (sand), 0.05-0.02 mm (silt) and <0.002 mm (clay). The different soil compositions were expressed as percentages and compared to the USDA textural classification chart (Figure 3.2)

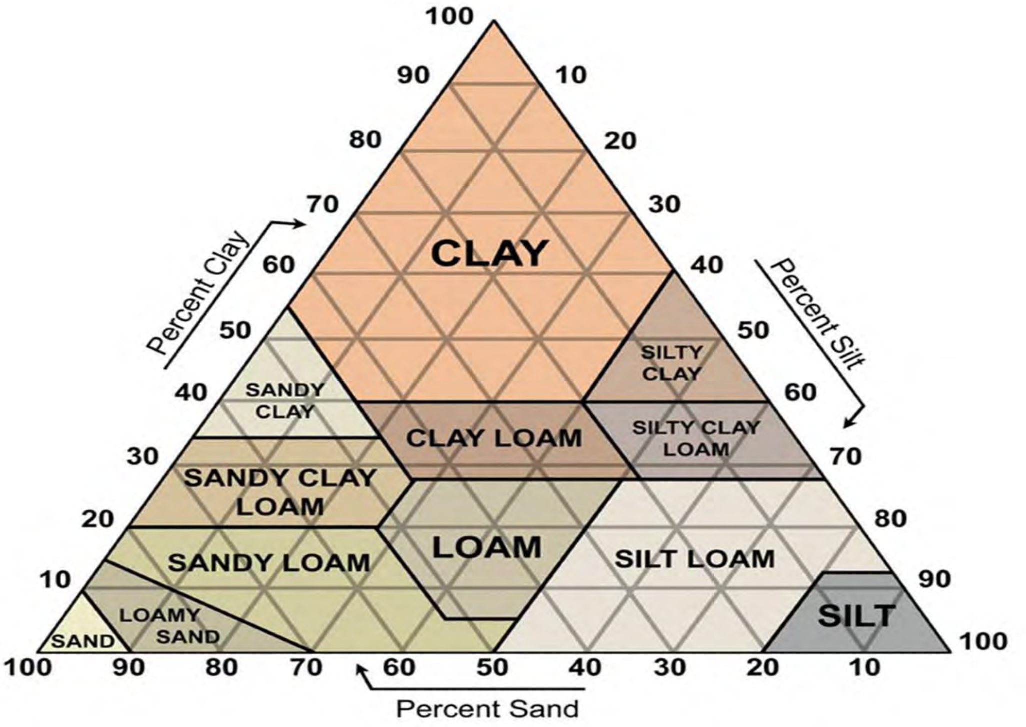

Figure 3.2 USDA soil textural classification chart used to determine soil textural class.

3.1.3.4 The determination of bulk density

Soil bulk density was determined using a core method according to Blake and Hartge (1986). Undisturbed soil cores, with a diameter of 100 mm and a thickness of 80 mm were taken from each layer and different blocks. The soil samples were covered when transported to the laboratory and were immediately oven-dried for 24 hours at 105°C until reached steady mass state. The volume of the core was calculated as per Eq. 3.1 below:

$$\text{Volume (V)} = \prod R^2 H \qquad \text{Eq. 3.1.}$$

$$=22/7 \times (5\ \text{cm}^2) \times 80\ \text{cm}$$

The bulk density (ρ_b) was then calculated by dividing mass of the soil per unit volume as in Eq. 3.2 below:

$$\rho_b = M/V \qquad \text{Eq. 3.2.}$$

M= mass of oven dried soil

3.1.3.5 Determination of saturated hydraulic conductivity (K_{sat})

Saturated hydraulic conductivity was determined in the laboratory according to the method proposed by Hillel (1980). A column of 2.7 cm diameter and 30 cm height was packed with the soil samples from the study site. The column had openings on the sides which were connected to permeameters in order to measure the soil water potential. Water was siphoned from a raised marriot flask to the bottom of the column. Water flow through the top of the column was collected in a graduated cylinder every 10 minute intervals. Once steady state was reached, the water flux density and the hydraulic head gradients were measured from which the saturated hydraulic conductivity was determined using Darcy's equation. During the siphoning of the water the water head was maintained at 400 mm above the soil column.

3.1.3.6 The determination of soil organic C

Soil organic C was determined according to methods by Walkey and Black (1934). The organic C was determined according to the calculations below:

$$(1 - S / B) \times 10 \times 0.68 = \text{organic matter (\%) of sample} \qquad \text{Eq. 3.3.}$$

Where,

S = Volume of Ferrous Sulphate solution required to titrate the sample, in mL.

B = Average Volume of Ferrous Sulphate solution required to titrate the two blanks, in mL.

10 = conversion factor for units.

0.68 was a factor derived from the conversion of % organic C to % organic matter

3.1.3.7 The determination of soil chemical properties

Initial soil chemical analysis was done before planting. Soil samples representative of the experimental site were collected from five randomly chosen points in each plot using an auger to a depth of 20-30 cm and bulked. Composite samples were sent to the Fertiliser Advisory Service, KZN Department of Agriculture and Environmental Affairs; Soil Fertility and Analytical Service, CEDARA for chemical analysis. Additional soil samples were collected for soil chemical analyses after harvesting the planted crops.

3.1.3.8 Experimental design and trial establishment

The plots were ploughed, disked and harrowed. The field experiment was laid out as a 3 x 3 factorial treatment structure in a split plot arrangement with three blocks. The main plot treatments were irrigation treatments (tap water with no fertiliser (TW); tap water + fertiliser (TWF) and rain-fed conditions with fertiliser (RFF)). The sub-plot treatments were crop species (maize, beans and Swiss chard) thus giving a total of 27 experimental units (sub-plots). Treatments were randomly allocated to plots within each block. Wetting front detectors (WFDs) were installed at two depth intervals (30 and 50 cm) (Fig. 3.3).

Figure 3.3 A 50 cm wetting front detector in situ showing the red knob (indicator) which pops up when it is full.

3.1.3.9 Planting of crops

Maize, Swiss chard and dry bean seeds were planted on specific dates, plant spacing and depths as described in Table 3.1. Fertilisers (Urea, DAP and KCl) were applied on the TWF and RFF treatments based on CEDARA Fertiliser Advisory Services recommended optimum rates (Table 3.2 and 3.5). DAP was applied at planting while KCl and Urea was applied two weeks after planting amongst all the crops. For maize and dry bean urea was split applied at two and six weeks after planting. The plots were watered using tap water for two weeks to stimulate germination and establishment at a specified flow rate and time (five to seven minutes). Emergence percentage was recorded after two weeks.

Table 3.1 Swiss chard, dry bean and maize planting information (fertilisers applied, spacing, planting date and depth) according to Smith, 2006.

Crop	Fertiliser applied kg ha^{-1}	Spacing	Planting date	Planting depth
Swiss chard	DAP: 200 Urea: 217 KCl: 288.5	30 cm x30 cm	14 February 2012	2 cm
Maize	DAP:300 Urea: 395	30 cm X 45 cm	29 February 2012	5 cm
Dry bean	KCl: 19 DAP: 100 Urea: 174	20 cm X 75 cm	29 February 2012	5 cm

Table 3.2 Nutrient recommendations for Swiss chard, dry bean and maize based on soil chemical properties

		Nutrient recommendations			
Crop	**Target yield t ha^{-1}**	**Nitrogen kg ha^{-1}**	**Phosphorus kg ha^{-1}**	**Potassium kg ha^{-1}**	**Lime kg ha^{-1}**
Beans	2	80	20	0	0
Swiss chard	40	100	40	150	0
Maize	12	200	60	10	0

3.1.3.10 Irrigation system and management of trial

Irrigation treatments were applied using a modified drip system. Coke bottles (2 litres) were perforated at the bottom and used for irrigation. These were submerged 5 cm below ground and used for drip irrigation between TW and TWF treatments (Figure 3.4). Irrigation of the crop was done according to an irrigation schedule which took into account crop water requirements, soil physical properties and rainfall. Rainfall data was acquired from the South African Weather Services, Mt. Edgecombe. Water was quantified based on different soil water requirements amongst different blocks down to a 50 cm depth. No pests and diseases were observed during the study but the weeding of the trial was done manually when necessary.

Figure 3.4 Two litre coke bottle perforated at the bottom using a 6 inch nail (A) and coke bottles submerged 5 cm into the soil for drip irrigation of Swiss chard (B) and maize (C)

3.1.4 Data collection

3.1.4.5 The determination of chlorophyll content

Chlorophyll content of the crops under investigation was measured at different stages of growth using a CCM200 chlorophyll meter (Optisciences Inc., USA) see Table 3.2.

Table 3.3 Timing of chlorophyll content measurements for Swiss chard, maize and dry bean

Crop	Stage of data collection
Swiss chard	4 and 8 weeks after planting
Maize	2, 4 and 6 weeks after planting
Dry bean	4, 5 and 6 weeks after planting

3.1.4.6 Leaf yield, fresh and dry mass determination

Swiss chard was harvested at eight weeks after crop emergence while maize and dry bean were harvested at 16 weeks after crop emergence (maturity stage). The crops were harvested 1 cm above the soil surface to determine the above ground biomass. Swiss chard yield is based on fresh biomass (t ha^{-1}). Above ground dry mass was then measured after oven drying the plants at 70 ^{o}C for 72 hours.

3.1.4.7 Plant height

Plant height in maize was measured at silking stage from the base to the bottom of the tassel (Yada, 2011).

3.1.4.8 Seed yield

No data on grain yield was recorded for maize due the damage caused by monkeys during the dough stage.

3.1.4.9 Dry bean 100 seed mass

Seed mass was estimated by measuring the mass of 100 seeds in grams.

3.1.4.10 Plant tissue nutrient content determination

Maize leaves were collected for plant tissue analysis at the silking stage. The leaves were collected from opposite direction to the ear leaf as prescribed by Campbell (2000). Similarly, full plant samples were collected from Swiss chard 1 cm above the soil surface to determine the plant nutrient status at eight weeks after crop emergence. The plants were oven dried at 70 ^{o}C for

72 hours. Dried plants were selected, bulked per each plot and sieved through a 1 mm sieve before being taken for plant tissue analysis at Fertiliser Advisory Service, KZN Department of Agriculture and Environmental Affairs; Soil Fertility and Analytical Service, CEDARA where they were analysed for macro and micronutrients.

3.1.5 Data analysis

All statistical analyses were performed using GenStat® 14th Edition (VSN International, Hemel Hempstead, UK). Means were compared using SEDs at the 5% level significance. T-tests were done to compare differences between two soil sample means (before planting and after harvesting).

3.2 RESULTS

3.2.3 Soil physical properties before irrigation with ABR effluent

Table 3.3 shows the particle size distribution, organic C (%) bulk density (g cm^{-3}), water content (cm^{3} cm^{-3}) at permanent wilting point, field capacity and saturated hydraulic conductivity K_{sat} (mm h^{-1}). Block 1 (B1) and 2 (B2) are similar with regards to particle size distribution; however, Block 3 (B3) is slightly different. Clay content tends to increase as you go down the profile but the clay is higher in B1 and B2 than in B3. Organic C also decreases down the profile which as expected but the decrease is greater in B1 and B2 than in B3. There was not much difference in the bulk density within the whole profile except at 50 to 100 cm (Top - B1) and 100 cm (Middle – B2). This could probably be attributed to machinery, which may have caused soil compaction. Some of the figures on the saturated hydraulic conductivity (Top 50 cm, middle 30 cm, middle 50 cm and middle 100 cm) could not be determined as there was negligible infiltration of water probably due to high clay content as you move down the soil profile.

Table 3.4 Soil physical properties sampled at different depths (10, 30, 50 and 100 cm)

Profile position	**Soil depth (cm)**	**Particle size distribution (%)**			**Org C (%)**	**Bulk density (g /cm^3)**	**Water content at -33 kPa (cm^3/cm^3)**	**Water content at -1500 kPa (cm^3/cm^3)**	**K$_{sat}$(mm/h)**
		Sand	**Silt**	**Clay**					
Top (B1)	10	30	46	24	3.8	1.406	0.247	0.013	4.68
	30	22	43	35	2.5	1.638	0.251	0.045	0.10
	50	26	31	43	0.6	-	0.268	0.048	-
	100	26	29	45	0.3	-	0.292	0.018	0.03
Middle (B2)	10	32	39	29	3.7	1.307	0.261	0.139	1.60
	30	28	41	31	1.6	1.322	0.287	0.142	-
	50	31	26	43	0.4	1.484	0.262	0.118	-
	100	26	24	50	0.1	-	0.410	0.039	-
Bottom (B3)	10	33	46	21	2.4	1.636	0.233	0.162	0.17
	30	28	48	24	2.1	1.551	0.235	0.182	1.76
	50	28	44	28	2.0	1.215	0.446	0.278	-
	100	16	42	42	1.3	1.567	0.294	0.102	1.01

3.2.4 Soil chemical properties before planting

Table 3.5 shows the initial soil chemical properties of the experimental site before planting. The soils at Newlands Mashu site are clay loam soils with 32.2% clay content. The nitrogen and phosphorus content of the site is 0.22% and 74.6 mg kg^{-1} respectively. Table 3.2 shows the nutrient recommendations (N, P and K) for dry bean, Swiss chard and maize. The table generally shows that there is no need for liming amongst all the crops.

Table 3.5 Soil chemical properties of Newlands Mashu sampled before planting, within the top 30 cm soil profile.

Property	**Value**
Organic C (%)	2.24
N (%)	0.22
P (mg kg^{-1})	74.6
K ($cmol_c$ kg^{-1})	0.3
Ca ($cmol_c$ kg^{-1})	10.2
Mg ($cmol_c$ kg^{-1})	6.5
Exch. acidity ($cmol_c$ kg^{-1})	0.05
Total cation ($cmol_c$ kg^{-1})	17.1
Acid sat. (%)	0
pH (KCl)	5.23
Zn (mg kg^{-1})	43.5
Mn (mg kg^{-1})	4.81
Cu (mg kg^{-1})	14.6

3.2.5 Soil chemical properties after harvesting

Table 3.6 shows soil chemical properties amongst the three treatments after harvesting during the baseline studies. Insignificant differences were observed in most of the soil chemical properties except for the pH which differed significantly ($P<0.05$).

Figure 3.5 shows soil pH observed amongst the three treatments after harvesting during the baseline studies. Higher soil pH values were observed within the TW and the TWF treatments (5.4 and 5.2 respectively) as compared to the RFF treatments (4.9)

Table 3.6 Soil chemical properties after harvesting amongst the three treatments tap water with no fertiliser (TW), tap water with fertiliser (TWF) and rain-fed with fertiliser (RFF)

S .O.V.	**D.f.**	**P**	**K**	**Ca**	**Exch. Acid**	**Total Cat.**	**Acid. Sat**	**pH**	**Zn**	**Mn**	**Cu**	**N**	**Org. C**
Block	2	n	n	n	n	n	n	n	n	n	n	n	n
Treatment	2	n	n	n	n	n	n	s	n	n	n	n	n
Residual	22	n	n	n	n	n	n	n	n	n	n	n	n
Total	26												

*n denotes insignificant difference *s denotes significant differences at 5% level.

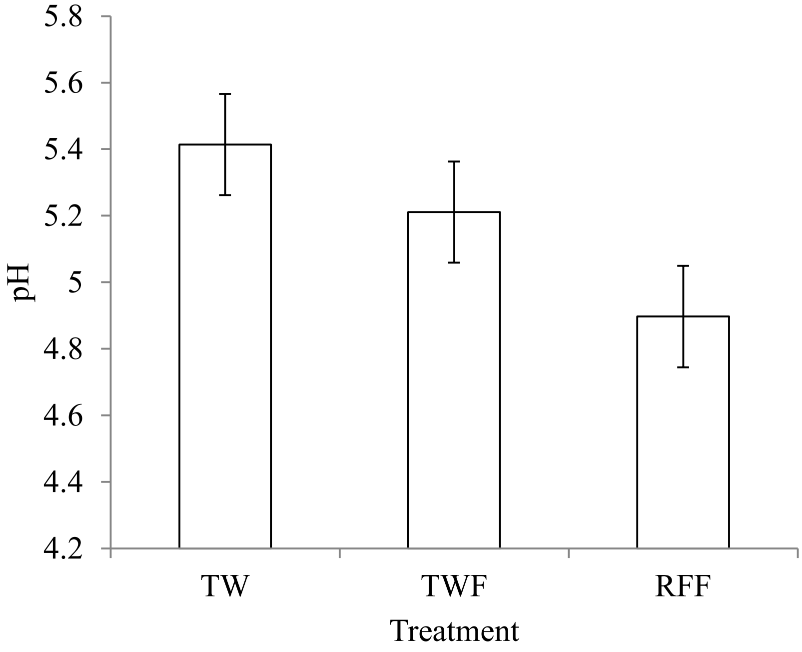

Figure 3.5 Soil pH amongst the three treatments (TW, TWF and RFF) after harvesting, during the baseline studies

3.2.6 Comparing the soil chemical properties (before planting and after harvesting) in summer 2012 season.

Table 3.7 shows F values for the t-test to compare the changes in soil chemical properties before planting and after harvesting. Changes were observed with respect to Mn ($P<0.05$), organic C and N ($P<0.001$).

Figure 3.6 shows the concentrations of soil Mn, N and organic C after the harvesting of crops during the baseline studies. There was a higher concentration of Mn after harvesting (11.03 mg kg^{-1}) as compared to the amounts available before planting (4.826 mg kg^{-1}). A significant increase in soil N content was also observed after harvesting (0.3314 %) compared to before planting (0.222%). A similar trend was also observed with respect to organic C which increased from 2.24% to 3.061%.

Table 3.7 T- test (F values) to compare the soil chemical properties after crop production during the summer 2012 season.

Soil chemical property	**F probability**
P	0.086
K	0.48
Ca	0.174
Exch. Acid	0.24
Total. Cat	0.07
Acid. Sat	0
pH	0.58
Zn	0.95
Mn	0.01
Cu	0.24
N	< 0.001
Org. C	<0.001

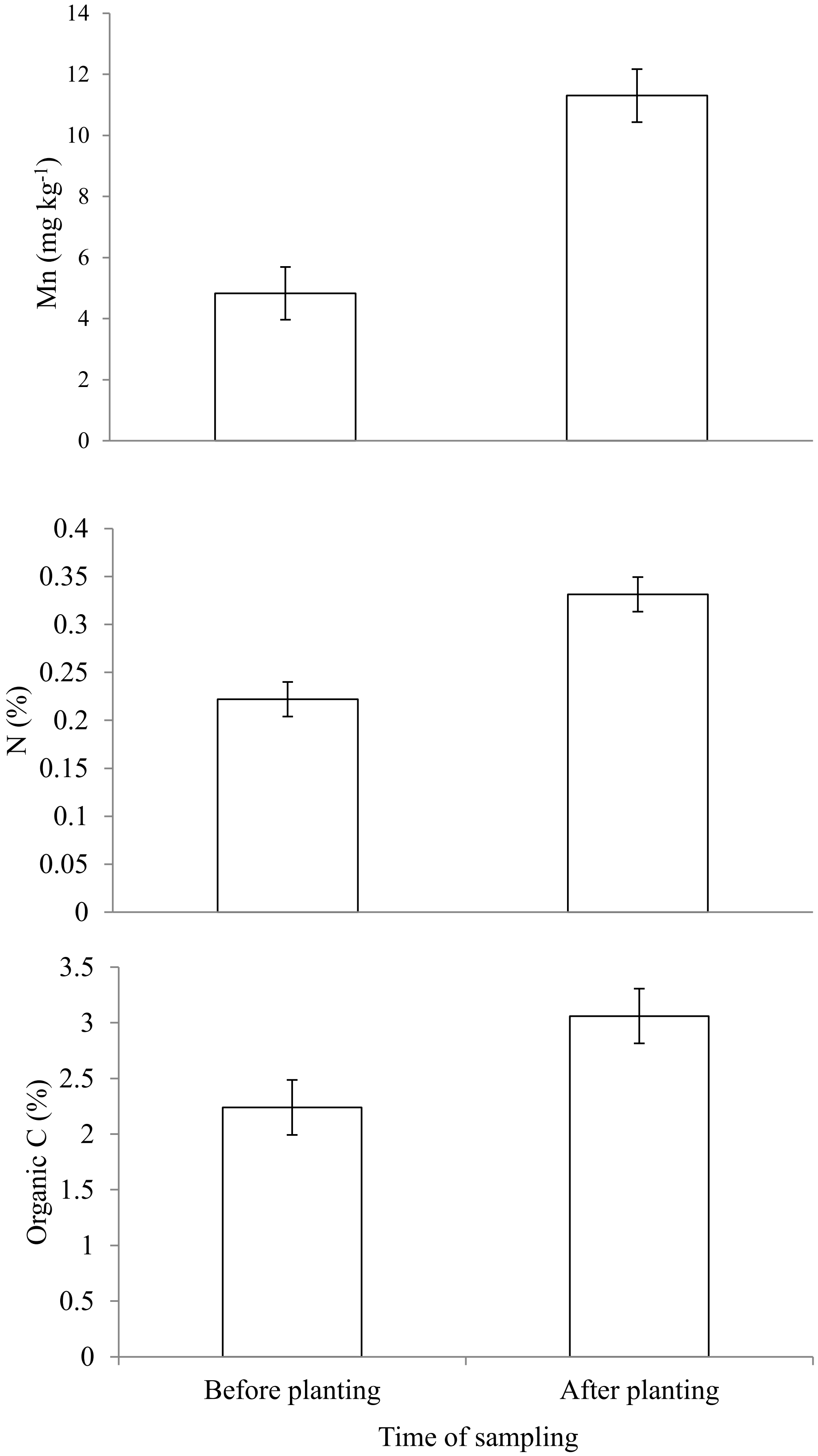

Figure 3.6. The analysis of soil Mn, N and organic C after the first harvest during baseline studies.

3.2.7 Effect of soil fertility on maize, dry bean and Swiss chard growth and yield

3.2.7.5 Swiss chard

Table 3.8 shows mean of squares for plant biomass production (Fresh mass, dry mass and yield) and chlorophyll content of Swiss chard during the baseline studies. No significant differences in all the above mentioned parameters were observed amongst the treatments (Figure 3.7).

Table 3.8 Mean squares for Swiss chard growth (fresh mass, dry mass, yield and chlorophyll content) results amongst the 3 treatments (TW, TWF and RFF).

S.O.V.	**D.f.**	**Fresh mass**	**Dry mass**	**Yield**	**Chlorophyll week 4**	**Chlorophyll week 8**
Block	2	7967	91.05	98.36	24.41	0.96
Treatment	2	10935	12.57	135	0.59	1.92
Residual	4	6635	91.24	81.91	34.68	17.19
Total	**8**					

Figure 3.7 Swiss chard plants from the TW treatment (A) and from the TWF treatment (B) during the 2012 summer baseline studies.

3.2.7.6 Maize

Figure 3.8 shows plant growth results of maize amongst the 3 treatments (TW, TWF and RFF) during the baseline studies. TWF treatment had a significantly high plant height (174.8 cm plant^{-1} as compared RFF and TW treatments which were 148.8 cm plant^{-1} and 146.7 cm plant^{-1} respectively. However, TWF and TW treatments had significantly higher biomass values (353.3 g plant^{-1} and 311 g plant^{-1} respectively) as compared to RFF treatment (235.6 g plant^{-1}). Chlorophyll content results showed insignificant differences among treatments on similar sampling dates, however, the chlorophyl content increased significantly as the plant grew.

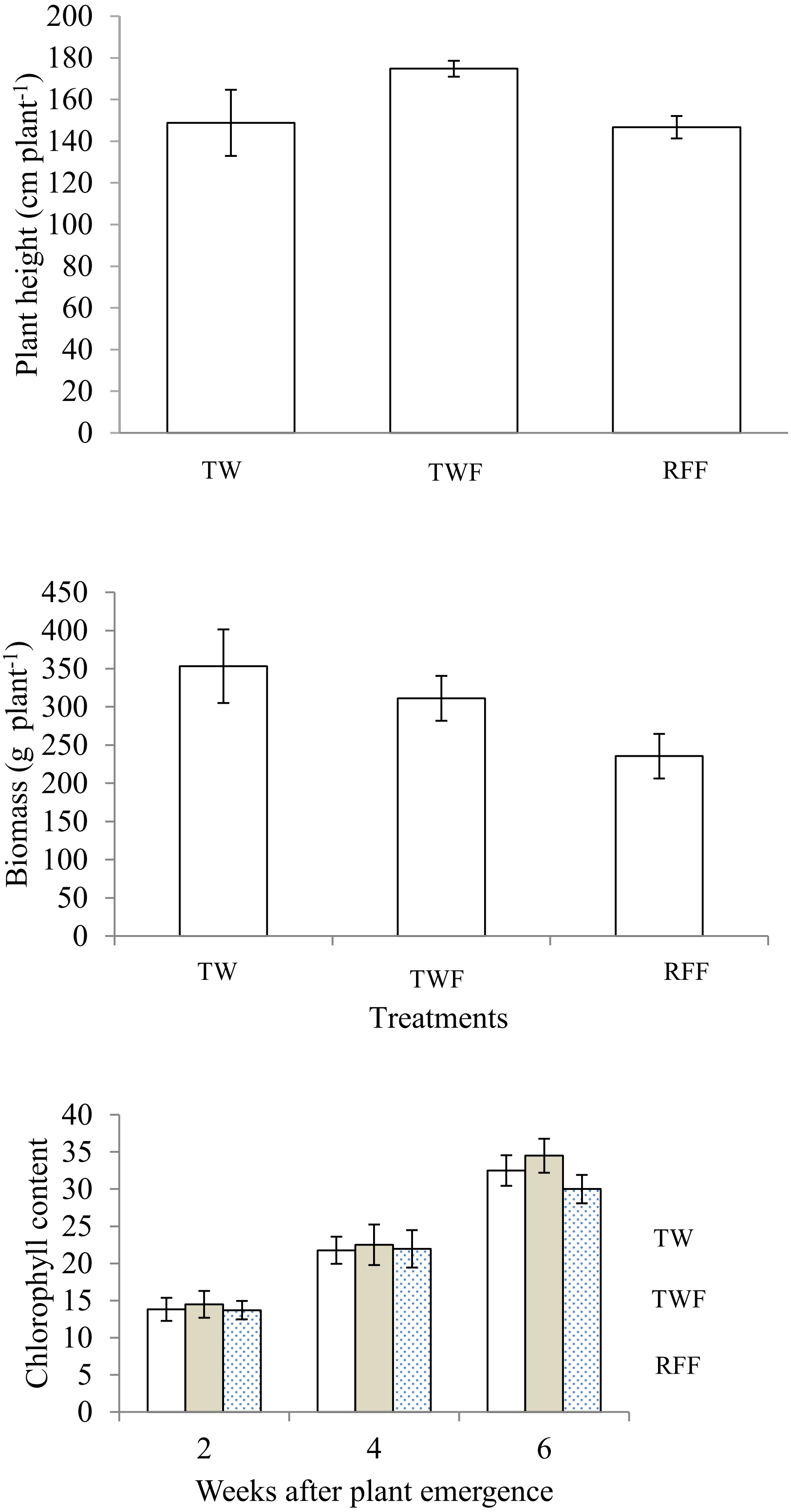

Figure 3.8 Maize growth (Biomass and plant height) and chlorophyll content during the baseline studies.

3.2.7.7 Dry bean

Figure 3.9 shows dry bean growth and yield results amongst the three treatments (TW, TWF and RFF) during the baseline studies. Insignificant differences were observed with respect to dry bean 100 seed mass amongst the three treatments. However significant differences were observed with respect to bean dry mass (g plant^{-1}). TWF and TW treatments had higher dry mass (87.3 g plant^{-1} and 68.5 g plant^{-1} respectively) while the RFF treatment had the least dry mass (50.4 g plant^{-1}). Insignificant differences were observed with respect to dry bean chlorophyll content amongst the treatments. Chlorophyl content, however, varied significantly across time during the growing season.

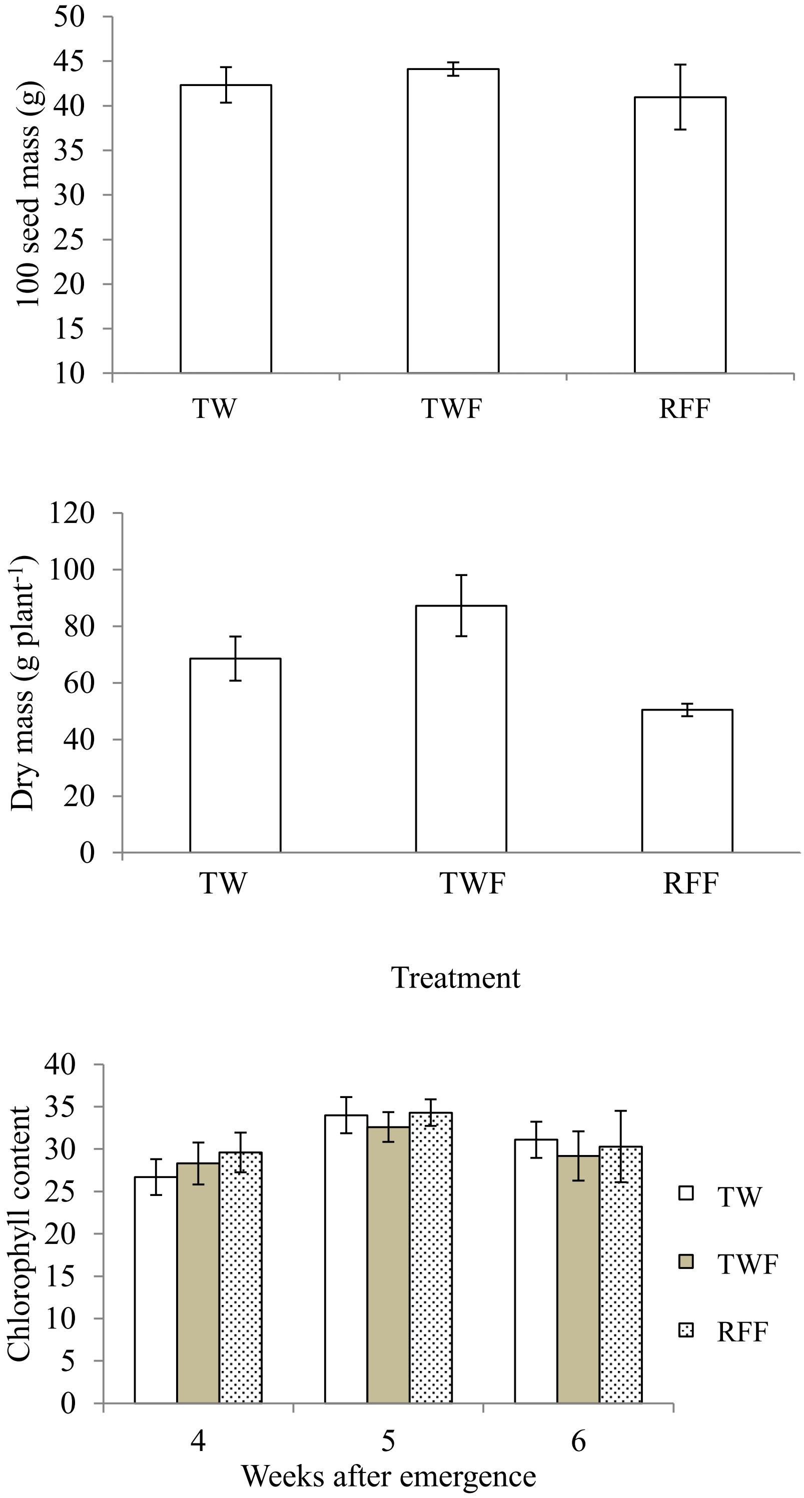

Figure 3.9 Dry bean growth (dry mass), chlorophyll content and 100 seed mass (g) results during the baseline studies.

3.2.8 Maize and Swiss chard plant tissue nutrient analysis results.

Table 3.9 shows mean of squares for plant tissue nutrient analysis results for maize and Swiss chard amongst the three treatments (TW, TWF and RFF) during the baseline studies. Significant differences were observed with respect to Swiss chard Na uptake ($P<0.05$). The concentrations of Na taken up by different Swiss chard treatments (TW, TWF and RFF) are described in figure 3.10. The results were characterised by high uptake of Na in Swiss chard RFF treatment (4.6 %) as compared to TW (3.78%) and TWF (3.13%) treatments.

Table 3.9 Mean of squares for plant tissue nutrient analysis results for Swiss chard and Maize during the baseline studies

S.O.V.	D.f.	N	P	K	Ca	Fe	Zn	Cu	Mn	Na	Mg
						Maize					
Block	2	0.01879	0.00603	0.0319	0.00824	3341	29.82	0.04777	103.35	0.00104	0.08252
Treatment	2	0.07709	0.00328	0.23945	0.01361	10404	81.11	0.1681	3.95	4.04E-05	0.0003
Residual	4	0.05374	0.00166	0.0694	0.00823	2318	41.5	0.04777	63.89	0.00045	0.02663
Total	**8**										
						Swiss chard					
Block	2	0.0196	0.00488	0.02683	0.01389	432685	11566	4.92	421	0.6924	0.0055
Treatment	2	0.0635	0.00242	0.093	0.03583	261164	346	5.52	536	1.6329*	0.0093
Residual	4	0.1831	0.00196	0.04625	0.0132	142215	8357	12.94	1072	0.1651	0.1306
Total	**8**										

*Denotes significance at <0.05 **Denotes significance at <0.01 ***Denotes significance at <0.001

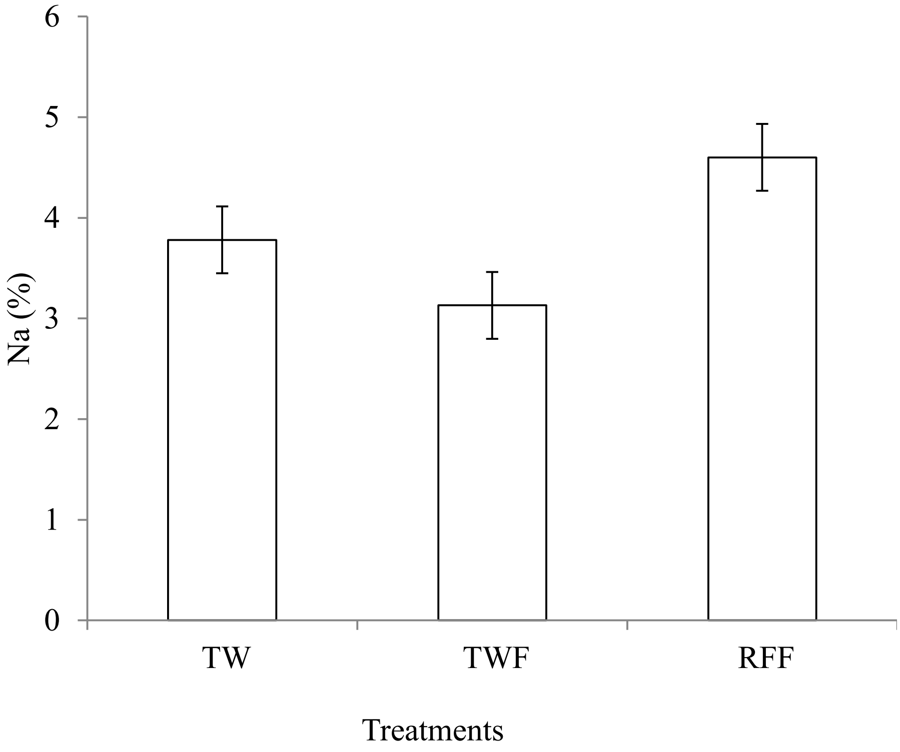

Figure 3.10 Differences in Na concentration in different Swiss chard treatments (TW, TWF and RFF)

3.3 DISCUSSION

A significant increase in soil Mn content observed was not clearly understood and needs further investigation. Organically bound N from organic matter (e.g. humus) can be converted to inorganic forms through the process of mineralisation (Bar-Tal, 2011). The increase in soil inorganic N through mineralisation of organic N takes several years. The reasons behind increased soil N were not clear and cannot be concluded from a single season experiment hence needs further investigation. Soil pH differences observed were attributed to differences in underlying rock minerals properties as stated in Clemston (2013) factsheet. Different factors including the application of nitrogen fertilisers such as urea and ammonium nitrate and dry plant residues might have contributed to increased acidity (Samuel *et al.*, 1993). The pH values observed were statistically similar between TW and TWF (Figure 3.5) and also organic C values were not significantly different amongst the treatments (Table 3.6). This observation implies that neither plant residues nor fertilisers contributed to soil pH. Fresh plant residues left in the soil are referred to as labile pool of organic matter added to the soil and they can increase soil organic C (Palm *et al.*, 2001; Chan, 2008). These are broken down very fast over a period of between few weeks and years (Bell and Lawrence, 2009). The breakdown of labile material in the soil is associated with the release of mineral nutrients such as N, especially when the residues are from more succulent plants such as Swiss chard. This is implies that an increase in soil N, Mn and organic C during the baseline studies could have been attributed to the breakdown of labile organic matter.

Insignificant differences in plant growth parameters observed in Swiss chard have been attributed to adequate rainfall during its growth period and probably soil fertility. Moreover, Swiss chard is a short season crop which grows over a period of 8 weeks and its growth coincided with high rainfall period (Appendix 1). This observation further agrees with Jiménez (2006) that a soil environment is a complex mixture of organic and inorganic compounds with a wide variation. Implying that sometimes increased growth in plants following irrigation with wastewater can be affected by residual fertility hence baseline studies are necessary.

According to Schepers *et al.* (1998) nitrogen sufficiency can be related to chlorophyll content in plants. Insignificant differences in maize, Swiss chard and dry bean chlorophyll content amongst the treatments at different stages of growths was due to significant soil nitrogen content. This observation has also supported insignificant differences in nutrient uptake between all the treatments in all crops (Table 3.9) implying that the soil was fertile enough to support plant growth. Chlorophyll synthesis is affected by mineral nutrients such as Fe, Mg and N (Thapliyal *et al.*, 2011). The chlorophyll content increased within the maize, Swiss chard and dry bean as they grew due to increased photosynthetic capacity (Homayoun *et al.*, 2011). A decrease in chlorophyll content observed in dry bean at six weeks after emergence (Figure 3.6) was due to plant senescence (Ahmadi, 1985)

Maize growth results have reported a significantly high growth (Biomass and plant height) between TW and TWF treatments as compared to RFF. Inorganic fertilisers were applied to RFF and TWF so lower growth observed could not be attributed to nutrient deficiency. Furthermore, TW was irrigated with tap water only without any application of inorganic fertiliser meaning that higher growth was due adequate water and residual fertility. The reason behind low growth in RFF treatment is a decline in rainfall three weeks after crop emergence and later, however, TW and TWF were supplemented with irrigation water during that period and never succumbed to water stress (Appendix 1). Dry bean showed a similar trend as in maize with special reference to dry mass. Dry bean has a long growing season as compared to Swiss chard (about 3 to 4 months) the RFF treatment was affected by water stress, giving rise to low biomass within that particular treatment.

High uptake of Na by Swiss chard in RFF treatment was not well understood but could have probably be associated with the Na concentrations within the plots. However, further investigations need to be done to assess the Na concentrations in different plots. One of the possibilities concerning high Na uptake within the RFF treatment could be salinity (Maksimovic and Ilin, 2012). Studies by Liu *et al.* (2013) showed that increasing Na concentration in the soil leads to its accumulation in Swiss chard tissue, coupled with reduced K uptake. Studies by Subbarao *et al.* (2000) showed that under low soil K there is high Na uptake in halophytic plants. This implies that high Na uptake could have been attributed to higher proportion of Na compared to K within the RFF plots.

3.4 CONCLUSIONS AND RECOMMENDATIONS

The soil physical and chemical properties at the experimental site have been characterised. The soils are generally clayey loam soil type implying that they are characterised by low hydraulic conductivity hence irrigation with sewage effluent is less likely to contaminate underground water resources.

Swiss chard growth and yield between fertiliser (TWF and RFF) treatments and non-fertiliser treatment (TW) was comparable. In maize and dry bean high biomass observed in irrigated treatments (TW and TWF) implies that crop growth was limited by water than nutrients. The residual soil fertility was high enough to support crop growth hence nutrient loading must be considered when irrigating with treated sewage effluent. Due to high soil fertility irrigation with wastewater might add excessive N and negatively affect the yield of flowering plants.

There was no significant difference in nutrient uptake between all the treatments (TWF, TW and RFF) in both crops. This gives further evidence that site fertility could support optimum crop growth when there is adequate water.

The information generated can be used to monitor the changes in soil physical and chemical properties after irrigation with treated wastewater. This can also be used as reference information in modelling the movement of water and nutrients within the soil.

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CHAPTER 4

NUTRIENT LEACHING, UPTAKE, GROWTH AND YIELD OF SWISS CHARD (*Beta vulgaris* subsp. *cicla*) IRRIGATED WITH ABR EFFLUENT.

Abstract

Significant challenges with regards to the provision of centralised wastewater treatment systems particularly to informal settlements not connected to existing sewer systems exist in many developing countries. The Anaerobic Baffled Reactor (ABR) which forms part of the Decentralised Wastewater Treatment System (DEWATS) is a low cost sanitation technology that can degrade human waste into biogas and effluent and could potentially provide suitable alternatives to these challenges. However, the disposal of treated effluent into rivers leads to massive algal blooms and its use in agriculture might lead to contamination of underground water resources through leaching. The objectives of the study were firstly, to investigate the effect of irrigation with ABR effluent on Swiss chard biomass; and secondly to determine nutrient uptake and leaching of nitrates and phosphates. Experiments were done at Newlands Mashu in a one factor analysis with three treatments (ABR, TWF and RFF) during winter 2012 and summer 2013. All statistical analyses were performed using GenStat® 14th Edition (VSN International, Hemel Hempstead, UK). Results obtained were compared to baseline studies (Chapter 3). There was a significant decrease in soil N ($P<0.01$), P ($P<0.01$) and Mn ($P<0.001$) across all three seasons. There were significantly high concentrations of plant tissue N in RFF and ABR treatments compared to TWF ($P<0.05$). TWF has a significantly high plant tissue K concentration compared to ABR ($P<0.01$) and RFF ($P<0.001$). The winter results showed high fresh mass in ABR followed by TWF and then RFF ($P<0.001$). A significantly low dry mass ($P<0.05$) was observed within the RFF treatment. No significant differences in Swiss chard biomass were observed in summer 2013. Chlorophyll content results shows that there was no significant differences between the treatments across all seasons. N and P concentrations were significantly higher within the 30 cm depth than 50 cm depth at 5% level. Irrigation with ABR effluent on soil chemical properties, Swiss chard growth, plant tissue nutrient uptake and nutrient leaching is comparable to TWF and RFF.

Keywords: Nutrient uptake, leaching, Swiss chard growth, ABR effluent

4.0 INTRODUCTION

Technologies such as the DEWATS (Decentralised Wastewater Treatment System) are being developed as low cost solutions to the problems of inadequate sanitation especially in densely populated informal settlements. These settlements are expanding at rates causing severe challenges to the ability of municipalities to connect them to the current centralised infrastructures (Hudson, 2010). The DEWATS involves the use of an ABR (Anaerobic Baffled Reactor) and can treat human waste at a high treatment rate leading to a considerable reduction of COD and BOD (Foxon *et al.*, 2005; Nasr *et al.*, 2009). The ABR effluent contains mineral elements (N, P, K, Ca, Na and Mg) which are important for crop growth. The management of such treated effluent must consider handling of effluent generated and effects of mineral nutrients on environmental pollution. Some strategic measures could be recycling in a manner that will benefit poor farmers (Mateo-Sagasta *et al.*, 2013).

The use of treated effluents in agriculture considers the effect of water quality as stipulated by the Department of Water, Agriculture and Forestry (DWAF) guidelines in South Africa. Treated wastewater is characterised by certain levels of solids and these can impact on the irrigation structures (Pescod, 1992). The presence of elements such as Na and their effects on salinity could also be of concern. Some other factors to consider when using wastewater for irrigation include salinity and its impact on crops. Some crops can be tolerant to salinity for example Swiss chard (Pokluda and Kuben, 2002). High concentrations of Na in wastewater can cause soil sodicity (Levy *et al.*, 2011). Irrigation using ABR effluent could also have an effect on soil pH (Leal *et al.*, 2009) and hence the availability of N and P. However, according to different studies ABR effluent pH is almost neutral (Foxon *et al.*, 2005; Hudson, 2010; Bame *et al.*, 2013) and this suggests that its impact on soil pH could be minimal.

N and P uptake is affected by the existence of forms which can be taken up by plant roots (Levy *et al.*, 2011). Usually N in treated effluents exists in both inorganic (predominantly NH_4^+) and organic forms (for example proteins and uric acid) (Bar-Tal, 2011). Inorganic forms of P found in treated effluents include orthophosphates and pyrophosphate, which are taken up by plants (Lusk *et al.*, 2012). Organic matter can adsorb mineral P within the soil and immobilize it for either plant uptake or leaching (Bar-Yosef, 2011). Studies by Bame *et al.* (2013) reported that irrigation with ABR effluent increases the quantities of nitrates and phosphorus within the plant rooting zone. Furthermore, nutrients such as nitrates are very mobile (Samuel *et al.*, 1993) and this has an implication on leaching and subsequent contamination of underground water resources. Studies by McLaren and Cameron (1996) have shown that nitrate concentrations in the soil can also be reduced by other factors such as microbial immobilisation, plant uptake and denitrification.

Soil biotic and abiotic processes leading to the mineralisation or immobilisation of mineral elements (N and P) are affected by factors such as soil pH, temperature, weather conditions and soil physical properties (Levy *et al.*, 2011). Furthermore, subsequent processes leading to the depletion of these nutrients in the soil through nutrient uptake can be affected by plant vigour, root morphology and density (Somma *et al.*, 1998). Root growth can be affected by factors such as weather conditions, soil physical and chemical properties such pH (Samuel *et al.*, 1993). Moreover, the rate of leaching can be driven by soil physical properties such as texture, organic matter, hydraulic conductivity and rainfall intensity (Helmar and Hespanhol, 1997; Levy *et al.*, 2011). In the previous chapter (chapter 3) the experimental site was characterised and baseline information on soil physical and chemical properties, weather conditions, plant growth and proximity to available water resources was generated. Swiss chard was selected as a test crop because of its high nitrogen requirements thus making it ideal for irrigation using effluent with high N concentrations. In the previous study Swiss chard growth and yield was comparable to those grown using inorganic fertilisers; however the experiment was planted during the summer when rainfall was high. Seasonal effects on using ABR effluent either as nutrient or water source or to provide both nutrients and water need to be considered particularly during winter when rainfall is lower. Moreover, the effect of site physical characteristics in influencing N and P uptake and leaching after irrigation of Swiss chard with the ABR effluent needs further investigation. The characterisation of the effluent used for irrigating the crops could help in quantifying the amount of N and P supplied through irrigation. This information could be useful in generating a nutrient mass balance that would account for losses through leaching, plant uptake and/or, immobilisation and/or volatilization. The aim of this study was to investigate the effect of ABR effluent on Swiss chard biomass during winter and summer seasons.

The specific objectives were:

1. To investigate changes in soil chemical properties after irrigation with ABR effluent,
2. To determine the effect of ABR effluent irrigation on Swiss chard biomass during the winter and summer seasons.
3. To monitor nutrient leaching beyond the root zone after irrigating with ABR effluent during the summer season,
4. To determine nutrient mass balances after the application of ABR effluent to irrigate a Swiss chard crop during summer season.

4.1 MATERIALS AND METHODS

4.1.1 Experimental Site

Field experiments were carried out at the Newlands Mashu Permaculture Centre in Durban (30°57'E, 29°58'S) (Figure 3.1 chapter 3). The site has an annual rainfall of ~1000 mm and mean daily temperatures of 20.5° C. The soils at the site are clayey loam soils with 1.7% organic C, 27.2% sand, 38.25 % silt and 34.5% clay (Chapter 3: Table 3.5).

4.1.2 Experimental methodology

4.1.2.1 ABR effluent characterisation for irrigation purposes

The ABR effluent was analysed to determine the mineral element content. Aliquots of 500 ml ABR effluent were collected after irrigation and analysed on site for nitrate and phosphate using Merck Reflectoquant; and pH and salinity using the pH and salinity meter. The rest of the samples were transported to Pietermaritzburg under cold storage for further tests (K, Fe, Cu, Na, Al, Ca, Mn, Mg, Pb, Cd and Ar) using the Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP-AES). Other water quality tests (COD, BOD and TSS) were done at the Chemical engineering (Pollution Research Group) according to the standard methods (Foxon *et al.*, 2005).

4.1.2.2 Soil chemical properties

Soil samples representative of the experimental site were collected from five randomly chosen points on nine different plots measuring 25 m^2. Five samples were collected within each plot using an auger to a depth of 20-30 cm and bulked. Composite samples were sent to the Fertiliser Advisory Service, KZN Department of Agriculture and Environmental Affairs; Soil Fertility and Analytical Service, CEDARA for analysis. Changes in soil chemical properties were monitored from baseline studies and after the irrigation with ABR effluent. Soil sampling was done in April 2012 (baseline studies), August 2012 (winter experiment) and April 2013 (summer experiment). Fertiliser application to the inorganic fertiliser treatments of follow up crops was conducted based on soil analysis results after harvesting the previous crop.

4.1.2.3 Installation of access tubes and the calibration of the neutron probe for the determination of soil water content

Soil water content was measured using a neutron probe, which was calibrated for the study site. Two representative spots were selected at the study site for wet and dry spot calibration. The wet spot calibration was determined by making a 2m x 2m (4 m^2) area dam. An access tube was installed to a 1.0 m depth at the centre of the dam. The access tube was inserted in the soil using an auger and a hammer and in such a way that 0.1 m was left above the ground surface. The dam was then filled continuously with water until it reached steady state and covered immediately with polythene plastic for three days to prevent evaporation. After three days the plastic cover was removed and neutron probe readings taken every 0.2 m depth. A soil profile was dug immediately close to the access tubes and undisturbed core samples collected every 20 cm for gravimetric water content determination (Figure 4.1). The soil samples were weighed immediately after collection (wet mass) and dried in the oven at 105°C until it reached steady mass (48 hours). Dry spot calibration was done as in wet spot calibration procedures except that there was no ponding.

Figure 4.1 Collection of soil cores within the 10 cm radius around the access tube during wet spot and dry spot calibration of the neutron probe.

Determination of gravimetric water content

$$\theta_g = \frac{M_w}{M_s}$$

Eq. 4.1

Where θ_g is gravimetric water content (%), M_w is mass of water (kg), and M_S dry mass of soil (kg).

Determination of volumetric water content

This is the ratio of the volume of water to the volume of soil and is calculated by multiplying the gravimetric water content by the bulk density.

$$\theta_v = \theta_g \left(\frac{\rho_b}{\rho_w} \right)$$

Eq.4.2

Where θ_g is gravimetric water content and ρ_b is the oven-dry bulk density (kg m^{-3}) and ρ_w density of water (kg m^{-3}).

A linear regression equation was fitted to the neutron probe reading ratios of the dry and wet spots against the corresponding volumetric water contents per each layer down to 60 cm (Figure 4.2). Reading ratios were calculated according to the formula below:

Neutron probe reading in soil /Average standard reading in air

Standard readings in air for that particular day were calculated by averaging ten neutron probe counts in air.

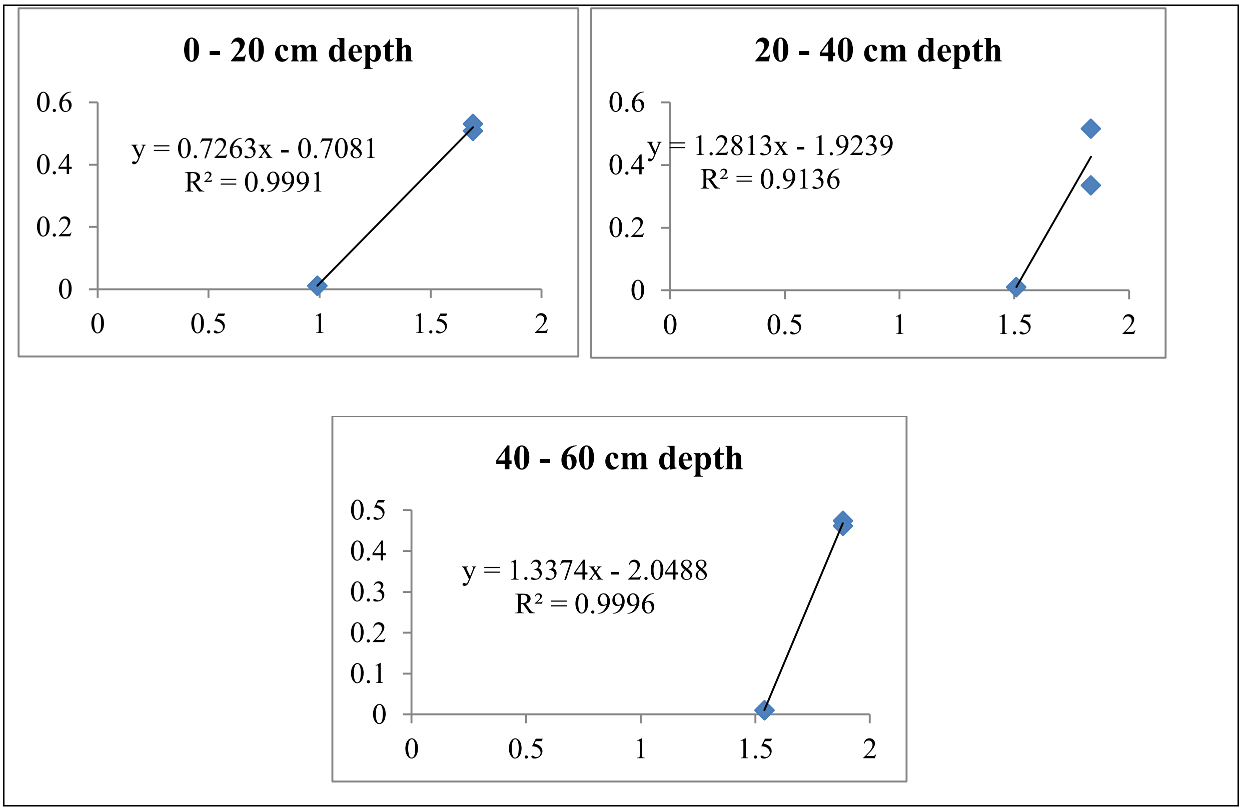


Figure 4.2 Neutron probe calibration equations at different soil layers (0-20 cm, 20-40 cm and 40-60 cm) showing the relationship between dry spot count ratios (Y axis) and wet spot count ratios (X axis)

Water deficit was estimated as the sum of the difference between the field capacity and neutron probe readings of each layer until 60 cm depth.

4.1.2.4 Trial establishment and management of field experiments

Two experiments were carried out, one was done during the winter in 2012 (May to July) and the other experiment during the summer 2013 (February to April). The experiments were laid out as a single factor analysis using a randomised complete block design (RCBD) with the following three treatments; ABR effluent irrigation (ABR), Tap water with fertiliser irrigation (TWF) and Rain-fed conditions with fertiliser application (RFF). Each treatment was replicated three times giving a total of nine experimental units (4 m x 4 m plots). The winter experiment focussed on investigating the effect of ABR effluent on soil chemical properties and Swiss chard biomass production; whereas the summer experiment included the determination of the effect of ABR effluent nutrient (N and P) leaching and Swiss chard biomass production.

Swiss chard seeds purchased from McDonalds store in Pietermaritzburg were planted in the plots on 15 May 2012 (winter planting) and 31 January 2013 (summer planting) at a spacing of 30 cm x 30 cm. Three seeds were planted per hole at 25 mm depth and all plots were irrigated using tap water for two weeks until seedling establishment. Swiss chard from ABR effluent (ABR) and tap water + fertiliser treatment (TWF) were irrigated using drip irrigation while the rain-fed + fertiliser treatment (RFF) was not irrigated further after seedling establishment. Thinning was done to leave one plant per hill three weeks after planting and the final emergence was recorded. No additional fertiliser was applied to the ABR plots, however, fertilisers (Urea, DAP and KCl) were applied to the TWF and RFF treatments according to the soil fertility analysis and Swiss chard crop nutrient requirements (Table 4.1).

Table 4.1 N (Urea), P (DAP) and K (KCl) fertilisers applied to the Swiss chard during the experiment showing the mineral nutrients (N, P and K) applied to the crop.

Treatment	**Block**	**N (kg ha^{-1})**	**P (kg ha^{-1})**	**K (kg ha^{-1})**
		Winter 2012		
TWF	1	100	40	145
TWF	2	100	40	180
TWF	3	100	0	120
RFF	1	100	40	190
RFF	2	100	40	260
RFF	3	100	40	160
		Summer 2013		
TWF	1		40	180
TWF	2	100	40	280
TWF	3	100	40	180
RFF	1	100	40	185
RFF	2	100	40	305
RFF	3	100	40	190

Plastic coke bottles (2 litres) perforated at the bottom using a 15.24 cm nail were submerged 5 cm below the ground level to provide a modified drip irrigation system according to Rodda *et al.* (2011). Crop management operations (weeding, pest and disease control) were carried out when necessary to keep the field weed free and maintain healthy plants. Irrigation was done at a four to five day interval to maintain water at field capacity within the 30 cm soil depth and the soil moisture content was determined using a neutron probe.

4.1.3 Data collection

4.1.3.1 Plant growth and chlorophyll data during the winter experiment

Data on chlorophyll content, fresh and dry biomass was collected from plants which were randomly sampled from nine quadrants measuring 1 m^2. From each quadrant 18% of the plants were selected for data collection. Chlorophyll content was measured using a CCM200 chlorophyll meter (Optisciences Inc., USA) four weeks after crop emergence and at harvesting (eight weeks after crop emergence). Fresh biomass was measured on-site immediately after harvesting using a CPA22025 precision balance (Sartorius CPA Precision balances, LA). Dry mass was determined from the plants measured fresh mass by oven drying at 70˚C for 72 hours.

4.1.3.2 Determination of plant biomass, chlorophyll content and plant tissue nutrients during the summer experiment

Chlorophyll content, dry mass and fresh mass were measured as done in winter season and results were compared among three seasons (Summer 2012, winter 2012 and summer 2013). Swiss chard plants were cut 1 cm from the ground and dried at 70˚C for 72 hours, crushed and sieved past a 1 mm sieve before being taken for macro and micro nutrients analysis at the KZN Department of Agriculture and Environmental Affairs; Soil Fertility and Analytical Service, CEDARA. The plant tissue were ground and sieved through a 0.84 mm sieve before being analysed using an ICP-AES for macronutrients and micronutrients (Rodda *et al.*, 2011). The plant tissue analysis results obtained after irrigation with ABR effluent were compared to the baseline studies results.

4.1.3.3 Collection and analysis of leachates from the soil

Wetting front detectors (WFD) installed in the plots at 30 cm and 50 cm depth were used to collect leachates at the respective depths. Due to low rainfall in winter leachates were only collected during the summer 2013. The WFDs were sampled immediately after a heavy rain event and emptied after sample collection. The collected leachates were tested immediately at the site for nitrates and phosphates using the Merck Reflectoquant (Figure 4.3). Leachate samples showing values outside the range for the nitrate test were diluted x5, x10 and x15 and the results obtained multiplied by the dilution factor to get the actual nitrate concentration within the sample.

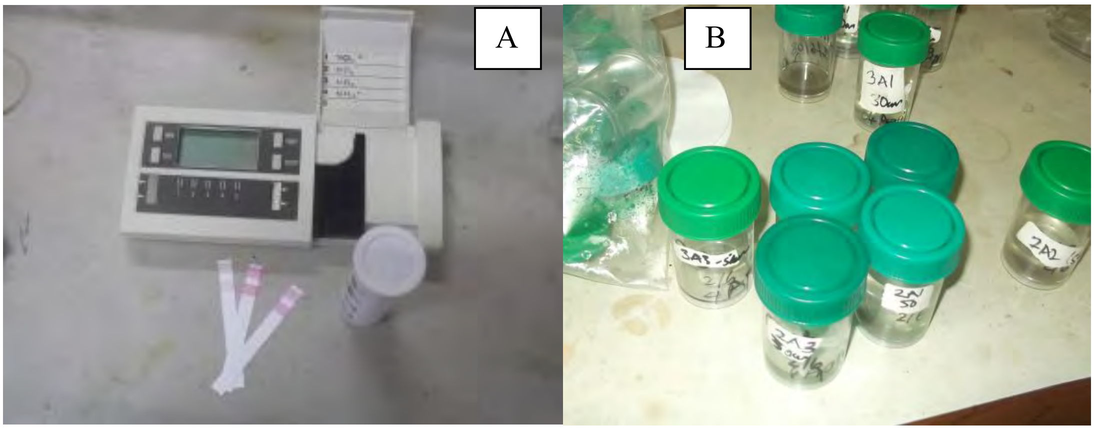


Figure 4.3 Diagram showing the Merck Reflectoquant test kit (A) and leachates collected from the field (B)

4.1.3.4 Determination of N and P mass balances

Nutrient mass balances were calculated according to the equation developed by the Food and Agricultural Organization (FAO, 2003).

$$Rn_{tn} = \sum^{tn}(AP_t + AR_{\Delta t} - RM_{\Delta t} - L_{\Delta t}) \qquad \text{Eq. 4.3}$$

Where;

Rn_{tn} is the quantity of inorganic and organic nutrients remaining in the soil at a certain period of time (*tn*);

AP_t is the soil inorganic and organic nutrients present at time *t*;

AR_{Dt} is the inorganic and organic nutrients added or returned to the soil during the time interval D*t*.

RM_{Dt} estimate is the plant nutrients removed with the harvested product and residue management during the time interval D*t*,

L_{Dt} is the inorganic and organic nutrients lost through plant uptake and leaching during the time interval D*t.* The value of *t* represents the beginning time period, *tn* represents the ending time period, and D*t* is the time interval between *t* and *tn*.

1. Soil nutrients remaining = (soil nutrients present before + soil nutrients added – nutrients removed after plant harvest – nutrients lost) Eq. 4.4

2. Soil nutrients (kg) = nutrient (%) x (soil mass per 4.8 m^3) Eq. 4.5

3. Nutrients removed through plant harvest (kg)= Plant tissue nutrient (%) x (Dry biomass kg x plants/16 m^2) Eq. 4.6

4. Leached nutrients (kg):

a. Nitrate N to N (kg) = Nitrate x 0.226 x (1/10000) x soil mass per 4.8 m^3 Eq.4.7
b. Phosphate P to P (kg)= Phosphate x 0.336 x (1/10000) x soil mass per 4.8 m^3 Eq.4.8

4.1.4 Data analysis

All statistical analyses were performed using GenStat® 14th Edition (VSN International, Hemel Hempstead, UK). Means were compared using SEDs at the 5% level significance.

4.2 RESULTS

Field experiments on irrigation with ABR effluent were carried out during the winter 2012 and summer 2013. Results on plant growth and soil chemical properties obtained after irrigation with ABR effluent were compared to the baseline studies carried out in summer 2012.

4.2.1 Characterisation of the effluent

Table 4.2 shows the chemical characteristics of the effluent used to irrigate the Swiss chard. The ABR effluent did not contain significant amount of heavy metals (Al, Pb, Ni, Hg, Cd and Cr). The recommended crop nutrient requirements for Swiss chard were N (100 kg ha^{-1}), P (40 kg ha^{-1}) and K (123 kg ha^{-1}). The N supplied to the Swiss chard crop by the effluent amounted to 91 kg ha^{-1} which was close to the N requirements. Phosphorus content supplied amounted to 7.6 kg ha^{-1} which was considerably lower than the crop needs. The potassium concentration in the effluent amounting to 21.2 kg ha^{-1} was similarly much lower than the crop requirements. The average sodium (Na) concentration in the ABR effluent applied to the Swiss chard crop is 52.8 kg ha^{-1}.

Table 4.2 Elemental composition of the ABR effluent used for the irrigation and estimates of the major nutrients supplied during the irrigation of the Swiss chard plants

Element	**ABR effluent sampling**				**Average**	**Nutrient content (kg ha^{-1})**			**Average**
	ABR1	ABR2	ABR3	ABR4		Block 1	Block 2	Block 3	
Element	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
N	61	-	-	-	61	99	77	97.6	91.2
Ca	22.1	31.2	48.2	14.2	28.9	46.9	36.5	46.3	43.2
K	15.7	19.4	8.34	13.3	14.2	23.1	17.9	22.7	21.2
Mg	14.9	12.5	27.1	4.2	14.7	23.9	18.6	23.5	22.0
P	4.46	9.34	3.48	3.01	5.1	8.3	6.4	8.2	7.6
Al	0.36	0.02	0	0	0.1	0.2	0.1	0.2	0.1
Na	nd	35.9	36.8	33.3	35.3	57.3	44.6	56.5	52.8
Fe	0.12	0.09	0.08	0.09	0.1	0.2	0.1	0.2	0.1
Mo	0.11	0.07	0.04	0.05	0.1	0.2	0.1	0.2	0.1
Zn	0.06	0	0	0.01	0	0	0	0	0
B	0	0.1	0.07	0.03	0.1	0.2	0.1	0.2	0.2
Cu	0	0	0	0	0	0	0	0	0
Mn	0	0	0	0	0	0	0	0	0
Co	0	0	0	0	0	0	0	0	0
Cr	0	0	0	0	0	0	0	0	0
Cd	nd	0	0	0	0	0	0	0	0
Hg	0	nd	nd	nd	0	0	0	0	0
Ni	0	0	0	0	0	0	0	0	0
Se	nd	0	0	0	0	0	0	0	0
V	nd	0.01	0	0	0	0	0	0	0
S	nd	13.8	24.8	16	18.3	29.7	23.1	29.3	27.4
Pb	nd	0.09	0.12	0.07	0.1	0.2	0.1	0.2	0.1

*nd- not detected

4.2.2 Effect of ABR effluent on soil chemical properties during the winter 2012 and summer 2013.

4.2.2.1 Winter 2012 experiment

Table 4.3 shows mean squares for the effect of irrigation with ABR effluent on soil chemical properties during the winter 2012 season. A significant change after irrigation with ABR effluent was observed with respect to Mn ($P<0.001$), N ($P<0.5$) and organic C ($P<0.05$). Figure 4.4 shows the differences in soil Mn, organic C and N content between two sampling periods (before planting and after harvesting). Soil Mn content declined significantly from 14 mg kg^{-1} before planting to 7.19 mg kg^{-1} after planting. The same trend applies to both soil N content and soil organic C which decreased from 0.35% to 0.31% and 3.4% and 2.83% respectively.

4.2.2.2 Summer 2013 experiment

Table 4.4 shows mean squares for the effect of ABR effluent on soil chemical properties during the summer 2013 season after harvesting. There was a significant difference in the soil Ca content ($P<0.05$) between the treatments. Significant changes from planting to harvesting was observed with respect to soil P ($P<0.01$), Zn ($P<0.001$) and N ($P<0.05$). Figure 4.5 shows soil Ca content between the different treatments (ABR, TWF and RFF). Results show significant high soil Ca content in ABR (12.75 cmol$_c$ kg^{-1}) and TWF (11.56 cmol$_c$ kg^{-1}) as compared to the RFF treatment (8.98 cmol$_c$ kg^{-1}).

Figure 4.6 compared the changes in soil N, Zn and P from planting to harvesting within all the treatments. There was a significant decline in the soil P (79 to 36.9 mg kg^{-1}), Zn (49.9 to 20.5 mg kg^{-1}) and N (0.31 to 0.28 %) from planting to harvesting.

Table 4.3 Mean squares for the effect of ABR effluent irrigation on soil chemical properties sampled after harvesting during the winter 2012 season.

S.O.V.	P	K	Ca	Mg	Exch. Acid	Total Cat.	pH	Zn	Mn	Cu	N	Org. C
Block	1787.3	0.0073	3.653	2.0436	8E-04	9.69	1.27974	1306.2	22.39	16.85	0.001876	0.0929
Treatment	4.6	0.0022	3.478	0.7414	6E-05	5.25	0.35291	36.4	12.405	3.71	0.000096	0.0082
Sampling time	52.7	3E-05	2.334	1.5804	0.002	7.85	0.09534	248	215.01***	50.07	0.007332*	1.4539*
Sampling time x Treatment	269.6	0.0112	1.421	0.5509	2E-04	12.47	0.05621	198.8	1.508	11.24	0.000785	0.1247
Error	713.9	0.0029	2.436	0.9857	2E-04	29	0.08607	606.6	3.101	18.16	0.001454	0.2361
Total												

Table 4.4 Mean squares for the effect of ABR effluent on soil chemical properties sampled after harvesting during the summer 2013 season

S.O.V.	P	K	Ca	Mg	Exch. Acid	Acid sat.	Total Cat.	pH	Zn	Mn	Cu	N	Org. C
Block	327.2	0.0009	13.124	2.2	0.004	1.7	8.03	0.9126	140.1	0.332	18.507	0.0023	0.8894
Treatment	7994	0.0073	22.275*	1.5	0.004	2.7	10.91	0.2473	3867.7	20.406	7.475	0.0005	0.0142
Sampling time	367.3**	0.0059	1.626	0.01	0.001	2.7	8.16	0.5698	102.1***	17.833	40.691	0.00402*	0.28
Sampling time x Treatment	49.4	0.011	5.032	6.6	0.003	2.7	63.12	0.0245	31.1	2.461	0.189	0.00016	0.1436
Error	590.4	0.0073	3.51	3.5	0.002	1.7	41.28	0.2057	166.8	6.337	8.281	0.00076	0.4006
Total													

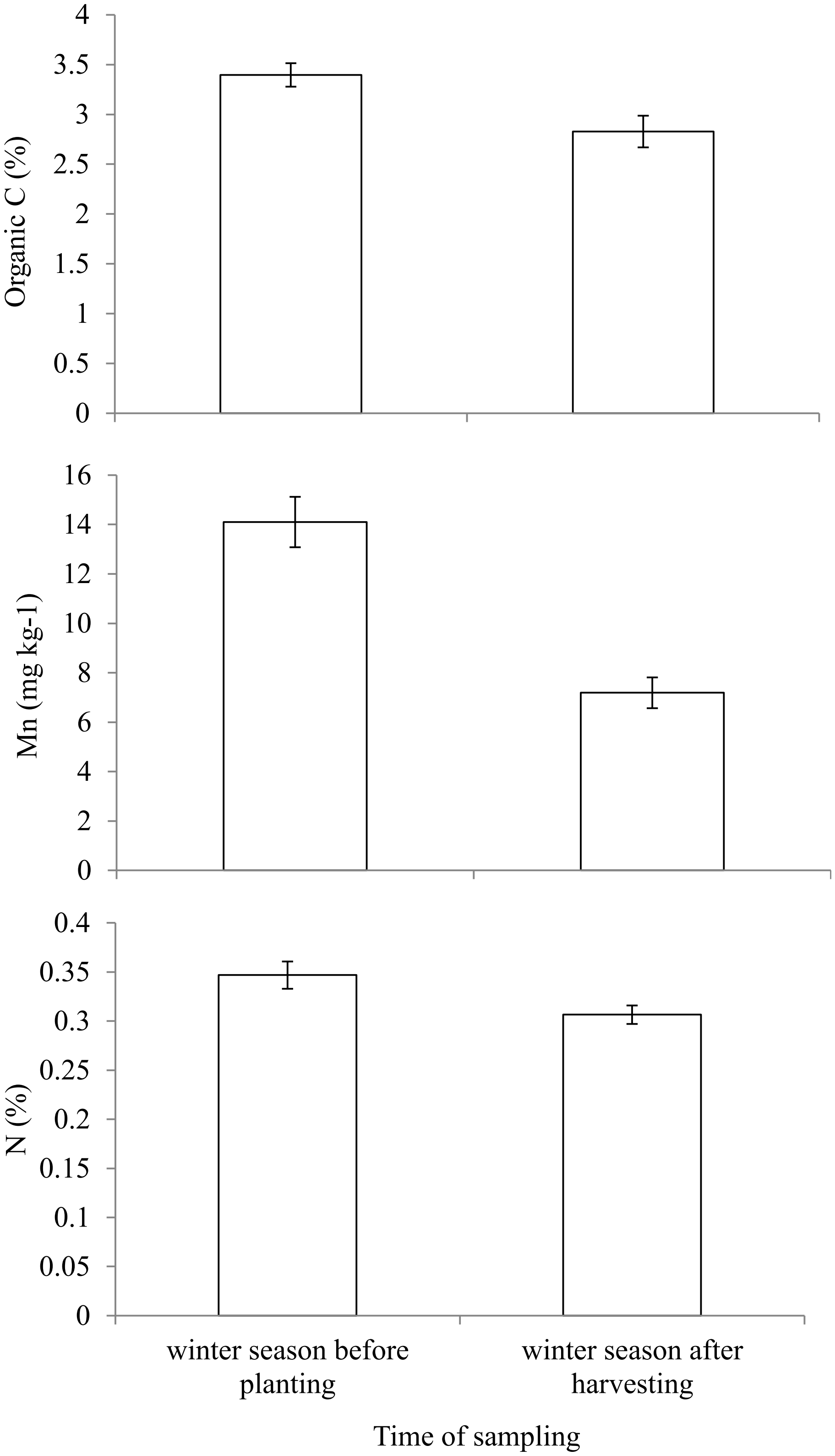


Figure 4.4 Comparison between the soil N, organic C and Mn before planting and after harvesting during the winter 2012 season.

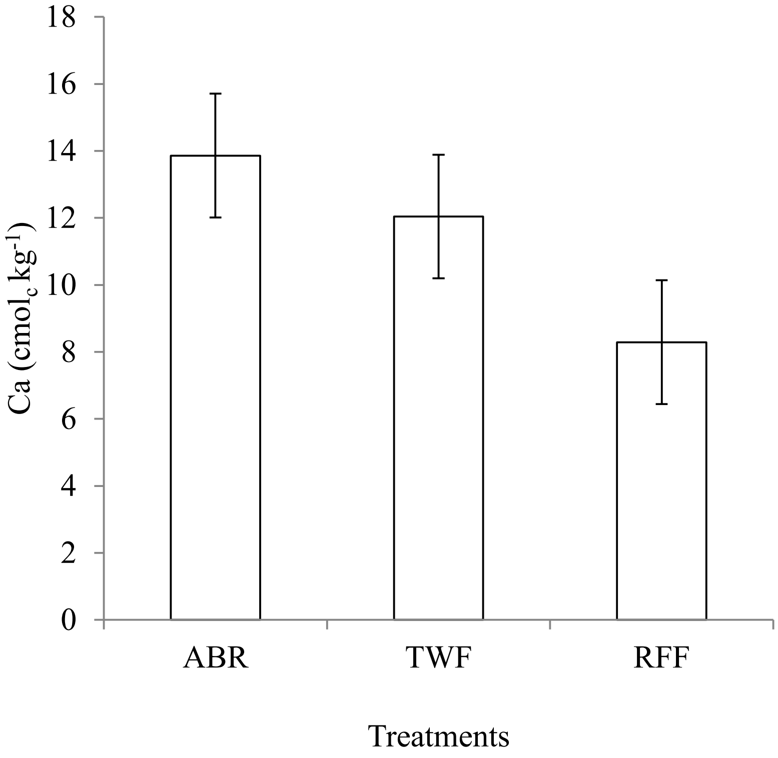


Figure 4.5 The effect of ABR effluent irrigation on the soil Ca content during the summer 2013 season

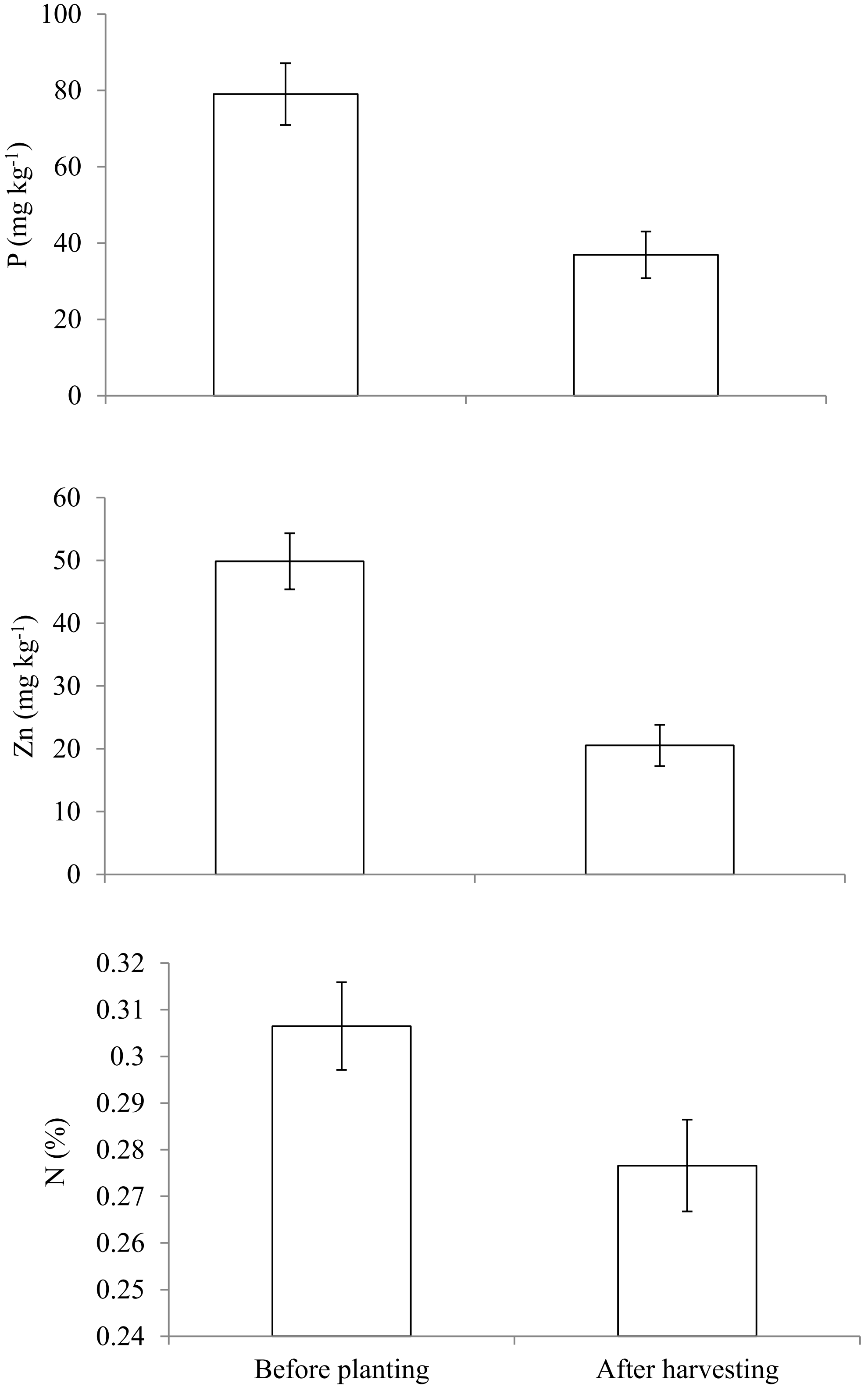


Figure 4.6 Comparison between the soil N, Zn and P before planting and after harvesting during the summer 2013 season.

4.2.3 Comparing the effect of ABR effluent irrigation on soil chemical properties over three seasons and between treatments

Table 4.5 describes the mean square values for the soil chemical analysis over three seasons (summer 2012, winter 2012 and summer 2013) comparing the effect of ABR effluent on soil chemical properties. Contrasts were done to compare the chemical properties at different seasons (Table 4.5). Generally no significant differences were observed across all seasons with respect to changes in soil chemical properties except for N, P and Mn. Significant differences were observed for N ($P < 0.001$), P ($P < 0.01$) and Mn ($P < 0.001$) (Figure 4.7). N, P and Mn content decreased generally over the seasons for all the plots irrespective of ABR irrigation.

A comparison of the irrigation treatments (Table 4.6) showed a significant increase in Ca content in plots irrigated using ABR effluent (12.25 $\text{cmol}_c\ \text{kg}^{-1}$) compared to tap water with fertiliser and rain-fed (11.84 and 9.63 $\text{cmol}_c\ \text{kg}^{-1}$ respectively). Contrastingly plots irrigated with ABR showed the lowest Mn content (7.45 mg kg^{-1}) compared to tap water with fertiliser and rain-fed (8.25 mg kg^{-1} and 10.79 mg kg^{-1}) respectively. ABR effluent seemed to have caused an increase in pH as evident from the observed results ABR had a pH of 5.4; TWF was 5.1 and RFF was 4.9 (Table 4.6).

Table 4.5 Mean squares for soil chemical properties for samples collected from plots irrigated with tap water (TW), tap water with fertiliser (TWF) and rain-fed (RFF) after planting in 2012 and before and after ABR irrigation in 2013.

S.O.V.	**D.f.**	**N**	**P**	**K**	**Ca**	**Mg**	**Exch. Acid**	**Total. Cat**	**Acid. Sat**	**pH**	**Zn**	**Mn**	**Cu**	**Org. C**
Block	2	0.002505	707.9	0.000998	13.752	4.915	0.004378	14.15	1.148	1.4412	674.9	6.752	9.02	0.4583
Season	2	0.011183**	4931.8**	0.004227	1.342	1.156	0.002543	6.34	1.815	0.1261	3396.6	196.509***	90.6	0.8829
Contrast 1	1	0.022201***	6748.6**	0.006748	0.064	1.875	0.00499	0.25	2.722	0.0356	6074.3	356.685***	181.04	1.1805
Contrast 2	1	0.004016	7994**	0.005903	1.626	0.013*	0.000722	10.91	2.722	0.2473	3867.7*	17.833	40.69	0.0142
Contrast 3	1	0.007332*	52.7	0.000028	2.334	1.58	0.001915	7.85	0	0.0953	248	215.01***	50.07	1.4539
Treatment	2	0.000043	102.1	0.000854	17.886*	0.859	0.001591	6.23	1.815	0.7*	30.5	27.317*	4.72	0.1156
ABR vs. RFF	1	0.000019	189.9	0.000003	30.878**	0.703	0.002747	10.64	2.722	1.4**	30.5	50.116*	5.4	0.1399
TWF vs. RFF	1	0.000024	13.1	0.001216	22.036*	1.668	0.001958	7.83	2.722	0.35	32.4	28.95*	8.42	0.2013
ABR vs. TWF	1	0.000085	103.2	0.001343	0.744	0.205	0.000067	0.22	0	0.35	56	2.886	0.33	0.0056
Season x Treatment	4	0.000521	237.2	0.011237	5.623	3.786	0.002411	33.96	1.815	0.0401	152.5	2.528	7.26	0.203
Contrast 1 x Treatment	2	0.000616	392.6	0.011535	10.416	4.262	0.004342	26.29	2.722	0.0396	227.6	3.616	10.33	0.3406
Contrast 2 x Treatment	2	0.000163	49.4	0.010998	5.032	6.545	0.002694	63.12	2.722	0.0245	31.1	2.461	0.19	0.1436
Contrast 3 x Treatment	2	0.000785	269.6	0.011178	1.421	0.551	0.000197	12.47	0	0.0562	198.8	1.508	11.24	0.1247
Residual	16	0.001238	711.4	0.00578	3.371	2.312	0.001549	26.94	1.148	0.1537	494.1	6.682	15.95	0.3541
Total	26													

N.B.Contrast 1 denotes April 2012 vs. August 2012

Contrast 2 denotes August 2012 vs. April 2013

Contrast 3 denotes April 2012 vs. April 2013

*Significance at 5% level **Significance at 1% level ***Significance at <0.001 level

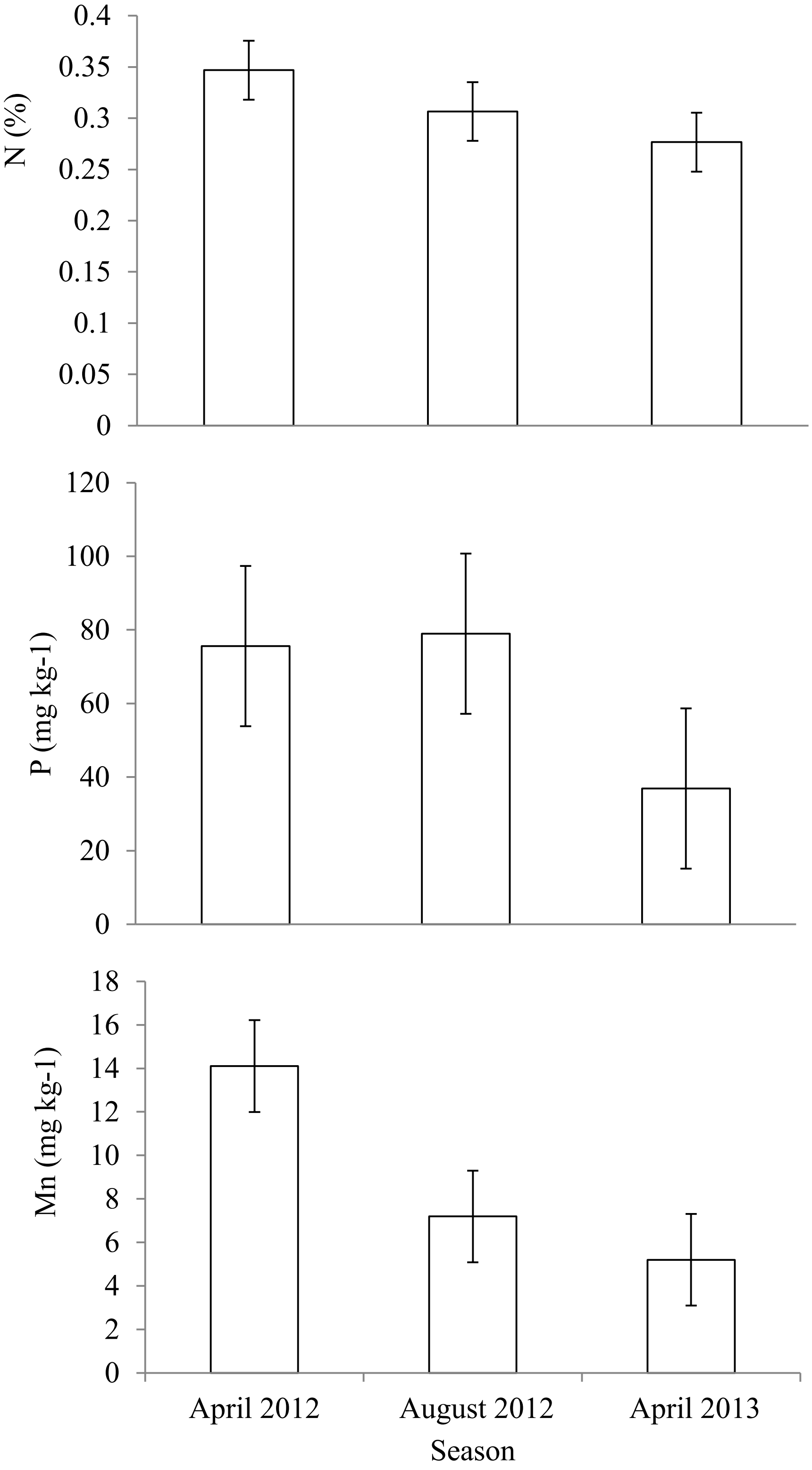


Figure 4.7 Changes in soil N, P and Mn in the experimental plots over three planting seasons.

Table 4.6 The effect of ABR effluent irrigation (ABR), tap water with fertiliser (TWF) and rain-fed on Ca and Mn content and soil pH over three seasons.

Treatments	Mineral elements		Soil pH
	Ca (cmol$_c$ kg^{-1})	Mn (mg kg^{-1})	(KCl)
ABR	12.25^a	7.45^a	5.4^a
TWF	11.84^a	8.25^a	5.1^{ab}
RFF	9.63^b	10.79^b	4.9^b
SED	0.87	1.22	0.18

Superscripts $^{a, b \text{ and } ab}$ denote means which are significantly different.

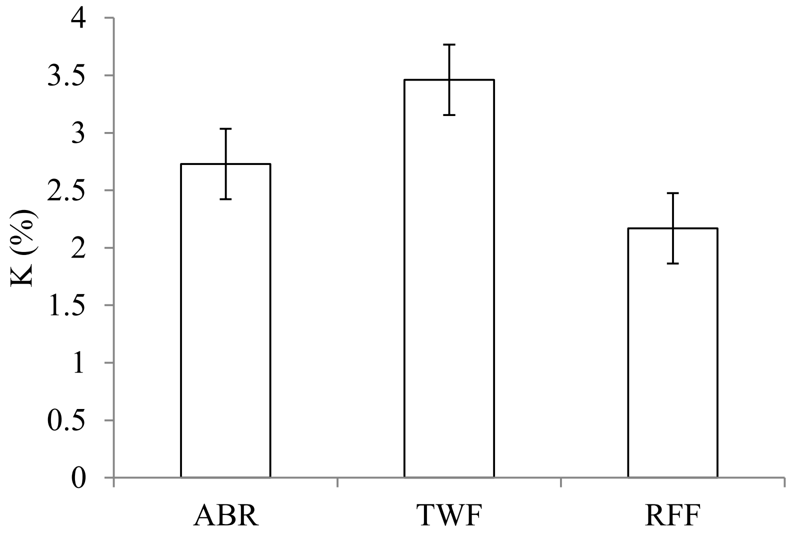
4.2.4 The effect of ABR effluent on Swiss chard plant tissue nutrient content during the summer 2013.

Table 4.7 shows mean squares for Swiss chard plant tissue analysis results after irrigation with ABR effluent during the 2013 summer season. Significant differences between the treatments were observed with respect to N ($P<0.01$), K ($P<0.05$) and Zn ($P<0.05$).

Figure 4.8 shows the effect of ABR effluent on the uptake of N and K during the summer season. Higher N concentrations were reported in ABR (4.78 %) and RFF (5.01%) as compared to the TWF treatment (4.58 %). Plant tissue K content was high within TWF (2.73 %) followed by the ABR treatment (3.46%) and RFF had the least value of 2.17%.

Table 4.7 Mean squares for the effect of irrigation with ABR effluent on plant tissue nutrient uptake between 3 treatments (ABR, TWF and RFF) during the summer 2013 season

S.O.V.	**D.F.**	**N**	**P**	**K**	**Ca**	**Na**	**Mg**	**Fe**
Block	2	0.13262	0.01216	0.003	0.00669	0.09	0.0539	1.00E+06
Treatment	2	0.59421**	0.01138	1.25*	0.01113	0.09	0.0803	3.00E+06
Error	4	0.03691	0.0101	0.141	0.02092	0.03	0.0628	2.00E+06
Total	**8**							



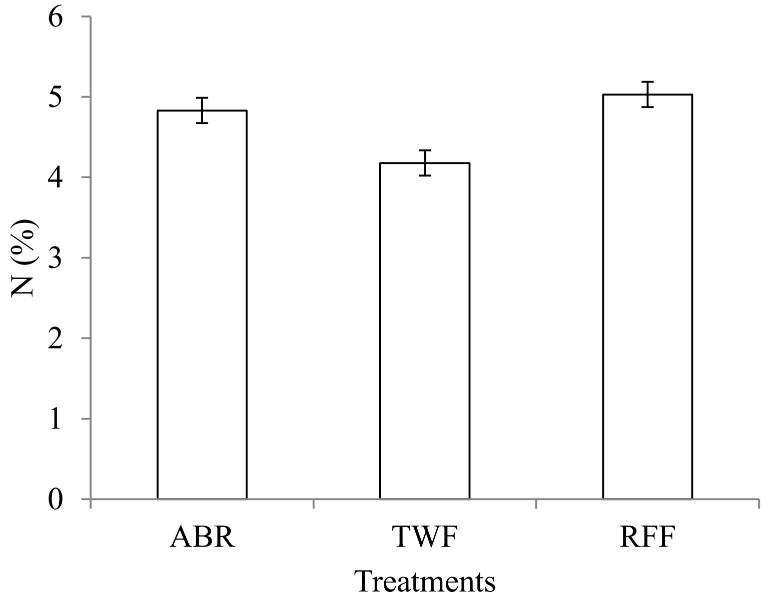


Figure 4.8 The effect of ABR effluent irrigation on N and K uptake during the summer 2013 season.

4.2.5 Comparison of plant tissue analysis results before (Baseline studies) and after irrigation with ABR effluent

Table 4.8 shows the mean squares for the plant tissue analysis over two seasons (summer 2012 and summer 2013) and between irrigation treatments: ABR effluent irrigation (ABR); tap water irrigation with fertiliser (TWF); and rain-fed (RFF). There was a statistically significant difference for P ($P<0.001$), Mg ($P<0.01$) and Fe ($P<0.05$) across seasons. Furthermore, significant differences were observed for the season and treatment interaction with regards to Na ($P< 0.01$) and K ($P<0.05$).

Table 4.9 shows the concentrations of P, Mg, Fe and Mn (mg kg^{-1}) in Swiss chard plant tissue before (summer 2012) and after irrigation with ABR effluent (summer 2013). During summer 2013 there was a significant uptake of P (0.655 mg kg^{-1}), Mg (1.1 mg kg^{-1}) and Fe (2036 mg kg^{-1}) compared to summer 2012 P (0.367 mg kg^{-1}), Mg (0.720 mg kg^{-1}) and Fe (625 mg kg^{-1}).

The interaction between seasons and treatments with respect to K and Na taken up were described in table 4.10. High uptake of K was recorded in summer 2013 within the TWF treatment (3.46%) followed by ABR (2.73%) and RFF (2.17%) as compared to summer 2012. In summer 2012 TWF treatment has high K uptake (1.66%) as compared to TW (1.32%) and RFF (1.41%). Na uptake was high in RFF treatment (4.6%) as compared to TW (3.8%) and TWF (3.1%) in summer 2012. On contrary, in summer 2013 high Na was recorded in ABR treatment (4.19%) as compared to TWF (4.17%) and RFF (3.88%).

Table 4.8 Mean squares for mineral nutrient concentrations in plant tissues sampled from Swiss chard plants irrigated with tap water (TW), tap water with fertiliser (TWF) rain-fed (RFF) in summer 2012 and after ABR irrigation in summer 2013.

S.O.V.	D.f.	N	P	K	Ca	Na	Mg	Fe
Block	2	0.1263	0.013958	0.03183	0.01993	0.5934	0.0152	242606
Season	1	0.22311	0.373233***	7.843***	0.0005	0.2719	0.65098*	8955407*
Treatment	2	0.28165	0.01205	1.86921**	0.04301	0.5186*	0.02465	1029131
Season x Treatment	2	0.37609	0.001752	0.82129*	0.00396	1.2075**	0.06485	2092813
Residual	10	0.09318	0.005436	0.77573	0.01378	0.1152	0.08622	1240026
Total	17							

N.B.

*Significance at 5% level

**Significance at 1% level

***Significance at <0.001 level

Table 4.9 P, Mg and Fe (mg kg^{-1}) concentration in plant tissue before (summer 2012) and after irrigation with ABR effluent (summer 2013)

Season	**Mineral elements**		
	P (%)	**Mg (%)**	**Fe (mg kg^{-1})**
Summer 2012	0.367 ^{a}	0.720 ^{a}	625 ^{a}
Summer 2013	0.655 ^{b}	1.100 ^{b}	2036 ^{b}
SED	**0.0348**	**0.1384**	**524.6**

N.B.

*Significance at 5% level

**Significance at 1% level

***Significance at <0.001 level

Table 4.10 Interaction between season and treatment with respect to K and Na uptake in Swiss chard plants irrigated with ABR effluent (ABR), tap water with fertiliser (TWF) and under rain-fed conditions (RFF). Note that in summer 2012 TW refers to tap water with no fertiliser which was the treatment assigned to the ABR plots in 2013.

Summer 2012		
	K (%)	Na (%)
TW	1.32^a	3.8^b
TWF	1.66^a	3.1 c
RFF	1.41^a	4.6^a
Summer 2013		
ABR	2.73 c	4.19^d
TWF	3.46^e	4.17^d
RFF	2.17^d	3.88^d
SED	0.2274	0.2772

Superscripts $^{a, b, c, d}$ and ^{e} denotes means which are significantly different

4.2.6 Plant growth analysis after irrigation with ABR effluent

4.2.6.1 Chlorophyll content determination

Table 4.11 shows mean squares for Swiss chard chlorophyll content, recorded at different stages of growth (4 weeks and 8 weeks after crop emergence). No significant differences between the treatments and seasons were observed.

4.2.6.2 Swiss chard biomass results (dry mass and fresh mass)

Irrigation with ABR effluent affected biomass production during the winter 2012 season. Significant differences were observed with regard to fresh mass ($P<0.001$) and dry mass ($P<0.05$) (Table 4.11).

Table 4.11 Mean squares for crop growth variables (fresh mass, dry mass and chlorophyll content) of Swiss chard plants irrigated with ABR effluent during the winter 2012 and the summer 201 three seasons.

Winter 2012					
S.O.V.	**D.f.**	**Fresh mass**	**Dry mass**	**Chlorophyll (week 4)**	**Chlorophyll (week 8)**
Block	2	6724	61.51	2.824	2.963
Treatment	2	120715***	515.2*	1.075	2.564
Residual	4	4998	37.93	3.29	2.721
Summer 2013					
Block	2	30929	321.61	49.51	8.497
Treatment	2	28277	118.77	37.59	2.413
Residual	4	9275	25.15	46.46	5.233
Total	**8**				

Figure 4.9 shows Swiss chard biomass results (fresh and dry mass) during the winter between the three treatments (ABR, TWF and RFF). ABR treatment had the highest fresh mass (497.7 g plant^{-1}) followed by TWF (299.3 g plant^{-1}) and RFF had the least value of 96.7 g plant^{-1}. The same trend was observed with respect to dry mass, ABR and TWF having high dry mass (44.4 g plant^{-1} and 34.7 g plant^{-1} respectively) compared to RFF treatment (18.3 g plant^{-1}).

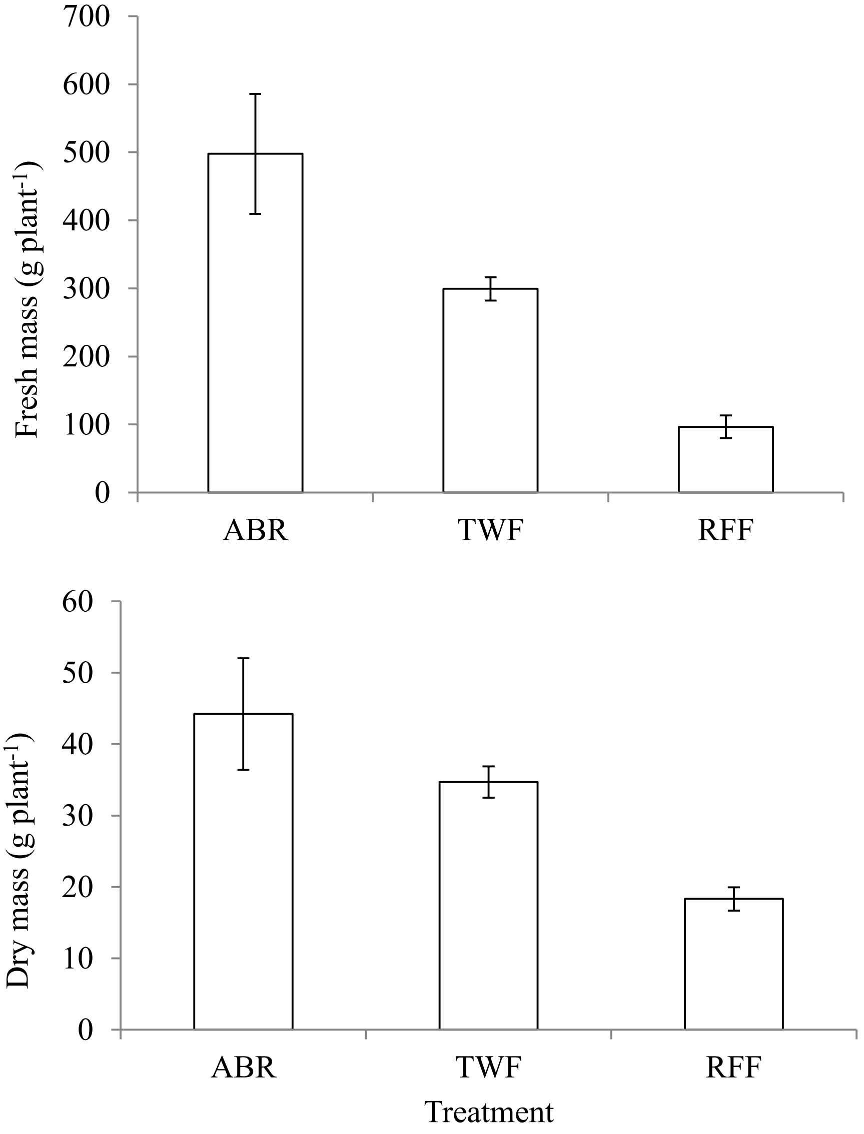


Figure 4.9 Swiss chard biomass results (fresh mass and dry mass) among the three treatments (ABR, TWF and RFF) during winter 2012 season.

4.2.7 Comparison of plant growth among the 3 different seasons and treatments

4.2.7.1 Chlorophyll content determination

Table 4.12 shows chlorophyll content results at four and eight weeks after plant emergence. Significant differences in chlorophyll content were observed among the three seasons and between different growth stages, four and eight weeks of growth ($P<0.001$). There were significant differences between summer 2012 and summer 2013 at week four ($P<0.05$) and week eight ($P<0.01$) and this was similar to winter 2012 and summer 2013 at weeks four and eight respectively (Figure 4.10). The difference between summer and winter 2012 was very significant ($P<0.01$) at both week four and eight. However the differences between the irrigation treatments were not significant at both week four and eight across the three seasons.

4.2.7.2 The effect of ABR effluent irrigation on plant biomass

Table 4.12 shows crop growth variables (fresh mass, dry mass and yield) among three treatments across three seasons. There were significant differences in fresh mass ($P<0.01$), dry mass ($P<0.001$) and yield ($P<0.01$) across the three seasons. Contrasts were done to compare seasons. A comparison between summer 2012 and summer 2013 showed significant differences in fresh mass ($P<0.05$), dry mass ($P<0.001$) and yield ($P<0.05$). Significant differences ($P<0.001$) were observed with respect to fresh and dry mass and yield between summer 2012 and winter 2012 and summer 2013.

Mean squares for treatments showed highly significant differences for fresh mass and yield ($P<0.001$) and dry mass ($P<0.05$). Highly significant differences were observed in fresh ($P<0.001$) and dry mass ($P<0.05$) in response to ABR effluent irrigation and rain-fed irrigation (RFF). Similarly the TWF treatment differed significantly with RFF ($P<0.05$) with respect to fresh mass and yield. However there were no significant differences observed between ABR irrigation and TWF irrigation with respect to all growth variables (fresh mass, dry mass and yield). Significant interactions were observed between season and treatment for fresh mass and yield ($P<0.001$) and dry mass ($P<0.05$). Contrasts were done between the season and treatment interactions and, these revealed highly significant results which are shown in Figure 4.12.

The results shown in Figure 4.10 compares fresh and dry mass over three seasons and for the three treatments. During the summer 2012 planting no ABR effluent or fertiliser was applied to the experimental units assigned for the ABR irrigation. The reason for not irrigating with

ABR was to allow a comparison of ABR effluent irrigation on the same plots so as to take into account the effect of the inherent soil fertility. The ABR plots showed lower mean values for fresh mass compared to TWF and RFF; however this was not significantly different. ABR effluent was used to irrigate Swiss chard plants planted in these experimental unit (plots that were assigned for ABR effluent irrigation in summer 2012) in winter 2012 and the results showed a significant difference with respect to fresh mass between the treatments. Plots irrigated with ABR effluent produced Swiss chard plants with the highest fresh mass than those irrigated using tap water with fertiliser and rain-fed (Figure 4.11). Mean values for fresh mass of Swiss chard plants irrigated using tap water with fertiliser were significantly higher than those under rain-fed conditions and fertilised. The results on the effect of ABR effluent irrigation on dry mass showed more or less similar pattern.

Table 4.12 Mean squares for fresh and dry mass , yield and chlorophyll content for Swiss plants irrigated with tap water (TW), tap water with fertiliser (TWF) and rain-fed in summer 2012 and ABR irrigation in winter 2012 and summer 2013.

S.O.V.	D.f.	Fresh mass	Dry mass	Yield	Chlorophyll week 4	Chlorophyll week 8
Block	2	36743	348.45	453.79	10.03	4.474
Season	2	51480**	1568.02***	633.83**	480.2***	724.448***
Summer 2012 vs. Summer 2013	1	47814*	2101.46***	590.25*	238.88*	1436.745***
winter 2012 vs. summer 2013	1	8843	24.35	108.01	241.32*	253.874***
summer 2012 vs. winter 2012	1	97783***	2578.25***	1203.23***	960.39***	482.724***
Treatment	2	58904***	302.14*	728.16***	11.03	5.529
ABR vs. RFF	1	116427***	597.47*	1439.28***	12.03	2.396
TWF vs. RFF	1	41121*	209.68	508.25*	20.03	3.15
ABR vs. TWF	1	19163	99.26	236.96	1.01	11.042
Season x treatment	1	50512***	172.2*	624.32***	14.11	0.686
Summer 2012 vs. Summer 2013 x treatment	2	35787*	103.23	441.81*	15.26	0.33
winter 2012 vs. summer 2013 x treatment	2	16096	79.95	199.33	25.65	1.371
summer 2012 vs. winter 2012 x treatment	2	99653***	333.42*	1231.81***	1.43	0.358
ABR vs. RFF x season	2	100265***	332.21*	1239.26***	18.94	1.106
TWF vs. RFF x Season	2	18452	112.84	228.12	23.12	0.944
ABR vs. TWF x Season	2	32819*	71.54	405.57*	0.29	0.008
Residual	16	6337	54.3	42.56	29.45	7.281
Total	26					

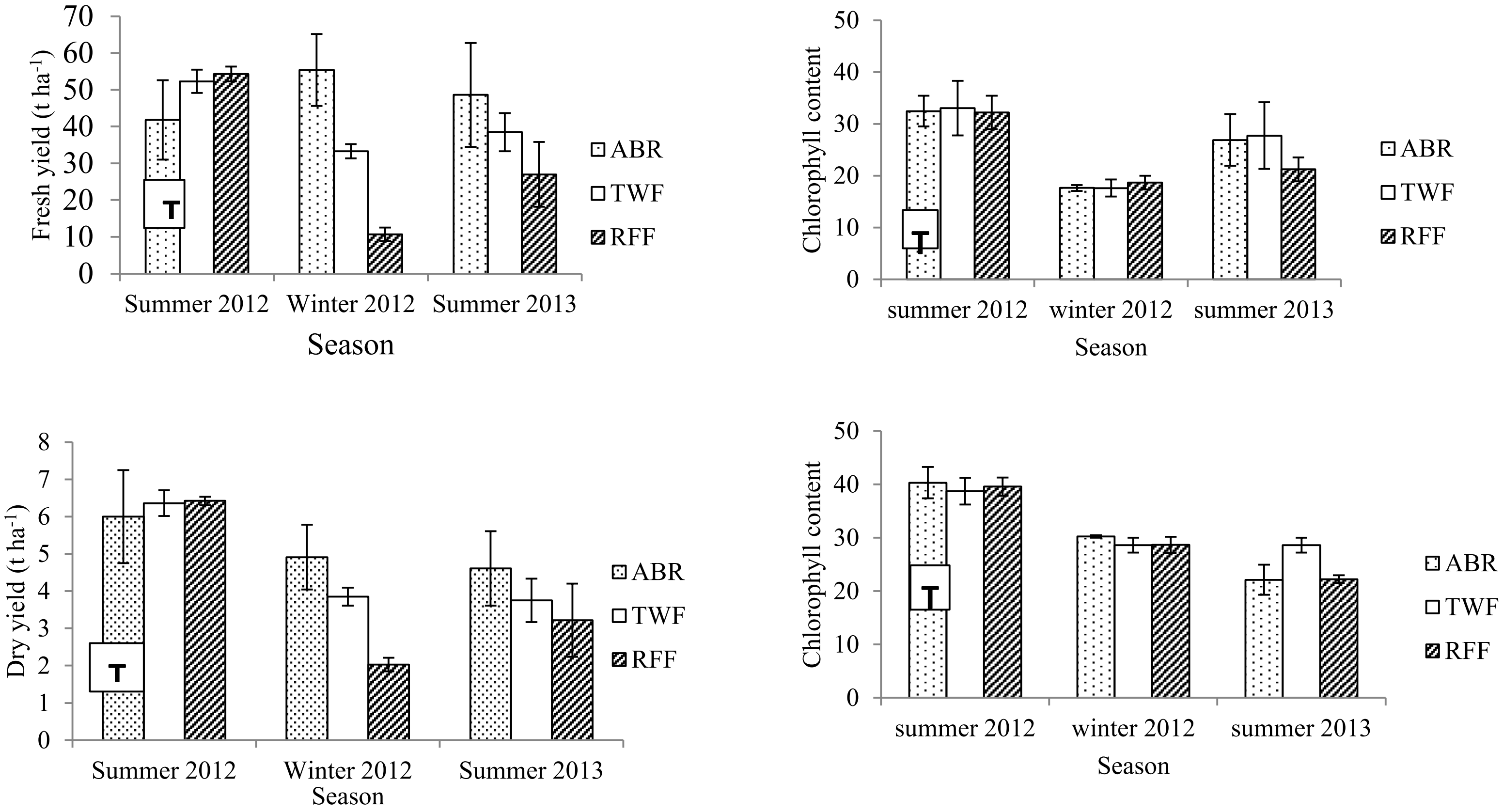


Figure 4.10 Means ± SED for Swiss chard growth (dry mass, fresh mass and chlorophyll content) within three seasons at different levels of treatment, ABR effluent irrigation (ABR) or Tap water + no fertiliser (TW), tap water with fertiliser (TWF) and rain-fed (RFF)

Symbol T denotes TW (Tap water without fertiliser treatment) during baseline studies

Figure 4.11 Swiss chard plants irrigated using ABR effluent (A) and under rain-fed conditions (B) + fertiliser in the winter season (2012).

4.2.8 The determination of nitrate and phosphate leaching in plots irrigated with ABR effluent, tap water with fertiliser and under rain-fed conditions.

Table 4.13 shows mean squares for the analysis of nitrate and phosphate leachate collected to depths (30 cm to 50 cm) measured at four different time intervals: seven days after crop emergence, 45 days after crop emergence, 53 days after crop emergence and 72 days after crop emergence in plots irrigated with ABR effluent, tap water with fertiliser and rain-fed conditions. Leachate nitrate concentration from the ABR, TWF, and RFF treatments were 59.2 mm, 65 mm and 42.4 mm, respectively. The difference, however, was not statistically significant.

Table 4.13 Mean squares for Nitrate-N and Phosphate-P concentrations (mg L-1) at 30 and 50 cm depth for the three irrigation treatments (ABR, TWF and RFF) sampled over four time intervals.

S.O.V.	**D.f.**	**N (mg L^{1})**	**F prob.**	**P (mg L^{-1})**	**F prob.**
Block stratum	2	6517		4.373	
Treatment	2	3400	0.081	5.046*	0.049
Time	3	2982	0.087	2.823	0.16
Depth	1	5250*	0.049	121.095***	<.001
Treatment x Time	6	2154	0.147	2.381	0.192
Treatment x Depth	2	1894	0.239	11.712**	0.002
Time x Depth	3	2778	0.104	6.32**	0.012
Treatment x Time x Depth	6	1718	0.258	1.448	0.486
Residual	46	1281		1.564	
Total	**71**				

Significant differences ($P<0.05$) were observed with respect to nitrate concentration between the 30 and 50 cm depths. Mean values for nitrate concentration at 30 and 50 cm were 64 and 47 mg L^{-1}, respectively and clearly indicate that nitrate concentration was higher at the 30 cm depth (root zone). The median value for nitrate concentration is clearly higher at 30 cm than 50 cm (Figure 4.12).

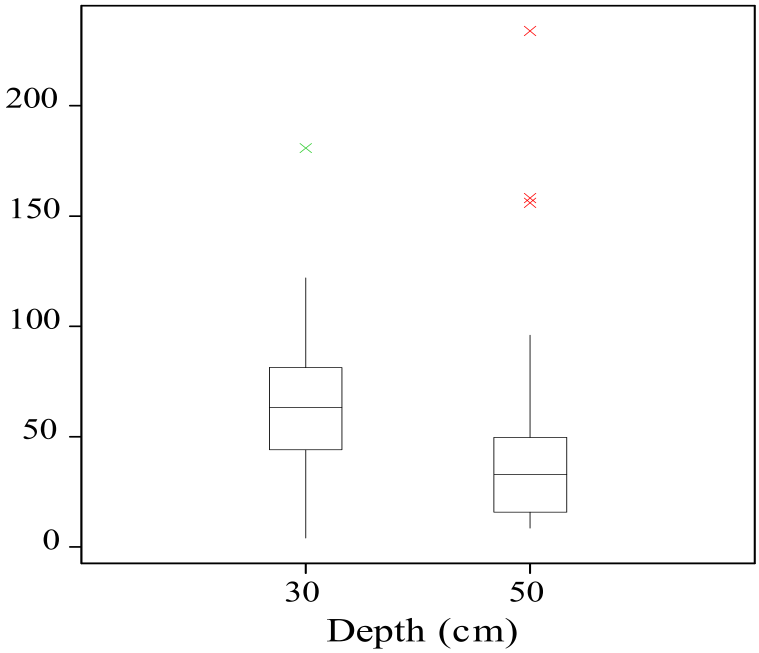


Figure 4.12 Nitrate concentrations (mg L^{-1}) at two soil depths 30 and 50 cm averaged over three irrigation treatments.

Significant differences ($P<0.05$) were observed between the treatments, and depth ($P<0.001$) (30 and 50 cm) with respect to phosphate concentration (Table 4.13). A highly significant interaction between depth and treatment and depth and time ($P<0.01$) was also observed with respect to phosphate-P concentration. Figure 4.13 compares the median values with respect to phosphate concentration. The median value for phosphate concentrations at the two depths is highest for the ABR treatment, followed by TWF and RFF. However the mean phosphate concentration for the ABR treatment was 1.76 mg L^{-1} and 1.98 mg L^{-1} for the TWF. The RFF treatment had the lowest value of 1.10 mg L^{-1} (Figure 4.13.).

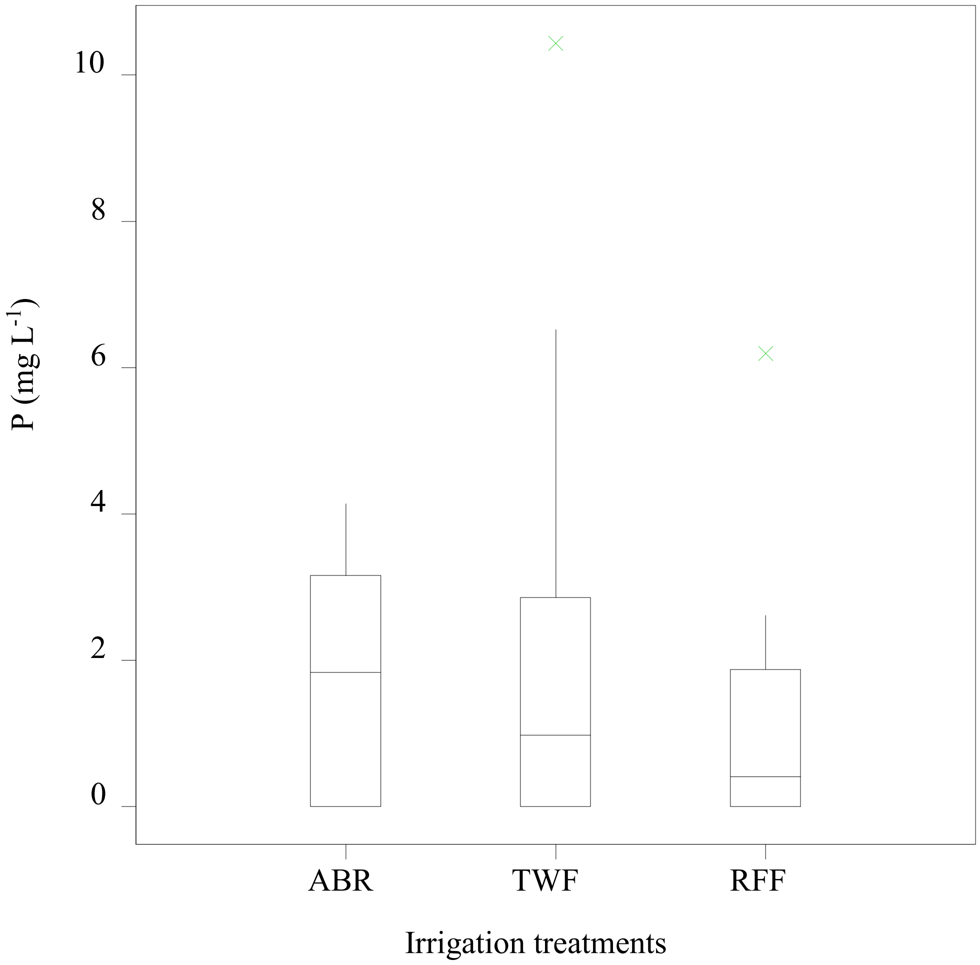


Figure 4.13 Phosphate concentrations (mg L^{-1}) in plots irrigated with ABR effluent (ABR), tap water with fertiliser (TWF) and rain-fed (RFF).

Table 4.13 shows that highly significant differences (P<0.001), were observed with respect to phosphate concentrations at 30 cm and 50 cm. Figure 4.14 shows a box and whisker plot, comparing the variation in phosphate concentrations at 30 and 50 cm depths. The median phosphate value is clearly significant (above 2 mg/L) which is consistent with the observed mean values. The median value at 50 cm is very low and phosphates were hardly detectable at 50 cm. Mean phosphate values recorded at 30 and 50 cm were 2.91 mg/L and 0.31 mg/L respectively. Figure 4.15 shows the interaction between depth and treatments. Results shows that P was not detected at 50 cm especially in the TWF treatment, although some were detected within ABR and RFF treatments.

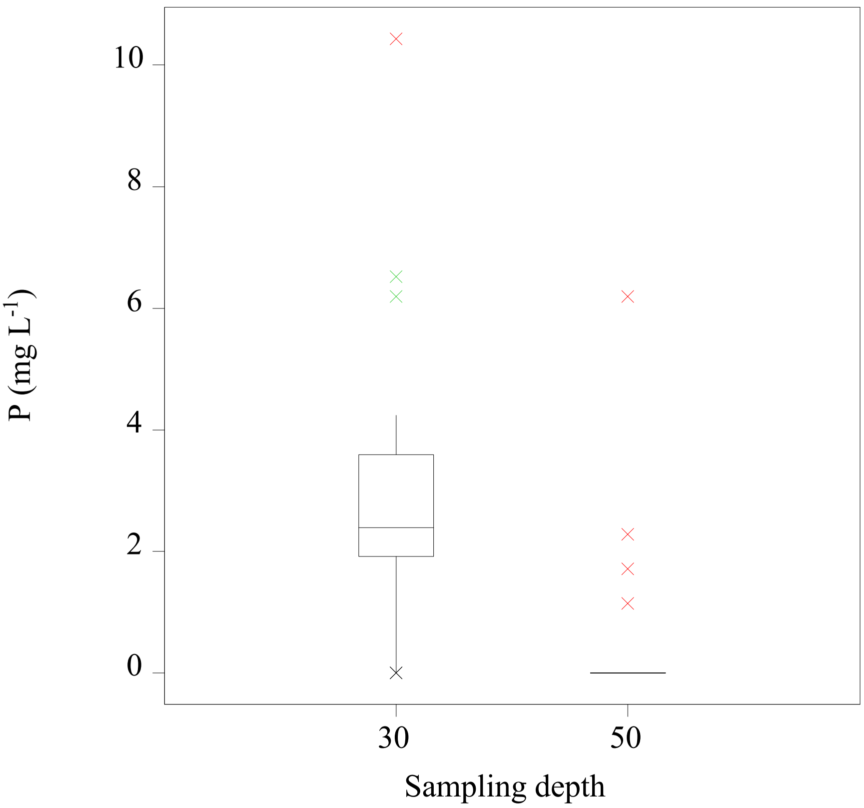


Figure 4.14 Phosphate concentrations (mg L^{-1}) at two sampling depths (30 and 50 cm).

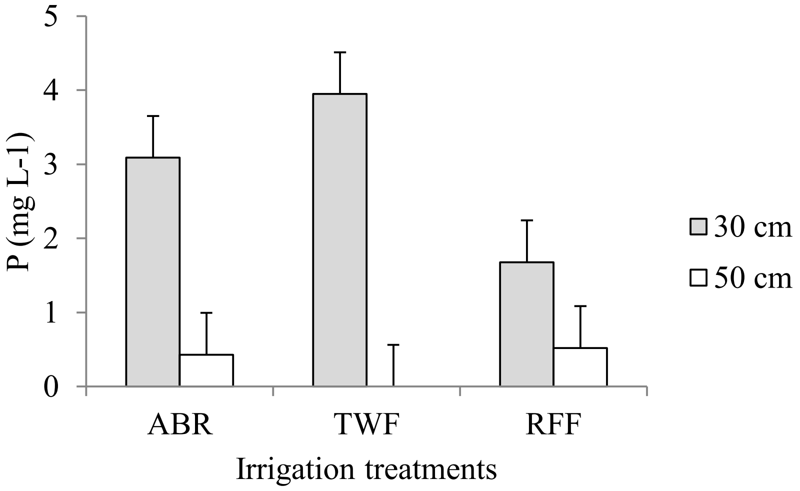


Figure 4.15 Treatment x depth interaction with respect to phosphate concentrations (mg L^{-1}) at 30 and 50 cm depth.

Highly significant (P<0.01) interactions between depth and time were observed with respect to phosphate concentration (P < 0.01) (Table 4.13). Phosphates could only be detected at the 30 cm depth at early growth stages (Figure 4.16).

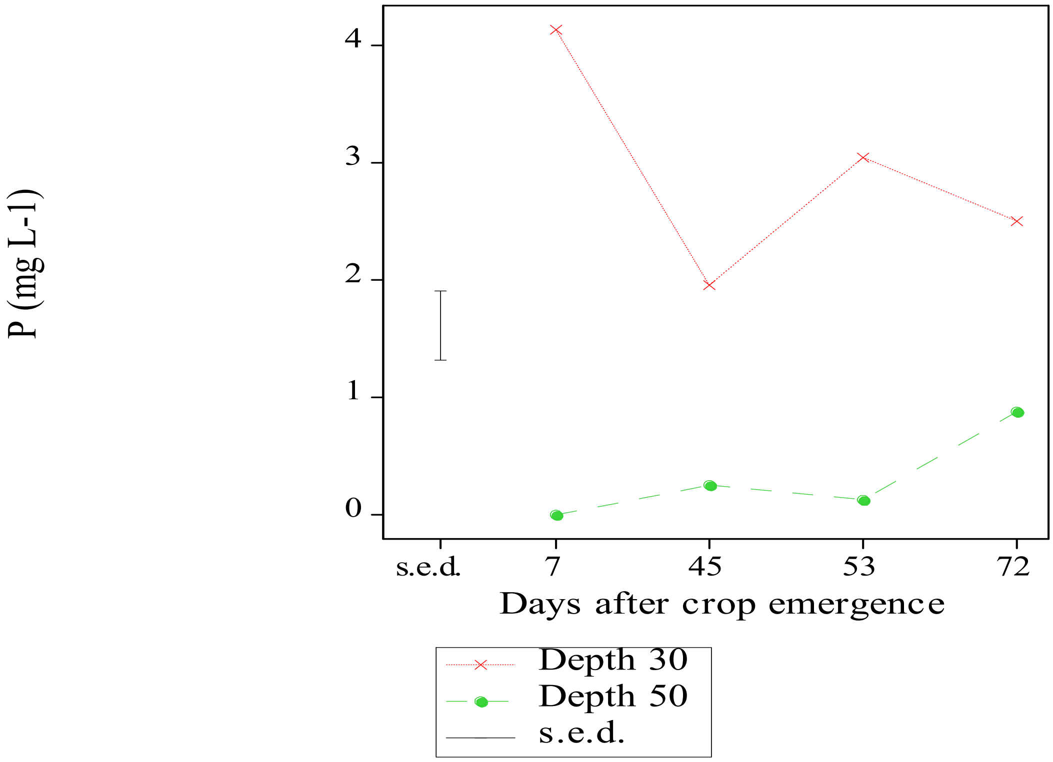


Figure 4.16 Interaction between profile depth and time with respect to phosphate concentrations (mg L^{-1}).

4.2.9 N and P mass balances after irrigation with ABR effluent in summer.

Table 4.14 shows mean squares for nutrient (N and P) mass balances in Swiss chard irrigated with ABR effluent during the summer season between three treatments (ABR, TWF and RFF). Insignificant differences in the amount of N added (P>0.05) were observed while highly significant difference were observed with respect to P added to the soil (P<0.001). No significant differences were observed with respect to N and P lost or gained within the soil system. Figure 4.17 shows the amounts of P supplied to the soil, ABR had the least amount of P (0.00076 kg m^{-2}) supplied compared to TWF and RFF (0.004 kg m^{-2}).

Table 4.14 Mean squares of Swiss chard nutrient (N and P) mass balance after irrigation with ABR effluent during 2013 summer season

Source of variation	**Soil N (before planting)**	**Soil N (after harvesting)**	**N (added to soil)**	**N (plant tissue)**	**N (leached)**	**N (Unaccounted loss)**
Block	3.846	6.024	0.00013	0.023055	0.88664	3.217
Treatment	4.032	2.264	0.000198	0.010289	0.13969	2.391
Residual	1.219	3.362	0.00013	0.001523	0.06983	1.143
	Soil P (Before planting)	**Soil P (After planting)**	**P (added to soil)**	**P (plant tissue)**	**P (leached)**	**P (Unaccounted loss)**
Block	0.02509	0.00544	9.76E-07	0.000567	8.43E-05	0.04327
Treatment	0.00571	0.00729	0.002682***	0.000147	8.43E-05	0.01016
Residual	0.01425	0.01086	9.76E-07	0.000143	0.000206	0.03121

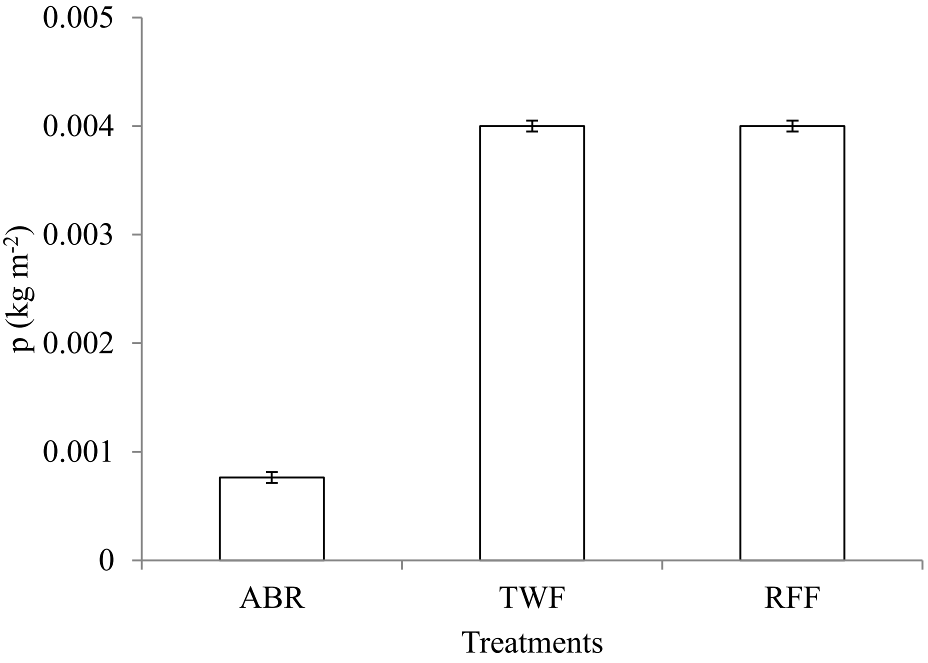


Figure 4.17 Amounts of P (kg m^{-2} plot) added to different treatments (ABR, TWF and RFF) during the Swiss chard growing season

4.3 DISCUSSION

In this study the effect of using ABR effluent on crop growth and the leaching of N and P into soils was investigated. Initial tests included the characterisation of the ABR effluent used for irrigation. The general characteristics of the ABR effluent showed that the effluent was low in heavy metals. A number of studies have shown that treated sewage effluents are low in heavy metals since they originate from households and animals which rarely consume these toxic metals unless water has been contaminated with industrial waste (Levy *et al.*, 2011). Treated wastewater is constituted by 20 to 85 mg L^{-1} of total N and 6 to 20 mg L^{-1} P depending on the strength (Pescod, 1992). The results observed suggest that ABR effluent can be classified as a major source of N. This implies that direct disposal of ABR effluent into rivers can cause water contamination. Its use in agriculture can be beneficial through nutrient supply and leaching might lead to contamination of groundwater.

The study further determined the effect of the ABR effluent on soil chemical properties. A decrease in soil Mn and N content was observed during the winter season. This could perhaps be due to uptake by plants. The lack of significant changes in the soil nutrients with respect to treatments (Table 4.3), suggest that using ABR effluent for irrigation may not result into dramatic changes in the soil chemical properties or significantly contribute to the build-up of these mineral nutrients in the soil. During this study a significant decrease in organic C regardless of irrigation with ABR effluent was observed during winter (Figure 4.4.). Studies by Leal *et al.* (2009) have confirmed that wastewater can increase soil organic C. According to Levy *et al.* (2011) the ability of wastewater to increase soil organic depends on the level of treatment, raw wastewater contains high content of organic C. Studies by Foxon *et al.* (2005) have shown that the ABR has a high reduction of BOD and COD implying that it contributes insignificantly to soil organic C and these agree with the results observed during this study. The reduction in soil organic C is probably due to decomposition by microorganisms (Brar *et al.*, 2000; Al-Omron *et al.*, 2011).

During the preceding season (summer) there was an increase in the soil Ca content in the ABR treatment as compared to the RFF treatment (Figure 4.5). This increase could perhaps be due to the chemical characteristics of the ABR effluent since it contains about 28.9 mg L^{-1} of Ca (Table 4.2). Interestingly the TWF was not supplied with any additional Ca but the amounts were statistically similar to the ABR treatment. However, the reason behind this was not well understood but might be related to other factors such as variability in soil pH within the different plots. Ca losses and retention in the soil are affected by factors such as high rainfall, hydraulic conductivity and soil pH; basic cations such as Ca are easily leached at low pH (Levy *et al.*, 2011). Thus, the lower Ca concentration in the RFF treatment could perhaps be attributed to pH which was low (4.9) as compared to ABR (5.4). A similar trend of decline in soil mineral nutrients was observed again in the summer with respect to N, Zn and P (Figure 4.6) and this could probably be due to uptake by plants. The observation that the irrigation treatments did not differ significantly suggests that the ABR effluent did not play a significant role in causing changes in the relative concentrations of these mineral elements in the soil, probably due to short period of the experiment. Moreover, a comparison over the three seasons shows that there was a decline in the soil P, Mn and N independent of any treatment. This was due to the insignificant effect of ABR effluent on the accumulation of these elements in the soil.

The effect of using ABR effluent on Swiss chard nutrient uptake was investigated. According to Campbell (2000) Swiss chard has a nutrient sufficiency range of 4 -6 % (N) and 3-8% (K), however results obtained showed a higher uptake of N in RFF and ABR as compared to TWF. Although the difference was statistically significant the values were within the optimum sufficiency range according to Campbell (2000). The reasons behind this observation could not be attributed to experimental treatments since there was adequate rainfall and N was applied to optimum quantities as in RFF treatment. Furthermore the leaching results showed insignificant differences amongst all the treatments. This means some other factors which need further investigation contributed to low N uptake in TWF during the 2013 season. Except for K and Na, a significant increase in nutrient uptake during the second year which was not dependant on treatments (Table 4.10) implies that seasonal variation in weather dynamics rather than treatments applied (ABR, TWF and RFF) might have contribute to this result. This agrees with Somma *et al.* (1998) that dynamics in root growth due to soil and weather conditions can affect nutrient uptake in plants. High rainfall and temperature regimes can increase root growth associated with increased nutrient uptake.

An antagonistic relationship with regards to K and Na uptake was observed amongst the treatments. ABR irrigated plants had a higher Na concentration compared to TWF and this was even higher than the RFF treatment during the second season (Table 4.10). High Na concentration within the ABR treatment could have been attributed to irrigation with ABR effluent since it supplied 52.8 kg ha^{-1} of the element (Table 4.2). According to Pokluda and Kuben (2002) Swiss chard is categorised as a saline tolerant vegetable with a capacity to uptake large amounts of tissue Na especially when it is present in the soil. However, higher uptake of K within TWF as compared to ABR is expected since KCl fertiliser was applied to the former based on the recommended rates from the CEDARA soil analysis results (Table 4.1) but in the latter ABR effluent used provided insufficient amounts of K which were 21.2 kg ha^{-1} (Table 4.2) compared to 225 kg ha^{-1} required for Swiss chard production (Schrader and Mayberry, 2003).

The interaction between seasons and treatments shows that the response of Swiss chard to irrigation was variable across seasons. The results shows that plant growth (dry yield, fresh yield and chlorophyll content) was high in summer 2012 compared to winter 2012 and summer 2013 (Figure 4.10). This was due to differences in weather conditions amongst the three seasons (Appendix 1).The analysis of fresh and dry biomass was done to investigate the response of Swiss chard to irrigation with ABR effluent. High fresh biomass values were observed in the ABR treatment compared to TWF and RFF treatment during the winter season. Furthermore the ABR and TWF treatment had high dry mass values than RFF treatment (Figure 4.10). The lower biomass observed in the RFF treatment was due to low rainfall during the winter season (Appendix 1). During summer 2013 season, similarly to summer 2012 no significant differences were observed in biomass (fresh and dry mass) among all the treatments (Figure 4.10). This implies that the use of ABR effluent for irrigation is less important in summer and this should be of major concern for the management of large wastewater volumes during the rainy seasons.

The analysis of leachate quality was conducted to monitor N and P leaching below the rooting zone. The higher concentrations of soil nitrates within the 30 cm depth indicate that there was low rate of N-leaching implying that most of the N was retained for plant uptake. This is expected since clay soils have a higher nutrient retention capacity due to texture and organic matter content compared to sandy soils (Samuel *et al.*, 1993). However, the movement of nitrates within the soil could not be linked to irrigation with ABR effluent because the irrigation treatments did not differ with respect to nitrate concentration at the 30 cm depth (Table 4.13).

Phosphorus is a very immobile nutrient which can be adsorbed by organic matter in the soil rendering it less mobile especially in ferric clay soils (Bar-Yosef, 2011) and this possibly explains why there was negligible movement of P between 30 cm and 50 cm (Table 4.13). A significant ($P<0.01$) treatment x depth interaction was observed with respect to phosphate concentrations (Table 4.13). The results show that there were higher concentrations of phosphates at the 30 cm depth compared to 50 cm depth for the ABR and RFF treatments (Figure 4.15). No phosphates were found at the 50 cm depth for the TWF. The presence of phosphates at the 50 cm depth for the RFF clearly suggests that phosphate movement in the soil cannot be conclusively attributed to ABR effluent irrigation only. The higher mean phosphate value for the TWF is inconsistent with the results shown in the box and whisker plots which show a higher median phosphate concentration for the ABR treatment. However this can be easily explained by the large single value (outlier) observed in the TWF which most likely pushed the mean value upwards (Figure 4.13).

Phosphate concentration within the 30 cm depth declined sharply at 45 days after crop emergence. It further increased from 53 days after crop emergence and the concentrations did not significantly change after 72 days. The lower phosphate concentration observed at 30 cm during the 45, 53 and 72 days after crop emergence (Figure 4.16) could probably be attributed to P-uptake by the plants. However no phosphates were detected at the 50 cm depth at early growth stages. There was a slight increase in phosphate concentration with time up to the fourth sampling at 50 cm. However the increase was not statistically significant over time.

Insignificant differences in the N mass balances between all the treatments could be an indication that the N cycle system was in a balanced state regardless of treatments applied. The amount of N added to the soil through irrigation with ABR effluent did not differ significantly in comparison to the amount added through inorganic fertilisers (Table 4.1 and 4.2). Based on the actual Swiss chard water requirement ABR effluent could provide sufficient amounts of N required by the plant. The amount of N taken up by plants between treatments did not differ significantly, implying that ABR irrigation did not affect N uptake. Insignificant N leaching values can further on explain the fact that the N supplied by ABR effluent was taken up by plants. Ammonium nitrogen found in ABR effluent can be nitrified to nitrates as reported by Bame *et al.* (2013) and subsequently taken up by plants. This may also explain the insignificant differences in amounts of N left after harvesting. The ability of Swiss chard take up mineral nutrients (N and P) implies that agricultural systems can be used sustainably to dispose treated wastewater (Abdel-Raouf, 2012).

Interestingly, the ABR effluent managed to provide about 16.7% of the total P requirements for Swiss chard production but no significant differences were reported with respect to leached P, taken up P, soil P after harvesting and before planting (Table 4.14). P is generally deficient in most soils, and exists mostly in organic forms unavailable for plant uptake (Schachtman *et al.*, 1998). However, the mineralisation of organic P is affected by certain microorganisms which operate under certain conditions (pH, temperature and moisture) (Bar-Yosef, 2011) but this process takes years. The reasons behind this observation are not clear hence they need further studies.

4.4 CONCLUSIONS AND RECOMMENDATIONS

No significant changes were observed with respect to changes in soil physical and chemical properties over the seasons following irrigation with ABR effluent due to short period of the experiment.

Seasonal effects were highly significant and ABR acted both as a fertiliser and water source particularly during winter. This was very important because plant biomass of Swiss chard plants that were under rain-fed conditions and fertilised (RFF) was significantly lower compared to those that were irrigated with ABR effluent and tap water with fertiliser (TWF) during the winter season.

Nitrate concentrations (mg L^{-1}) were comparatively higher at 30 and 50 cm for all treatments compared to phosphate concentrations. Nitrate concentration differed significantly with depth and the results showed a higher concentration at 30 cm compared to 50 cm. However nitrate concentrations did not differ between the three irrigations and it is therefore not possible to attribute nitrate movement within the experimental plots to ABR effluent irrigation. Most of the phosphates were detected at the 30 cm depth and insignificant amounts were detected at the 50 cm depth. Similarly, the movement of phosphates in the soil profile could not be attributed to ABR irrigation because RFF showed similar concentrations at 50 cm depth.

The irrigation with ABR effluent did not affect the leaching of nutrients (N and P) and did not affect the soil chemical processes which lead to subsequent uptake of nutrients by Swiss chard. Implying that irrigation of Swiss chard with ABR effluent can be used sustainably in a manner that will prevent environmental pollution.

Further studies should focus on the ability of different soil types to absorb different volumes of the effluent especially in summer when the rainfall is low. It is very important to monitor the soil chemical properties after long time of irrigation with ABR effluent.

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CHAPTER 5

SWISS CHARD GROWTH AFTER IRRIGATION WITH ABR EFFLUENT ON THREE CONTRASTING SOILS (ACIDIC, CLAY LOAM AND SAND LOAM SOIL)

Abstract

The use of DEWATS as an onsite sanitation technology leads to the production of large volumes of effluents which need sustainable management to avoid water pollution. The use of treated effluent in agriculture must consider potential effects on variable soil types around different areas. A factorial experiment was carried out in a complete randomised design with three soil types (Sandy loam, Clayey loam and Acidic soil), two irrigation water sources (ABR vs. tap water, TW), three fertiliser rates (no fertiliser, half optimum and optimum rate) and four replicates. The optimum rates for sandy loam were (N 100 kg ha^{-1}, P 270 kg ha^{-1} and K 435 kg ha^{-1}), clayey loam (N 100 kg ha^{-1}, P 195 kg ha^{-1} and K 10 kg ha^{-1}) and acidic soil (N 100 kg ha^{-1}, P 195 kg ha^{-1} and K 445 kg ha^{-1}). The aim of the experiment was to investigate the effect of ABR effluent on Swiss chard growth in three contrasting soils and different fertiliser application rates. Data was collected on biomass (fresh and dry) and leaf area index. Data was analysed using GenStat® 14th Edition (VSN International, Hemel Hempstead, UK). Results showed that ABR irrigation increased fresh mass ($P<0.01$) and Leaf Area Index (LAI) ($P<0.01$) at optimum fertiliser recommendation rate. Fertiliser application significantly increased fresh mass and LAI ($P<0.001$). Irrigation with ABR effluent significantly affected fresh mass at half optimum fertiliser application rate ($P<0.01$). Irrigation with ABR effluent has a liming effect in acidic soils. It also increased crop growth through supplementing nutrients requirements at different fertiliser application rates.

Keywords: Soil type, ABR effluent, Swiss chard growth, Fertiliser recommendation rate

5.0 INTRODUCTION

The Decentralised Wastewater Treatment System (DEWATS) involves the Anaerobic Baffled Reactor (ABR) which reduces BOD and COD from the human waste at a high treatment rate (Foxon *et al.*, 2005). The DEWATS plant could provide suitable options for the provision of on-site sanitation systems for communities living in peri-urban areas not connected to centralised waterborne sewers. However a key challenge with regards to the use of DEWATS system is the disposal of the effluent. The ABR effluent contains plant growth mineral nutrients (N and P) which when disposed into rivers can cause eutrophication. Furthermore dealing with volumes of effluent generated and disposing it on land could have negative impacts on soils. The use of treated wastewater from the DEWATS plant for agricultural production could therefore be of considerable benefit in water scarce areas of South Africa. Due to variability in soil types, rainfall distribution and physical features such as terrain around South Africa, the response of crops to irrigation with treated effluent is likely to differ with locations.

Different soils differ in physical properties such as texture and Cation Exchange Capacity (CEC) depending on the source of its origin (parent rock mineral content) (Samuel *et al.*, 1993). This has an impact on chemical properties such as nutrient content, pH and organic matter present due to biological activity (Chen *et al.*, 2011). Organic matter increases with increasing soil clay content due to reduced decomposition resulting from increased bonding between soil aggregates and organic matter and increased aggregation. Soils from temperate regions are generally characterised by low pH due to low rate of organic matter decomposition as compared to tropical soil (Samuel *et al.*, 1993). Soil pH has a significant effect on soil biological activity, mineralisation and availability of other macronutrients (Jüeschke *et al.*, 2008). Treated wastewater such as ABR effluent contains easily biodegradable dissolved organic matter (DOM) which is essential for nutrient recycling through improved microbial activity (Chen *et al.*, 2011). Several studies have been done to investigate the effect of treated wastewater on biomass production in different soil types. Studies by Al-Omron *et al.*, (2011) and Mojiri, (2011) reported a decrease in soil pH after irrigating with treated wastewater. On the other hand, Rousan *et al.* (2007) reported an insignificant change in the soil pH after irrigation with treated wastewater. These observations imply that the effect of irrigating with treated wastewater on soil pH and subsequent biomass production is variable depending on the nature of wastewater used. Studies by Bame *et al.* (2013) concluded that different soil types (acidic, sandy loam and clayey loams) have different capabilities in retaining macronutrients. They observed that the acidic (Inanda) soil has high P fertiliser requirements compared to clayey loam (Shortlands) and sandy loam (Catref) soils. However, the effect of ABR effluent irrigation on Swiss chard biomass in a range of soils has not been investigated. .

Macronutrients (NPK) are required for optimum plant growth in certain amounts (Munson, 1998). Clay soils are generally classified as high fertile soils while sandy soils are classified as low fertile soils because of their differences in CEC (Samuel *et al.*, 1993). Over application of N fertilisers (nitrates) in leaf vegetables is characterised by reduced quality (Santamaria *et al.* 1999) while under-fertilisation can lead to reduced yields (Schrader and Mayberry, 2003). Depending on the soil type irrigation with ABR effluent might either over or undersupply crops with nutrients hence the effect of irrigating with ABR effluent in three contrasting soils and at different fertiliser recommended rates on Swiss chard biomass production was investigated. The objective of this study was to investigate the effects of irrigation with ABR effluent on Swiss chard growth in three contrasting soils (acidic, clay loam and sandy loam) and different fertiliser rates (zero, half and optimum).

5.1 MATERIALS AND METHODS

5.1.1 Experimental site

The experiment was done in a tunnel at Newlands Permaculture Centre, Durban, South Africa. The site is located within longitude 30°57'E and latitude 29°58'S and has the following meteorological characteristics; annual rainfall of 1000 mm and mean daily temperatures 20.5 °C see (Chapter 3: Table 3.5).

5.1.2 Experimental material

Swiss chard (Ford hook giant variety) was obtained from the McDonalds seed company in Pietermaritzburg. Acidic (Inanda) soil was collected from World's view Pine tree plantation in Pietermaritzburg (29°35.003'S; 30°19.7404'E). Sandy loam soil (Catref) was collected from Kwadinhabakubo, Hillcrest (29°44.046'S; 30° 51.488'E). Clay loam soil (Shortlands) was collected from Ukulinga, University of KwaZulu-Natal farm, Pietermaritzburg (30°24'S; 29°24'E).

5.1.3 Experimental design

The experiment was designed as a 2 X 3X 3 factorial treatment structure using a Complete Randomised Design (CRD) with the following treatment: Irrigation water (2 levels- ABR effluent and tap water); soil types (3 levels - Acidic, Sandy loam and Clayey loam soils); and fertiliser (3-levels: Zero, half and full recommendations see Table 5.1) replicated four times giving a total of 72 experimental units. The fertiliser application rates were based on the soil analysis results from Fertiliser Advisory Service, KZN Department of Agriculture and Environmental Affairs; Soil Fertility and Analytical Service, CEDARA.

5.1.4 Experimental methodology

5.1.4.1 Soil collection and analyses

Soils were collected by clearing the top layer to about 5 cm depth using a spade and dug down to a 30 cm depth. The soils were packed in 50 kg bags and were transported to the Agriculture Faculty, UKZN Pietermaritzburg. There were sieved using a 2 mm sieve to remove debris and leave small soil particles. A representative sample was collected and submitted to Fertiliser Advisory Service, KZN Department of Agriculture and Environmental Affairs; Soil Fertility and Analytical Service, CEDARA for the analysis of chemical properties.

5.1.4.2 Soil mixing and potting

The sieved soils were mixed with fertilisers: SSP (10.5% P), KCl (52% K) and Urea (46% N) at three different recommended rates (no fertiliser, half optimum recommended rate and full recommended rate) based on soil analysis results from CEDARA (Table 5.1). For each soil type 80 kilograms of soil were mixed according to its respective fertiliser recommended rate and potted directly into 24 different 10 kg pots. Twelve pots were assigned to tap water treatment and the remaining 12 assigned to ABR effluent irrigation. Treatments were randomly allocated within each irrigation water source treatment.

Table 5.1 Fertiliser application rated for three different soils used during the experiment (kg ha^{-1})

Soil type	Optimum			Half		
	N	**P**	**K**	**N**	**P**	**K**
Sandy	100	270	435	50	135	217.5
Clay	100	195	10	50	97.5	5
Acidic	100	195	445	50	97.5	222.5

5.1.4.3 Characterisation of the ABR effluent and calculation of the N, P and K applied

Small aliquots (500 ml) of ABR effluent were collected after irrigation and were analysed for chemical properties. The samples were taken to the University of KwaZulu-Natal, Chemistry department where they were analysed for P and K using the (ICP-AES) (Chapter 4: Section 4.1.2.2).

5.1.4.4 Determination of the total N from the ABR effluent (Kjeldahl method)

Total N from the ABR effluent was determined according to Standard methods (Eaton and Franson, 2005). A receiving vessel was prepared to capture volatile ammonia and 60 ml of 2% boric acid solution and about two to three drops of indicator were added. Distillation was done after the addition of 90 ml of 32% NaOH to the ABR effluent sample. The solution condensate was titrated with sulphuric acid (0.5N) to the end point pH of 4.65.

$$\text{N (\%)} = ((\text{consumption} - \text{blank}) \times 1.4007 \times n \times 100)/\text{sample size} \qquad \text{Eq. 5.1}$$

1.4007 mg N = 1 ml of 0.1N volumetric solution

5.1.4.5 Planting and trial establishment

Seeds were planted at a seeding rate of four seeds per pot. Irrigation water type was applied within each treatment up to 70% field capacity to stimulate germination. Thinning of trials was done two weeks after planting to leave one plant per pot. The irrigation treatments were applied for eight weeks at a five day interval until the plants reached the harvesting stage after nine weeks. Weeding was consistently done throughout the growing season to keep the pots clean.

5.1.5 Data collection

5.1.5.1 The determination of Leaf Area Index (LAI)

Number of leaves per plant was counted at harvesting. Leaf area was measured according to Pokluda and Kuben (2002) method. Leaf length and leaf width were measured as in figure 5.1. The leaf length and width were regressed against each other to get the slope which was multiplied by the leaf length and width to get the leaf area (Eq. 5.2).

$$A = R \times L \times W \qquad \text{Eq. 5.2}$$

*(A=leaf area, R=slope, L=leaf length and W=leaf width)

Figure 5.1 Measurement of the Swiss chard leaf width (A) and length (B) for the determination of leaf area.

Results on leaf area and leaf number were used to determine leaf area index according to Ghoreish *et al.* (2012).

LAI= Leaf number per plant X leaf area per leaf (m^2) X number of plants per 1 m^2

5.1.5.2 Biomass determination

Plant fresh mass (g) was determined by weighing plants directly at harvesting. The dry mass (g) was then determined by weighing plants which were oven dried at 70° C for 72 hours. The values obtained were converted to mass per hectare (tonnes per hectare).

5.1.6 Data analysis

All statistical analyses were performed using GenStat® 14th Edition (VSN International, Hemel Hempstead, UK). Data were subjected to analysis of variance with treatments, irrigation source, and fertiliser recommendation rate and soil type as factors. Means were compared using SEDs at the 5% level significance.

5.2 RESULTS

5.2.1 Soil chemical analysis results before planting

Table 5.2 shows soil chemical properties for the three contrasting soil before Swiss chard planting. Inanda soil is characterised by high acidity and has an acid saturation of 40%, a pH of 4.11 and exchangeable acidity of 1.75. This soil also has high organic C (>6%) as compared to catref (0.5%) and shortlands (2.3%). The N content was high within the Inanda soil (0.56%) followed by shortlands soil (0.27%) and cartref soil (0.08%). Analysis of the C: N ratio shows that acidic soil has a high value (10.7:1) compared to shortlands soil (8.5: 1) and cartref soil (6.25:1). Total cations are high in shortlands soil (9.91 cmol$_c$ kg^{-1}) as compared to cartref (1.19 cmol$_c$ kg^{-1}) and acidic soil (5.92 cmol$_c$ kg^{-1}).

Table 5.2 Soil chemical and physical properties for three contrasting soils (Acidic, Sandy loam and clayey loam) before planting.

	Clay soil (Shortlands)	**Sandy loam soil (Catref)**	**Acidic soil (Inanda)**
N (%)	0.27	0.08	0.56
Clay (%)	34	11	23
Org. C (%)	2.3	<0.5	>6
C: N ratio	8.5:1	6.25:1	10.7:1
P (mg kg^{-1})	10.47619	0.7	12
K (cmol$_c$ kg^{-1})	0.501279	0.02	0.08
Ca (cmol$_c$ kg^{-1})	6.681637	0.51	3.23
Mg (cmol$_c$ kg^{-1})	3.209877	0.32	0.87
Exch. acid (cmol$_c$ kg^{-1})	0.019	0.34	1.75
Tot. cations (cmol$_c$ kg^{-1})	9.91	1.19	5.92
Acid sat. (%)	0	19.7	40
pH (KCl)	4.89	4.03	4.11
Zn (mg kg^{-1})	5.142857	0.14	2.8
Mn (mg kg^{-1})	35.24	1.41	10.67
Cu (mg kg^{-1})	6.67	0.35	3.6

5.2.2 Comparison of ABR effluent nutrients (N, P and K) applied and nutrients requirements for each soil type.

Table 5.3 shows the amounts of nutrients supplied by the ABR effluent in comparison to the standard recommended rates. There was variability in the nutrients requirements for specific elements within different soils. Acidic and sandy loam soils were generally deficient in K as compared to clayey loam soil. As compared to the field experiment, the soils used in this study were very deficient in P (Table 4.1 see chapter 4). Irrigation with ABR effluent could supply more than enough K required in the clayey loam soil. Moreover, based on the P requirements all the soils have a high requirement for P and large quantities of the effluent must be applied to meet the demand.

Table 5.3 Quantities of nutrients contained in the effluent used for the irrigation of Swiss chard in the tunnel showing the amount of N, P and K applied in kg ha^{-1}.

	ABR effluent characterisation (mg L^{-1})	Sandy loam (Catref)	Clayey loam (Shortlands)	Acidic (Inanda)
Bulk density (g/cm3):		1.42	1.28	0.77
Amount applied (L/10 kg pot):		7	7.5	9.5
Amount required to meet nutrient requirements (L/10 kg pot):				
N		3.846154	4.25	7.25
P		124.3421	100.15	165.4
K		71.81604	1.85	135.5
Optimum recommended rate (kg ha^{-1}):				
N		100	100	100
P		270	195	195
K		435	10*	445
Amount applied (kg ha^{-1}):				
N	61	182	175.6	133.8
P	5.1	15.2	14.6	11.2
K	14.2	42.4	41	31.2

*High K applied in clay soil from the ABR effluent.

5.2.3 Effects of fertiliser application rates, soil type and irrigation water type on Swiss chard growth.

5.2.3.1 Dry mass and fresh mass

Table 5.4 shows mean squares for the dry and fresh mass and leaf area index (LAI) amongst the three treatments (fertiliser application rate, soil type and irrigation source). Significant differences in dry mass were observed with respect to fertiliser rates ($P<0.001$), interaction between soil type and irrigation source ($P<0.01$), fertiliser rate and irrigation source ($P<0.05$) and the interaction between fertiliser rate and soil type ($P<0.05$).

Figure 5.2 describes the effects of the interaction between soil type and irrigation water source on dry mass and fresh mass. The interaction between soil type and irrigation water source described in figure 5.2 shows a significant difference ($P<0.05$) with special reference to acidic soil. Tap water irrigation had a lower average dry mass value of 0.084 t ha^{-1} as compared to 0.29 t ha^{-1} observed in ABR irrigation.

Figure 5.3 shows the interaction between fertiliser application rates and irrigation water source on crop biomass (dry and fresh biomass). The interaction between fertiliser recommended rates and irrigation water source on Swiss chard dry mass was significant ($P<0.05$). Within tap water treatment the dry mass was 0.542 t ha^{-1} at optimum fertiliser application rate compared to half recommended rate (0.18 t ha^{-1}) and no fertiliser treatment (0.006 t ha^{-1}). There were no significant differences in dry mass between the optimum and half optimum application rates in pots irrigated with ABR effluent. Dry mass was 0.373 t ha^{-1} in ABR treatments at optimum recommended rate and this did not differ significantly from half optimum recommended rate (0.24 t ha^{-1}). At optimum rate TW had a higher dry biomass (0.543 t ha^{-1}) compared to 0.373 t ha^{-1} for irrigation with ABR effluent.

Significant differences in fresh mass were observed with regards to fertiliser application rate ($P<0.001$) and the interaction between soil type and irrigation water source ($P<0.01$) (Table 5.4). Table 5.5 describes the effect of fertiliser application rate on fresh mass. There was in increase in fresh biomass from zero (0.61 t ha^{-1}), half (2.95 t ha^{-1}) to optimum application rate (5.22 t ha^{-1}). ABR effluent had a significantly higher fresh mass (4.29 t ha^{-1}) compared to tap water irrigation (1.08 t ha^{-1}) in the acidic soil (Figure 5.2).

5.2.3.2 Leaf area index (LAI)

Table 5.4 shows a significant interaction ($P<0.001$) between soil type and irrigation treatments on Leaf Area Index (LAI). Significant difference in LAI between ABR irrigation (1.092 m m^{-2}) and Tap water irrigation (0. 041 m m^{-2}) within the acidic soil was shown in figure 5.2. A significant difference in LAI was described in table 5.5 with respect to fertiliser application being: Optimum (183 648 m m^{-2}), half (102 167 m m^{-2}) and no fertiliser (24 982 m m^{-2}).

Table 5.4 Mean squares values for the Swiss chard dry mass, fresh mass and Leaf Area Index (LAI) amongst the 3 treatments (fertiliser application rate, soil type and irrigation source).

Source of variation	**D.f.**	**Missing values**	**LAI**	**Fresh biomass**	**Dry biomass**
Fertiliser	2		1.51×10^{11}***	127.2***	1.010***
Soil type	2		1.95×10^{10}	1.7	0.1
Irrigation	1		4.21×10^{10}*	5.2	0.001
Fertiliser x Soil type	4		1.86×10^{10}	7.1	0.113*
Fertiliser x irrigation	2		6.29×10^{10}	16	0.15*
Soil type x irrigation	2		7.81×10^{10}***	38.7**	0.223**
Fertiliser x Soil type x Irrigation	3		9.6×10^{9}	15.6	0.057
Residual	50	-4	8.74×10^{9}	6.316	0.042
Total	**66**	**-5**			

*Significance at <0.05 **Significance at<0.01 ***Significance at <0.001

Table 5.5 The effect of fertiliser application on Swiss chard Leaf Area Index and fresh biomass.

	Optimum	**Half**	**No fertiliser**	**SED**
Fresh yield (t ha^{-1})	5.22^{a}	2.95^{b}	0.61^{c}	0.513
LAI (m m^{-2})	183 648^{a}	102167^{a}	24982^{b}	38172.8

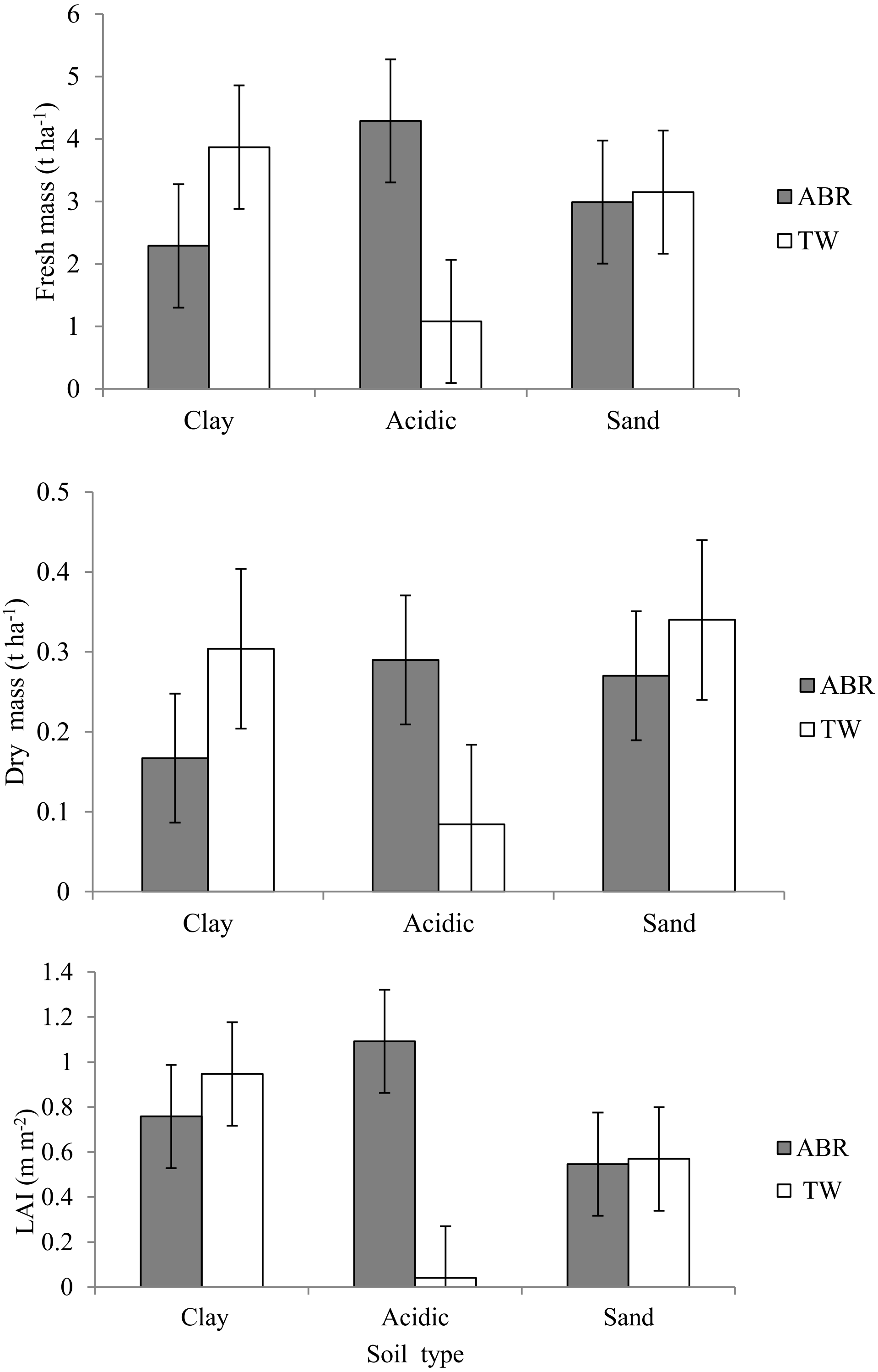

Figure 5.2 The interaction between soil type and irrigation water source on dry mass, fresh mass and leaf area index results for all the fertiliser recommended rates.

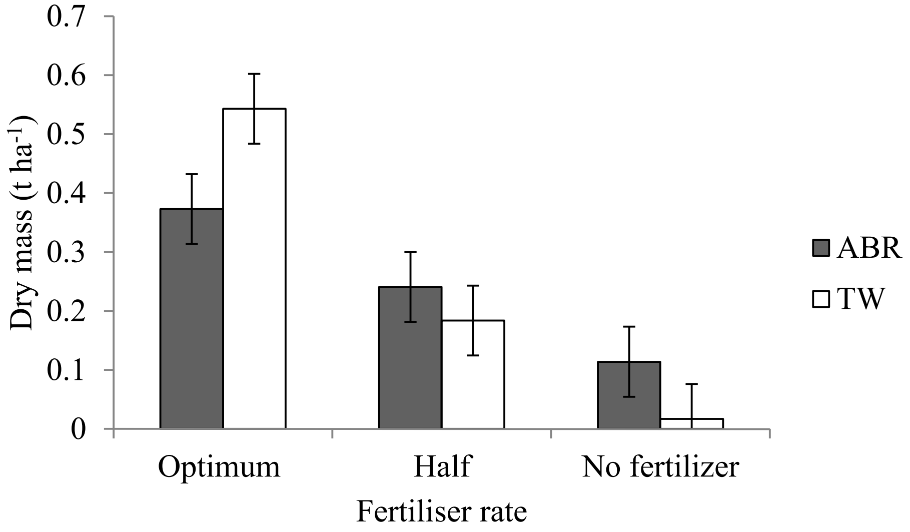

Figure 5.3 The interaction between fertiliser recommended rate and irrigation water source on biomass results for all the fertiliser recommended rates.

5.3 DISCUSSION

ABR effluent was more effective in increasing growth of Swiss chard as compared to tap water irrigation (Figure 5.2). This is expected because ABR effluent contains plant growth mineral nutrients such as N and P (Table 5.3) which hasten plant growth. Several studies in the literature have confirmed that irrigation with treated wastewater can increase crop growth (Shahalam *et al.*, 1997; Zavadil, 2009; Adewoye, 2010). This is through increased leaf area index, which increase photosynthetic capacity of the crop leading to increased biomass. A significant interaction between fertiliser rates and irrigation water source on Swiss chard growth was observed (Figure 5.3). Irrigation with ABR effluent increased Swiss chard growth at zero and half fertiliser rates as compared to tap water. These results are in agreement with those observed by Odindo *et al.* (2013) and Bame *et al.* (2013) on six weeks maize. This implies that ABR effluent provided mineral nutrients which supplemented the deficit required for these fertiliser recommendation rates.

The interaction between soil type and irrigation water source on Swiss chard showed that ABR effluent significantly increased its growth in acidic soil as compared to clayey loam and sandy loam soil (Figure 5.2). ABR effluent increased crop growth (dry mass, fresh mass and leaf area index) in acidic soil because it contains basic elements and compounds which have a buffering action on the soil pH (Bame *et al.*, 2013). High soil acidity can retard plant growth through aluminium toxicity, reduced nutrient availability and uptake (Robson and Abbott, 1989). The nitrification process is also faster between neutral and slightly alkaline pH (Bar-Tal, 2011), irrigation with ABR effluent moderates soil pH thereby hastening this process. However, higher Swiss chard growth in acidic soils irrigated with ABR effluent could have been due to faster conversion of ammonium to nitrates (Bame *et al.*, 2013) and their subsequent uptake. This means irrigation with ABR effluent can improve soil chemical properties such as pH. Improved soil chemical properties are associated with increased nutrient availability, uptake and plant growth.

Results show that Swiss chard growth (LAI and biomass) increased with increasing fertiliser application rate (Table 5.5). This is expected because plant growth increases with increasing fertiliser (NPK) concentrations until it reaches an optimum (Munson, 1998).

Tap water irrigation had higher dry biomass compared to irrigation with |ABR effluent at optimum fertiliser rate. A study by Khan *et al.* (2011) has shown that irrigation with treated effluent can increase tomato biomass even at low fertiliser rates. However, reasons behind low biomass after irrigation with ABR effluent at optimum fertiliser rate were not well understood and this needs further investigations.

5.4 CONCLUSIONS AND RECOMMENDATIONS

The crop growth response was influenced by an interaction between fertiliser application rate and irrigation water source. Irrigation with ABR effluent increased Swiss chard growth compared to tap water irrigation in all soil types and fertiliser application rates. The ABR effluent increased Swiss chard growth and acted as a fertiliser supplement especially at half optimum fertiliser recommended rate compared to irrigation with tap water. The increase in Swiss chard growth as a result of irrigating with the effluent was more significant in acidic soil compared to the sandy and clay soil, implying that ABR effluent have a liming effect.

Irrigation with ABR effluent can increase plant growth on low fertile soils. Knowledge on the soil fertility status prior to irrigation with ABR effluent can enable farmers to manage their fertiliser application programmes. Supplementing fertilisers is dependent on the soil type; some soils have higher fertiliser requirements which cannot be supplied by ABR effluent.

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CHAPTER 6

GENERAL DISCUSSION AND RECOMMENDATIONS

6.0 GENERAL DISCUSSION

This study investigated the effect of ABR effluent on the biomass of Swiss chard and the leaching of N and P in soils. When conducting studies of this nature it is important to factor in the residual fertility of the soils. This is because it may confound the results and affect the conclusions with regards to the effect of the effluent. Therefore a baseline study was conducted to determine the effect of residual fertility on Swiss chard biomass (Chapter 3). The results showed that the growth of Swiss chard in a field experiment was not reliant on fertiliser applied (chapter 3) since insignificant differences in growth were observed amongst all treatments (rain-fed with fertiliser RFF, tap water with fertiliser TWF and tap water without fertiliser TW) (Table 3.8). This implies that the inherent soil fertility was sufficient to support Swiss chard growth. The results suggest that the additional fertiliser applied in the TWF treatment may have been unnecessary. However, the recommendations from the soil fertility laboratory indicated that despite the high inherent soil fertility; there was need for supplemental fertiliser application to meet Swiss chard nutrient requirements (Table 3.5). The reasons for the lack of differences between the fertilised irrigated (TWF) and rain-fed plots (RFF) compared to the unfertilised but irrigated plots (TW) are not clear; however it is possible that the N and P supplied may have been lost through leaching. It was observed that there was heavy rainfall during the period of growth (Appendix 1). Interestingly the yields observed in all the three treatments were comparable to expected Swiss chard yields (Schrader and Mayberry, 2003). In chapter 4 the plots with no fertiliser application during the baseline studies were irrigated with effluent and this was compared with tap water irrigation with fertiliser and the rain-fed treatment with fertiliser. Planting was done in winter 2012 and summer 2013. During the winter 2012 planting (drier season) when ABR effluent was used for irrigation, higher plant growth was observed with respect to the irrigated treatments (TWF and ABR) compared to rain-fed with fertiliser (RFF) (Figure 4.9). Results obtained over all the seasons shows that during the rainy season (summer) no significant differences were observed with respect to plant biomass. This implies that the soil used during the field study was very fertile and according to Samuel *et al.* (1993) clay loam soils are classified as high fertile soils which contain >2% N.

The effect of irrigation with ABR effluent on Swiss chard growth under contrasting soil types and at different fertiliser recommendation rates was further investigated in chapter 5. The results obtained showed a significant increase in growth within the plants irrigated with ABR effluent. This is expected because wastewater contains mineral nutrients required for plant growth such as N and P. This observation agrees with studies by several authors on different wastewaters (Shahalam *et al.*, 1997; Zavadil, 2009; Adewoye, 2010). Irrigation with ABR effluent could increase Swiss chard growth even at zero and half fertiliser recommendation rates (Figure 5.4). This result further confirms that ABR effluent increased Swiss chard through supplementing fertiliser requirements. Increased nutrient application and uptake leads to increased chlorophyll content a major driver for increased plant biomass through photosynthesis. Insignificant differences in Swiss chard growth was also reported with regard to soil type and zero recommended fertiliser application rate (Figure 5.4). However, in comparison to findings from the field experiments (Chapter 3 and 4) whereby there was no significant differences in Swiss chard growth before and after irrigation with ABR effluent amongst all the treatments. In comparison to other fertilised treatments (TWF and RFF), pot experiments showed lower growth at zero fertiliser application rate in comparison to optimum application rate. This means residual soil fertility, regardless of soil type can impact crop growth response after irrigation with ABR effluent. Bearing in mind that during the field experiment Swiss chard was grown on a clayey loam soil we expected similar crop growth response with regard to this soil type. However, the clay loam soil used for the pot experiment was collected from a different location (Ukulinga) it had different nutrient composition compared to Newlands Mashu clayey loam (Table 3.4 and 5.1). Samuel *et al.* (1993) stated that different chemical and physical processes in different locations due to differences in natural and anthropological activities can contribute to variability in soil fertilities of certain soil types. This implies that different soils have different responses to irrigation with treated wastewater. However, conclusive results on the effects of ABR effluent on plant growth in different soils require a lot of experiments in different locations. This is difficult and expensive to do hence modelling studies must be conducted to predict the effects of irrigating with ABR effluent on different soils and crops.

Irrigation with ABR effluent did not lead to nutrient leaching under the field experiment (Table 4.13) probably due to the nature of the soil type (clay loam soil) which has a lower hydraulic conductivity than sandy loam soil. Moreover, the amounts of nutrients (P and K) supplied from the effluent during the irrigation of Swiss chard was less than the optimum recommended for the maximum growth of the crop (Table 4.2). Irrigation of Swiss chard with ABR effluent provided close to similar amounts of N required for its growth (100 kg ha^{-1}). Implying that amounts of N added to the soil were taken up by plant roots leaving less available for leaching. A nutrient mass balance was calculated in chapter 4 (Table 4.14) and insignificant differences in N concentrations added and lost from soil system amongst all the treatments were observed. According to Bame *et al.* (2013), irrigation with ABR effluent can increase the concentrations of nitrates within the rooting zone and these were taken up by plant roots. This implies that irrigating plants with ABR effluent is of little environmental concern in clay loam soils. The ability of crops such as Swiss chard to take up nutrients such as N and P from ABR effluent is environmentally beneficial. Different wastewater treatment systems to improve effluent quality prior to disposal have been tested but they cannot remove all the nutrients from wastewater (Meuleman *et al.*, 2002). However the use of ABR effluent in irrigating Swiss chard for the peri-urban farmers can provide a sustainable solution to dispose it.

Plant tissue nutrient analysis of Swiss chard was conducted during the summer 2012 and 2013 to determine the uptake of macro and micronutrients. During the summer 2012 tap water without fertiliser was used for irrigation while, within the same plots, ABR effluent was used to irrigate Swiss chard in 2013 (Chapter 4). Interestingly, TW (tap water without fertiliser) and ABR treatments were comparable to fertilised treatments (tap water with fertiliser; TWF and rained with fertiliser; RFF), implying that even the irrigation with ABR did not significantly impact nutrient uptake. These results were consistent with Swiss chard growth results obtained during both seasons. This implies that the inherent soil fertility could significantly support Swiss chard growth without showing any deficiency signs. One of the possibility regarding this observation could be the insignificant change in soil chemical properties over short period of irrigation (Section 4.2.3) considering the short growing season for Swiss chard. Studies by the Rousan *et al.* (2007) showed that irrigation with treated wastewater can significantly increase nutrient uptake after a long period of irrigation.

P is deemed to be generally deficient in most soils and exists in organic forms that are unavailable for uptake by plant roots (Schachtman *et al.*, 1998). During the study, ABR effluent provided insignificant amount of P (7 kg ha^{-1}) which was far below 40 kg ha^{-1} required for Swiss chard growth (Table 4.1). However, insignificant differences in P uptake were observed amongst all the treatments during the baseline studies (Table 3.9) and after irrigation with ABR effluent (Table 4.7). The reasons behind this observation were not clear and need further investigations.

The amounts of K and P supplied through irrigation with ABR effluent, after considering the plant water requirement, were very low to meet the optimum plant nutrient requirements (Chapter 4). This implies that large amounts of water were required to meet the K and P requirements for Swiss chard, which could lead to flooding of the field thereby negatively causing waterlogging, surface runoffs and nutrient leaching. Moreover, according to Sharpley *et al.* (2000) factors such as nutrient loading and runoffs are major drivers for the movement of P rich water into water surfaces leading to eutrophication. Eutrophication is caused by the interaction between N and P on algal growth (Pierzynski *et al.*, 2000). From an environmental point of view irrigation of Swiss chard with ABR effluent can be an effective way of nutrient (N, P and K) removal if there is proper irrigation scheduling which avoid runoffs and leaching.

However from an agronomic point of view, this practice needs significant P and K fertiliser supplement. The amounts of nutrients supplied per amount of soil is dependent on soil type, investigations from chapter 5 showed that ABR effluent could supply more nutrients (N, P and K) on sandy loam soils as compared to clayey loam soil and acidic soil. Furthermore, the use of ABR effluent as a source of irrigation water with regard to P and K was observed after irrigating crops at optimum fertiliser recommendation rate. With regard to N, within unfertilised treatments, it was effective in sandy loam soils (Table 5.2). It should be considered that the nutrient value of the ABR effluent is dependent on the initial soil fertility and specific nutrient requirements as shown by the clay loam soil which required less amounts of K in relation to the amount supplied by the ABR effluent (Table 5.2).

6.1 CONCLUSIONS, RECOMMENDATIONS AND FUTURE STUDIES

Nutrient uptake of macro and micro elements of Swiss chard irrigated with ABR effluent was comparable to RFF and TWF treatments under field conditions due to soil fertility.

Effects of ABR effluent on Swiss chard growth and yield were comparable to tap water with fertiliser under field conditions especially in winter when the rainfall is low. ABR effluent is an important source of irrigation water when used to irrigate Swiss chard and can meet some of its mineral elements requirements, depending on the soil type and fertility. Irrigation with ABR effluent is very influential in acidic soil where it increases crop growth due to its liming effect. ABR effluent irrigation can supplement fertiliser needs especially at half recommended fertiliser application rate.

Nutrient (N and P) leaching and uptake was not associated with ABR effluent when used to irrigate Swiss chard under field conditions.

When ABR effluent is used for irrigating Swiss chard it is regarded as a source of water rather than fertiliser. It is advisable to analyse the soil chemical properties before irrigation as a way of estimating the amount of N, P or K fertiliser required to be supplemented.

On an environmental point of view irrigation of Swiss chard with ABR effluent can be an effective way of nutrient removal. The concentration of N and P it contains can be taken up by this crop. There is need to investigate the potential of different crops, soils and locations in absorbing large volumes of effluent generated in summer when the rainfall is high.

Future studies must consider the effects of long term irrigation with ABR effluent on soil chemical properties and on different crops.

Considering time taken to carry out many field experiments, modelling studies will form part of the future work to complement the findings of the field experiments and the applicability of knowledge at a local and regional level.

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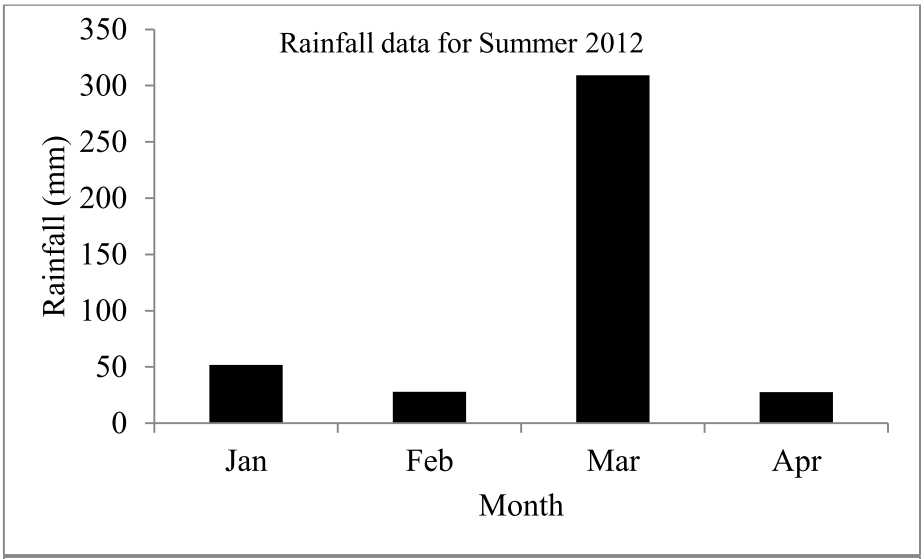
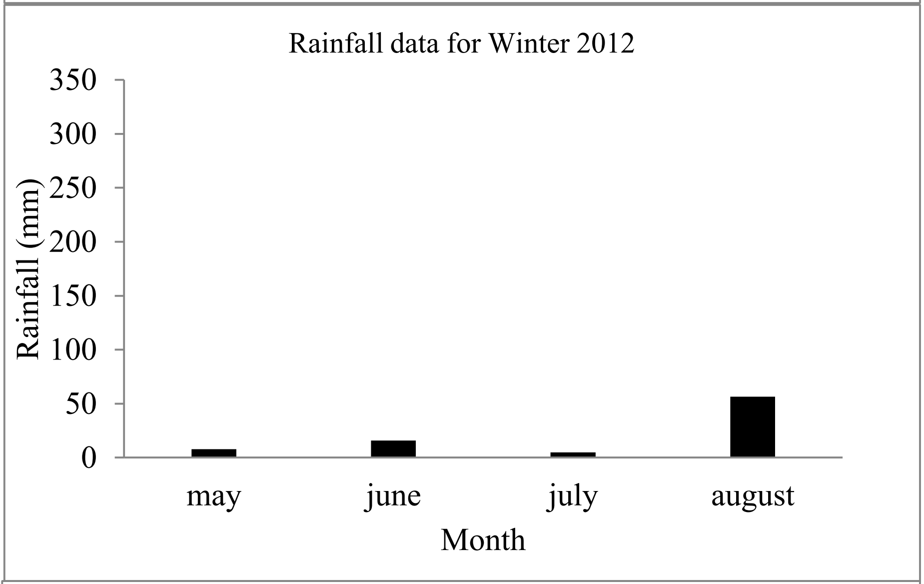
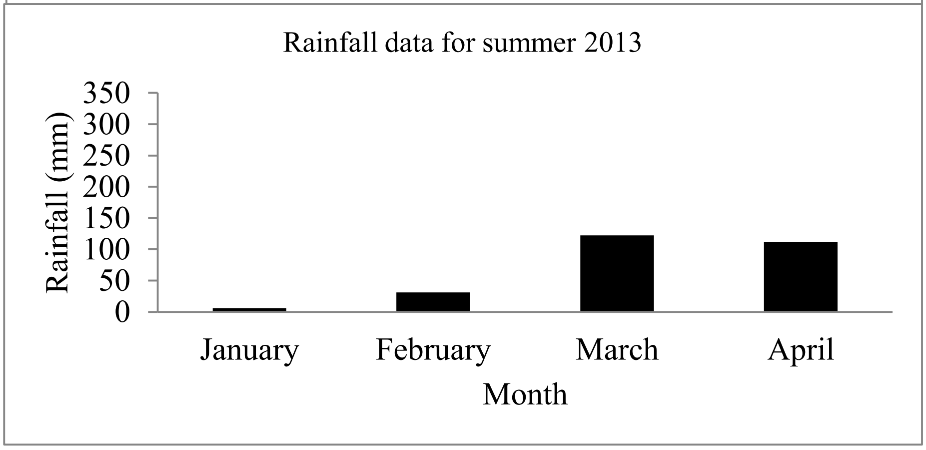
APPENDICES

Appendix 1 Rainfall data for Newlands during the growing seasons of Swiss chard.







Appendix 2 Tap water irrigation of Swiss chard during the seedling establishment (applied/deficit), amount applied per each 25 m^2 plot (mm) (2013).

Plot	**Week 1 Day 1**	**Week 1 Day 4**	**Week 2 Day 1**	**Week 2 Day 4**
ABR1	76	20	20	20
ABR2	39	20	20	20
ABR3	58	20	20	20
TWF1	44	20	20	20
TWF2	17	20	20	20
TWF3	71	20	20	20
RFF1	21	20	20	20
RFF2	19	20	20	20
RFF3	61	20	20	20