INVESTIGATING THE EFFECTS OF IRRIGATION WATER MANAGEMENT TECHNIQUES USING ANAEROBIC BAFFLED REACTOR (ABR) EFFLUENTS FOR CROP PRODUCTION

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ABSTRACT

The discharge of treated effluents from anaerobic baffled reactor (ABR) into surface and ground water bodies poses a challenge to the environment and can cause pollution. The need for the optimal use of land without a yield penalty in urban and peri-urban (UP) settlements such as Newlands KwaMashu Experimental site, Durban, South Africa is vital. The volume of ABR effluent generated by a decentralized wastewater treatment systems (DEWATS) in UP settings increased with population, urbanization and improved living conditions. Hence, the need to cultivate effluent irrigated crops is paramount and synonymous to treated wastewater reuse and management. Therefore, the study evaluated the effects of irrigation management techniques and intercropping on the growth and yield of flood irrigated Cocoyam (*colocasia esculenta)* and rice *(oryza sativa l.)* using ABR effluents. It was hypothesised that irrigation management techniques and intercropping do have a significant effect on the growth and yield of Cocoyam and rice irrigated with treated domestic wastewater

An open field trial using basin (flood) irrigation with ABR effluent and a pot experiment inside a tunnel house, for zero effective rainfall, were conducted concurrently with the same treatments in 2017 and 2018 planting seasons at the Newlands KwaMashu Experimental site, Durban, South Africa. The irrigation water management treatments consisted of alternate wetting and drying (AWD), conventional flood irrigation (CFI) and continuous wetting without flooding (WWF) and the cropping systems were sole Cocoyam, sole rice and intercropped Cocoyam and rice. The treatments with WWF was the control for Cocoyam and CFI was control for rice. Each of the treatments was replicated three times in a randomized complete block design (RCBD) layout.

Cocoyam from the open field and pot trials showed that the effects of the treatments were significant ($P < 0.05$) on the number of irrigation events, amount of irrigated water and daily water balance. The treatments had no effect on the growth parameters (plant height, leaf number and leave area index (LAI) ($P > 0.05$)). The treatments effects were, however, highly significant ($P < 0.001$) with respect to yield components (biomass, corm mass, corm number, corm size, harvest index), corm yield and water productivity (WP). The control (WWF) produced the highest yields of 7.52 and 9.84 t/ha for 2017 and 2018 seasons, respectively for field trials. The control (WWF) produced the highest yields of 4.97 and 6.40 t/ha for 2017 and 2018 seasons, respectively for pot trials.

The result for field and pot trials for rice revealed that the effects of irrigation management techniques were highly significant ($P < 0.001$) on number of irrigation events, amount of irrigation and daily water balance. However, there were no significant differences ($P > 0.05$) between irrigation management techniques with respect to the number of tillers per plant but significant ($P < 0.05$) on the number of panicles per plant. Similarly, irrigation management treatments did not differ significantly ($P > 0.05$) with respect to plant height and leaf area index (LAI). Significant differences ($P < 0.05$) were observed with respect to rice yield, though the treatment was not significant ($P>0.05$) with respect to rice yield in 2018 season. The effect was also significant ($P < 0.05$) on water productivity. The treatments AWD produced the highest grain yields of 5.68 in 2017 and 6.38 t/ha in 2018 season for field trials. The AWD treatments had the highest yields of 2.32 and 3.21 t/ha for 2017 and 2018 seasons, respectively for pot trials.

The effect of intercropping was significant ($P<0.05$) with respect to the total number of irrigation and total water use. There was a significant reduction ($P<0.05$) on the plant heights of both *Cocoyam* and rice under intercropping. A significant ($P<0.05$) reduction also occurred on the number of *Cocoyam* leaves per plant, number of panicles per plant and number of tillers per plant for rice. Intercropping significantly reduced ($P<0.05$) the *Cocoyam* corm and rice grain yield over the two seasons as compared to sole cropping. The land equivalent ratio (LER) showed that intercropping *Cocoyam* with rice was not productive ($LER < 1$) than sole cropping of Cocoyam. It was established that there was no significant ($P>0.05$) effects of the treatments with respect to the growth parameters but was significant on the yield of sole Cocoyam and sole rice. The yields of Cocoyam under intercropping were 4.96 and 6.96 t/ha for 2017 and 2018 seasons while grain yields under intercropping were 0.84 and 1.0 t/ha for 2017 and 2018 seasons.

This study concluded that both AWD and CFI resulted in yield reduction and WP as compared to WWF, and as such, not recommended for Cocoyam production in order to improve the productivity. AWD irrigation with ABR effluent should be encouraged among rice farmers and therefore, recommended among the rice farmers closer to ABR effluents. It was also concluded that over the two season period, intercropping Cocoyam and rice was not productive under any of the three irrigation management techniques applied. The hypothesis is thus accepted for yield and rejected for the growth parameters.

PREFACE

I, Isiaka Toyin Busari declare that:

(i) The research reported in this thesis, except where otherwise indicated, is my original work.

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As the candidate's supervisors, we agree to the submission of this thesis.

Supervisor: ……………………….. Date: ....
Co-Supervisor: ………………………....................................... Date: ....
Co-Supervisor: ………………………....................................... Date: ....

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DEDICATION

The whole of this work is dedicated to my wife (Mrs. Fatimoh Abiodun Ghali-Busari), for emotional support and for lifting my spirit when I was down. The contribution of my wife is immeasurable, hence the dedication.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABR	Anaerobic baffled reactor
AF	Anaerobic filter
ANOVA	Analysis of Variance
AWD	Alternate wetting and drying
DEWATS	Decentralised Wastewater Treatment
EWS	eThekwini Water and Sanitation Unit
EC	Electrical conductivity
E. coli	*Escherichia coli*
BOD	Biological oxygen demand (mg/L)
CFI	Continuous flood irrigation
COD	Chemical oxygen demand (mg/L)
COD	Total chemical oxygen demand (mg/L)
DO	Dissolved oxygen (mg/L)
LER	Land equivalent ratio
N	Nitrogen
O	Oxygen
O & M	Operation and maintenance
P	Phosphorus
PVC	polyvinyl chloride
S1	Season 1
S2	Season 2
SSA	Sub-Saharan Africa
TKN	Total Kjeldahl Nitrogen (mg N/L)
TN	Total Nitrogen (mg N/L)
TP	Total Phosphorus (mg P/L)
TSS	Total suspended solids (mg/L)
pH	potential of Hydrogen
UKZN	University of KwaZulu-Natal
UP	Urban and peri-urban
WWF	Wetting without flooding

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers (a, b, c, d and e), referred to in sections 3, 4, 5, 6 and 7 in the thesis:

(a) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. Evaluating the effect of irrigation water management techniques on (taro) *Cocoyam* (*colocasia esculenta* (l.) Schott) grown with anaerobic filter (AF) effluent at Newlands, South Africa.
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(b) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. Irrigation water management techniques with ABR: effect on rice growth, yield and water productivity.
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(c) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. The impact of irrigation water management techniques on the performance of potted-rice using treated wastewater reuse in Durban, South Africa.
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(d) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. Assessing the impact of intercropping *Cocoyam* (*colocasia esculenta*) and rice (*oryza sativa l.)* on yield and land productivity under different irrigation water management techniques with anaerobic baffled reactor (ABR) effluent water in Durban, South Africa. ***Manuscript submitted to Water SA (Water SA 3707).***

(e) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. Impacts of irrigation water management techniques on the growth, yield and water productivity of potted Cocoyam *(colocasia esculenta (l.) Schott)* grown with anaerobic baffled reactor (ABR) effluent ***Manuscript submitted to Agricultural Engineering International: CIGR Journal.***

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(a) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. 2018 Investigating the effects of ABR wastewater irrigation management techniques on growth and yield parameters of *Cocoyam* (*Colocasia esculenta*) in Durban, South Africa, *2018 International Conference and 69th annual Meeting of the International Commission on Irrigation and Drainage (ICID),* Saskatoon, Saskatchewan, Canada.

(b) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. 2018 The effect of anaerobic baffled reactor (ABR) effluent irrigation management techniques on corm/grain yield and land productivity of a *Cocoyam (Colocasia esculenta)/* rice *(Oryza sativa L.)*

intercrop in Durban, Republic of South Africa, *South African Institute of Agricultural Engineers' (SAIAE) Biennial Symposium and Continuing Professional Development (CPD) event*, Salt Rock Hotel & Beach Resort, South Africa.

(c) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. 2018 Alternate wetting and drying (AWD) irrigation technology: impact on the yield of rice grown with peri-urban anaerobic baffled reactor (ABR) effluents, *Symposium 2018 for South African Committee on Irrigation and Drainage (SANCID)*, White River, Mpumalanga, South Africa.

(d) **Busari, IT**, Senzanje, A, Odindo, AO and Buckley, CA. 2018 Impacts of irrigation water management techniques (pot trials) on the growth, yield and water productivity of Cocoyam (Colocasia esculenta (L.) Schott) grown with anaerobic baffled reactor (ABR) effluents, *8th National Water Conference organised by National Water Resources Institute and Ogun Oshun River Basin Development Authority*, Obasanjo Library Complex, Abeokuta, Nigeria.

The contribution of **Busari IT** to the papers included in this thesis was as follows:

Busari, IT, Senzanje, A, Odindo, AA and Buckley, CA planned and conceptualized the study. **Busari, IT** executed the study on the field trials, collected, processed data and did the writing with revision/editing by co-authors. Dr. Senzanje edited the whole report with more emphasis on irrigation engineering aspect, Dr. Odindo was responsible for the crop aspect as a crop scientist while Prof. Buckley was responsible for the aspect of treated wastewater reuse.

1 INTRODUCTION

1.1 Background

Water is a very valuable resource, it is a strictly insufficient resource in many nations (Rusan *et al.*, 2007). Hence, the need to preserve, protect and conserve fresh water and access lower quality water for irrigation (Al-Rashed and Sherif, 2000). Water is a natural asset critical for the survival of human beings. Different human activities, which include disposal of effluent into both surface and ground water resources, coupled with increasing population have made appropriate management of water resources a very complex requirement throughout the world. Essentially, an increase in the water demands by the urban populations is reducing the water available for agricultural purposes with a rise in associated costs. To counter the continually growing food and fibre requirements of an increasing populace, it is imperative to enhance irrigation water efficiency to guarantee sustainable agriculture (Hari *et al.*, 2016).

Globally, fast urbanization is tantamount to rapid increase in urban poverty and urban food insecurity. The developing countries of Africa, Asia and Latin America will be home to some 75% of all urban dwellers in 2020 because of the productive reuse of wastewater for irrigation, where crops of high value can be raised due to amount of nutrients in the wastewater and where the demand for tap water is more (de Zeeuw and Drechsel, 2015). In the next 25 years, Africa may face declining food security in the metropolises due to fast urbanisation because above one-third of the populace will live in cities. The growing demand for fresh and consumable agricultural crops in the major cities is driving the development of non-seasonal urban and peri-urban irrigation (UPI) requiring year-round production, dependent on irrigation (Sonou, 2001).

According to Renner (2012), surface irrigation is the application of water to the surface of the field. The entire field might be flooded (basin irrigation), the water might be fed into minor channels (furrows) or strips of land (borders). It is the most common irrigation method. It is usually applied when conditions such as sufficient or abundant supply of water are favourable, mild slopes, soil type is clayey-loam with medium to low infiltration rate. Basins are surrounded by low bunds. The bunds avert water from moving to the end-to-end fields (Renner, 2012).

Recycling of wastewater for irrigation is becoming a common practice (Alghobar and Suresha, 2016). Recycling of urban wastewater in agriculture has become public practice for a number of reasons, part of it being water scarcity, nutrient worth and environmental safety (Tamoutsidis *et al.*, 2009). The need for irrigation, since rainfall is not readily available throughout a season, and the need for water are constantly growing; therefore, water of higher quality is conserved for domestic use while that of lesser quality is suggested for irrigation purposes (Nafchi, 2016). Musazura *et al.* (2015) found that closely inhabited peri-urban settlements in developing nations like South Africa need cost effective solution systems called decentralized waste water treatment systems (DEWATS) to be developed which comprises the use of anaerobic baffled reactors (ABR). The need for DEWATS is because of the rate of expansion of the peri-urban populace and the implication of connecting it to the main central sewers. Wang *et al.* (2004) defined ABR as a series of baffles which allow wastewater to flow under and over them from inlet to outlet in the absence of oxygen. It is based on physical treatment that involves settling of sludge and biological treatment that involves anaerobic digestion.

An attempt to introduce mono-cropping systems to the environment, a tradition of farmers in the humid and sub-humid tropics, has failed because intercropping is almost synonymous with peasant agriculture (Njoku and Muoneke, 2008). On the contrary, intercropping suppresses weeds, reduces pest disease infestation and gives yield advantage. It encourages higher nutrient uptake than in mono-cropping and water use efficiency is high. It enhances high soil fertility maintenance particularly where legumes are used as a component crop (Ibeawuchi, 2007). According to Ouma and Jeruto (2010), two or more crops grown together should have enough spacing to exploit cooperation and avoid competition among them.

Cocoyam (*Colocasia esculenta*), being one of the food security crops, is a marginalized tuber food crop, with wide distribution in the tropics. The neglect of *Cocoyam* as an indigenous crop is one of the causes of food insecurity; therefore, production of indigenous crops will play a critical role in contributing to food security (Kamwendo and Kamwendo, 2014). It is the 14th most consumed vegetable worldwide (Lebot and Aradhya, 1991; Singh *et al.*, 2008; Tumuhimbise, 2015). All parts of the plant can be used for human consumption; nonetheless its starch-rich corm is by far the most frequently used part. The corms provide easily digestible starch and the leaves provide nutritious spinach-like vegetable, which is rich in minerals and vitamins. Despite its importance as a food and vegetable crop, it has received very limited research attention from agricultural, academic and development institutions and is therefore classified as a neglected and an underutilized crop species (Tumuhimbise, 2015). *Cocoyam* (an indigenous crop) is one of the food security crops but scientific research on it is scarce in South Africa (Mabhaudhi and Modi, 2013; Sibiya, 2015; Tumuhimbise, 2015). Cocoyam (corms and cormels) is "*an underexploited food and feed resource*" (Owusu-Darko *et al*., 2014).

Rice (*Oryza sativa L.)* is a main food for more than half of worldwide, plus thousands of families in Sub-Saharan Africa (SSA). Rice is grown in almost 115 nations in the world and is only next to wheat in terms of production globally (Carriger and Vallee, 2007). Approximately 40% of the rice consumed in Africa is imported. Africa is, therefore, seriously exposed to global market shocks with sometimes weighty consequences on food security and political stability as shown by events of 2008 food crisis (Seck *et al*., 2010). Luckily, Africa is blessed with an abundant source of natural resources which can support an enormous expansion in food, specifically precisely rice production (Balasubramanian *et al*., 2007).

The study area was chosen because of the presence of an existing DEWATS which is basically used for research purposes. There was the need to select crops that can withstand the excess treated wastewater and nutrients. The need for the optimal use of land without a yield penalty in urban and peri-urban (UP) settlements is vital. There has not been any reported study carried out to investigate the effect of irrigation water management techniques using ABR effluent as wastewater. There is also no report of an intercrop of *Cocoyam* with rice using flood irrigation in the presence of an abundant treated wastewater. *Cocoyam* production is synonymous with food and income security, hence, the need to carry out this study because it is expected to make *Cocoyam* available throughout the year, if the knowledge is adopted.

1.2 Problem Statement

The volume of wastewater generated by domestic-municipal sources in the study area has increased with population, urbanization, improved living conditions, and economic development. The productive use of wastewater has increased with millions of small-scale farmers in urban and peri-urban areas of developing countries depending on wastewater sources to irrigate high-valued edible crops for consumption and ornamental crops such as flowers and tree plants because they often have no alternative sources of irrigation water. Hence, there is need to utilize the continuous and abundant volume of municipal treated wastewater productively (e.g. irrigation) before safely discharging into water bodies. The need to maximize the use of nutrient-rich treated domestic wastewater at Newlands Mashu, Durban, republic of South Africa required different irrigation management techniques (flood irrigation).

It is of great importance to take proper monitoring measures for treated wastewater and nutrients balances in order to identify imbalances that exist and to take corrective measures. The challenges of water ponding (standing water) on the surface of the field especially during summer season also call for the need to investigate the water balance. Nutrients in treated municipal wastewater (effluents) are an advantage over conventional irrigation water sources. Hence, management and re-use of treated wastewater for irrigation has the possibility of reducing the hazards of environmental contamination, reducing the amount of fresh water resources that need to be extracted and increasing production of crops per household.

1.3 Main Research Objective

To investigate the effects of irrigation water management techniques using ABR effluent on the growth and yield parameters of *Cocoyam* and rice.

1.4 Hypotheses

It is hypothesized that irrigation water management techniques have an effect on the agronomic performance of *Cocoyam* and rice. It was also hypothesized that intercropping of *Cocoyam* and rice may not have effect on corm yield and land productivity. Furthermore, it was postulated that irrigation water management techniques do have an effect on the daily water balance and water productivity.

1.4.1 Specific objectives

The specific objectives of the study were, thus:

1. To evaluate the impact of irrigation water management techniques on the growth and yield parameters of *Cocoyam* using ABR effluent
2. To assess the effect of irrigation water management techniques on the growth and yield components of rice using ABR effluent
3. To quantify the effect of intercropping *Cocoyam* with rice in terms of yield complement
4. To examine irrigation water productivity, total water productivity and daily water balance analyses.

1.5 Thesis Structure

The thesis was written in chapters such that they could be read independently. This means that some repetitions appeared in the theory and methodology that is common to different chapters. Nevertheless, effort was made to minimize the repetitions.

Having presented the general introduction and preamble to the research topic in Chapter 1, Chapter 2 defines the context of the problem through a review of literature related to this study which include wastewater and agriculture, wastewater and irrigation management, intercropping and *Cocoyam* and rice production. Chapter 3 deals with evaluating the effect of irrigation water management techniques on (taro) *Cocoyam* (*Colocasia esculenta (l.)* schott) grown with anaerobic baffled reactor (ABR) effluent. Irrigation water management techniques with ABR: effect on rice growth, yield and water productivity was presented in Chapter 4. Chapter 5 deals with the impact of irrigation water management techniques on the performance of potted-rice using treated wastewater reuse in Durban, South Africa. Chapter 6 presents the work done on assessing the impact of intercropping *Cocoyam* (*Colocasia esculenta*) and rice (*Oryza sativa l.*) on yield and land productivity under different irrigation water management techniques with anaerobic baffled reactor (ABR) effluent water in Durban, South Africa. Chapter 7 presents the investigations carried out to examining the effect of continuous flood irrigation techniques on the water productivity, growth and yield of potted-taro using anaerobic baffled reactor effluent. Chapter 8 presents the general conclusion of the whole thesis, challenges, solutions proffered and future lessons or research possibilities while Chapter 9 lists the comprehensive references consulted and cited. Figure 1.1 is a schematic representation of this thesis.

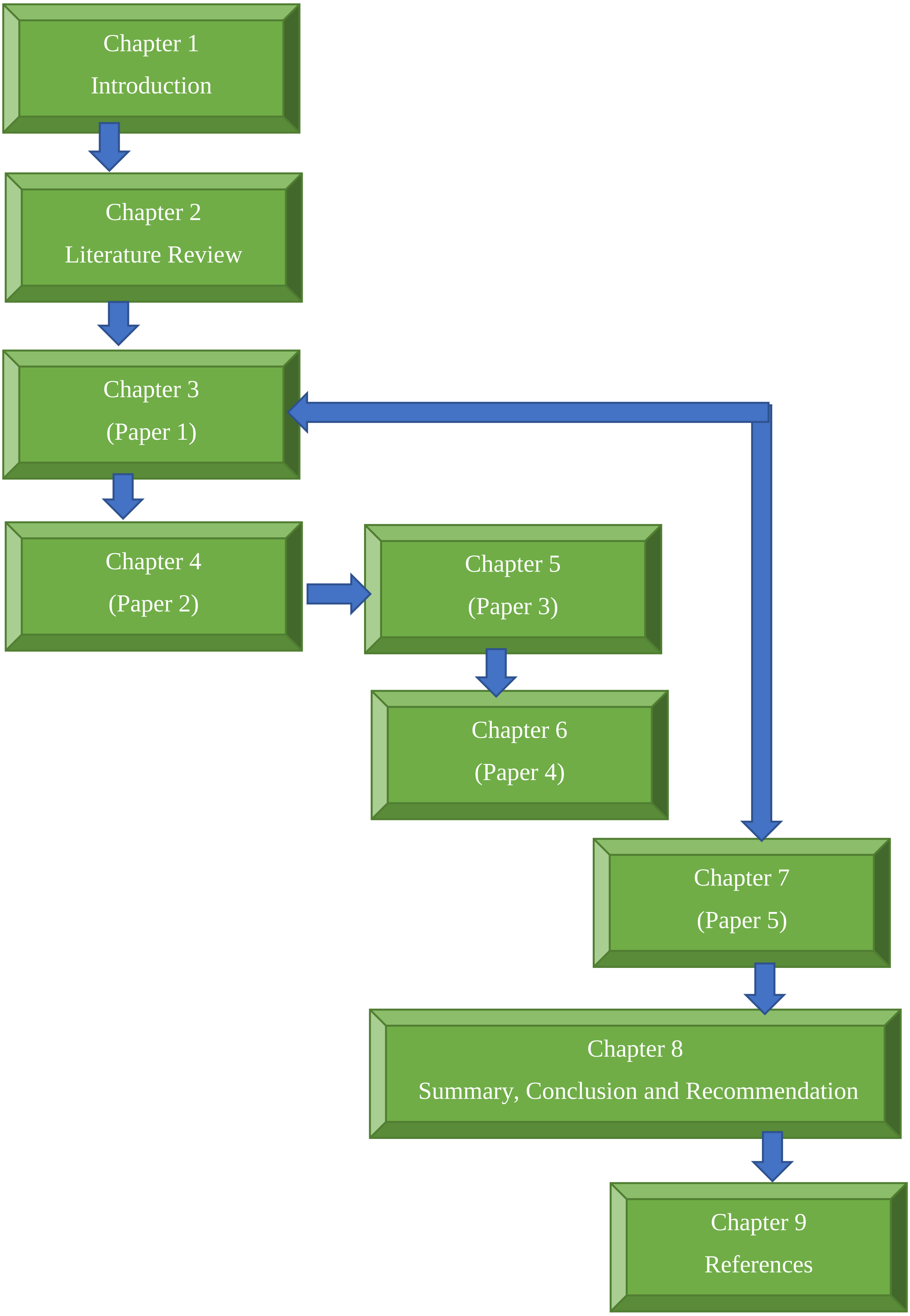

Figure 1.1 Schematic of the thesis structure

Having presented the general introduction and preamble to the research topic, it is pertinent to discuss the literature review (Chapter 2) in detail vis-à-vis wastewater and agriculture which include its effect, guidelines, benefits, potential risks, public concern and how to overcome wastewater reuse problems, wastewater irrigation management, intercropping, growth and production of *Cocoyam* and rice and previous studies on *Cocoyam* and rice.

2 GENERAL LITERATURE REVIEW

2.1 Wastewater and Agriculture

Urban wastewater is less expensive and considered an attractive source for irrigation. Any source of water which might be used carefully and efficiently should be considered to promote further development. Inadequate water supplies require careful management for effective agricultural production (Kiziloglu *et al.*, 2008). The growing competition for water in the world, inclusive of Sub-Saharan Africa, has resulted in the development of the application of wastewater for farming and landscaping. The only potential source of water that will rise as the population increases and the demand for freshwater rises, is wastewater (Heidarpour *et al.*, 2007). Sustainable techniques for wastewater disposal in a way that enhances crop production will ease water shortages and recycling of nutrients also necessitates the use of treated wastewater for irrigating crops (Pedrero *et al.*, 2010). According to Tabatabaei *et al.* (2017), the deteriorating water resources, ever growing drying time and increasing irrigated land, lead to deficit irrigated production which is not based on full water requirement.

The attention to recycling wastewater for irrigation is growing rapidly in most countries. Moreover, irrigation with communal wastewater is considered an environmentally sound wastewater dumping practice that helps to reduce the effluence of the ecosystem subjected to pollution by direct disposal of wastewater into surface or groundwater. Furthermore, wastewater is a valuable source for plant nutrients and organic matter needed for preserving fertility and productivity of soils. Nevertheless, the reuse of wastewater for irrigation may possibly create environmental problems if not suitably treated and managed (Kiziloglu *et al.*, 2008).

ABR is made up of a tank and discontinuous hanging baffles (Wang *et al.*, 2004) that separate the reactors and force domestic waste to move from one partition to another, permitting improved contact among the fresh wastewater (influents) entering the container, the residual (sludge) and the effluents leaving the reactor. According to Bame *et al.* (2014), ABR as a high rate digester (anaerobically), involves different hanging and vertical baffles premeditated for wastewater treatment. The ABR is an appropriate method for medium or short-term hygiene solutions in low-income societies (Foxon *et al.*, 2004).

2.1.1 Effects of recycled wastewater

The recycling of wastewater for irrigation use is becoming a widespread practice. Irrigation with wastewater has two distinct levels of consequences: may change the physico-chemical properties and microbiological content of the soil. The former may disturb soil productivity and fertility; the latter may pose severe dangers to human and environmental health (Alghobar and Suresha, 2016). Unnecessary build-up of large amounts of nutrients in the soil may cause adverse effects on productivity and quality of crops, if wastewater is used as the only source of irrigation water for field crops. Accordingly, use of irrigation with wastewater should take into consideration the nutrient content in relation to the specific crop requirements and the concentrations in the soil, and other soil fertility parameters.

According to Musazura *et al.* (2015), the ABR effluent comprises mineral elements (phosphorus and nitrogen) which are significant for growth of crops. Eutrophication and death of aquatic life can occur if the effluent is discharged into water bodies. It is expected under normal situations that users have no direct contact with either the influent or effluent because they contain high levels of pathogens. Both the influent and effluent produce odour and care must be taken in planning and establishing the ABR plant facilities to minimize odour problems to the nearby inhabitants (Tilley *et al.*, 2014). Generally, effluents from ABR have been proven to constantly meet the standard requirements for irrigation with regard to the removal of organics such as BOD or COD for reuse in agriculture, but not for disposal to surface waters. The high contents of nutrients, ammonia and phosphorous in the effluents may be viewed as a valuable resource from an agricultural perspective. Obviously, an important function of a system that produces effluent coming from raw wastewater should display removal of adequate pathogens to reduce the likelihood of infecting the public with waterborne pathogens (Foxon *et al.*, 2004). Introduction of wastewater below the surface of soil could reduce the surface microbiological contamination meaningfully (Najafi and Tabatabaei, 2008).

Irrigating with grey water produced statistically significant higher yields and general plant growth for spinach, peppers and onion than was attained with the use of hydroponic nutrient solution (Kanawade, 2015). Use of wastewater also increased dry and wet forage yield (Nafchi, 2016). Irrigating with wastewater significantly affected the plant height (Alghobar and Suresha, 2016). The cause of the improvement in yield is not immediately clear and neither are possible harmful effects of greywater on plant growth.

2.1.2 Effects of treated wastewater on physico-chemical properties of soils

Several studies evaluated the effects of using treated wastewater on soil physico-chemical properties. Bedbabis *et al.* (2014) reported no significant effect of treated wastewater on various soil properties such as electrical conductivity (EC), sodium adsorption ratio (SAR), pH, organic matter (OM), soluble cations, chloride (Cl) and infiltration rate of the soils. Musazura *et al.* (2015) also reported no significant changes in soil physical and chemical properties over three seasons following irrigation with ABR effluent. However, Bhardwaj *et al.* (2008) reported that treated wastewater improved hydraulic properties and structural formation (stability) of soils. The use of treated wastewater was also reported to contribute additional organic carbon (C) and nitrogen (N) to the soil, and to result in peak available phosphorous (P) levels which are above the optimal available P level in the soil (Mandal *et al.*, 2008b). The use of wastewater increased organic matter, soil salinity, exchangeable K, Na, Mg, Ca, plant available P and microelements but decreased soil pH (Kiziloglu *et al.*, 2008). Irrigating with K-rich wastewaters was also seen as valuable to overall soil fertility, though its long-term use could affect physical and chemical properties of soil (Howell and Myburgh, 2014). Mandal *et al.* (2008a), in their study, reported that regardless of aggregate slaking, irrigating with treated wastewater possessed steadily degrading effect on hydraulic conductivity, runoff and soil loss. The degradation in hydraulic properties of soils (Bhardwaj *et al.*, 2008) may be due to use of treated wastewater for irrigating semiarid and arid soils, but the extent of degradation may depend on the kind of irrigation system.

2.1.3 Reuse of wastewater

Pedrero *et al.* (2010) reported that about 70% of world water use (i.e. water abstracted from rivers and exploited from underground) is used for irrigation. According to Toze (2006), there is a growing need for effective use of water resources in urban and rural environments. The increasing effectiveness in crop administration and the continuing rise in crop production have increased demands on water resources for irrigation purposes. The reuse of water that once would have been ejected into the environment after use is a major practice to achieve greater efficiencies. The recycling of water for irrigation is often observed as a helpful means of reusing water due to the likely large volumes of water that can be used. The recycling of treated urban wastewater for purposes such as agricultural and landscape irrigation decreases the quantity of water that requires to be removed from natural water sources as well as reducing the release of wastewater to the environment. Accordingly, treated public wastewater is a valuable water source for reusing. The quality of treated wastewater relies to a large extent on the quality of the metropolitan water supply, nature of the wastes added during use, and the extent of treatment the wastewater has received.

Used water can have the benefit of being a continuous, dependable water source and decreases the amount of water removed from the environment. Treatment requirements in some cases may be less than for water used in a municipal environment due to reduced possible human contact. However, concerns and unknowns are raised about the effect of the quality of the recycled water on the crop itself and on the end users of the crops. Water quality issues that can generate actual or supposed difficulties in agriculture include nutrient, sodium concentrations, heavy metals, and the presence of pollutants such as human and animal pathogens, pharmaceuticals and endocrine disruptors (Toze, 2006).

2.1.4 Guidelines for interpretation of water quality for irrigation

The existing guidelines for wastewater use in South Africa have concentrated mostly on the possible harmful effects of heavy metals in water and have not yet considered the likely benefits of making use of nutrient-rich effluent coming from low cost sanitation technologies for the purposes of irrigation (Bame *et al.*, 2014). Water quality guidelines can be referring to a set of management targets that is based on the water quality criteria, the following of which is recommended but nonetheless not limited by law. The two basic international regulators are world health organization (WHO) and United state environmental protection agent (US EPA) (Table 2.1 and Table 2.2) (Jeong *et al.*, 2016). WHO recommended new guidelines consider the human health risk through *epidemiological studies and quantitative microbial risk assessment (QMRA)* while US EPA assumes stringent standards by totally removes the risk of infection (Jeong *et al.*, 2016).

Table 2.1 Irrigation water quality guidelines and standards for wastewater reuse in agriculture (WHO, 2006; Jeong *et al*., 2016)

Parameters	WHO [1]	US EPA
Coliform (/100 Ml)	Unrestricted - E. coli (cfu) ≤ 1000	Food crops – ND FC (median)
	Restricted - E. coli (cfu) ≤ 10,000	Processed food crops – FC (cfu) ≤ 200 (median)
Turbidity (NTU)	(a)	Food crops ≤ 2
		Processed food crops -
Suspended solids (mg/L)	-	Food crops -
		Processed food crops TSS ≤ 30
BOD (mg/L)	-	Food crops ≤ 10
		Processed food crops ≤ 30
COD (mg/L)	-	-
Odour	-	-
T-N (mg/L)	-	-
T-P (mg/L)	-	-
Intestinal nematodes (No./L)	≤ 1	-
pH	-	6.0-9.0
EC (μs/cm)	-	-

ND = not detected; FC = faecal coliform; TSS = total suspended solids. [1] The most stringent verification monitoring level, which refers to what has previously been referred to as effluent guideline levels, for each irrigation type and arithmetic mean value (a) No recommendation.

Table 2.2 Recommended minimum verification monitoring of microbial performance targets for wastewater use in agriculture (WHO, 2006)

Type of Irrigation	*E. coli* (cfu/100 mL) (Arithmetic Mean)	Helminth Eggs (No./L) (Arithmetic Mean)
	Unrestricted [1]	
Root crops (a)	$\leq 10^3$	
Leaf crops (b)	$\leq 10^4$	≤ 1
Drip irrigation, low-growing crops	$\leq 10^3$	
Drip irrigation, high-growing crops (c)	$\leq 10^5$	(d)
	Restricted [2]	
Labour-intensive, high-contact agriculture	$\leq 10^4$	≤ 1
Highly mechanized agriculture	$\leq 10^5$	≤ 1
Pathogen removal in a septic tank	$\leq 10^6$	≤ 1

[1] Use of treated wastewater to grow crops that are normally eaten raw. [2] Use of treated wastewater to grow crops that are not eaten raw by human. (a) Crops that may be eaten uncooked. (b) Vegetables eaten uncooked such as lettuce and cabbage. (c) Crops such as fruit trees and olives. (d) No recommendation.

2.1.5 Potential risks from using recycled water

As reported by Toze (2006), a few risk factors have been identified for using recycled waters for purposes of agricultural irrigation. The use of wastewater can result in a number of complications such as pathogenic contamination and accumulation of heavy metals in soil and crops to toxic levels (Alghobar and Suresha, 2016). Some of the risk are short term and differ in impact depending on the potential for human, animal or environmental contact (e.g., microbial pathogens), while others have long term effects and increase with continued use of recycled water (e.g., saline effects on soil). The common human microbial pathogens found in reused water are enteric in origin and they enter the environment through faeces of infected hosts and can enter water bodies directly by defecation into the water, contamination by sewage or by run-off from soils and other land surfaces. They include viruses, bacteria, protozoa and helminths. The risk of water-borne contamination from any of these pathogens can be dependent on an array of factors plus pathogen numbers and dispersal in water (Toze, 2006).

Alghobar and Suresha (2016) found out that the advantage derived from using wastewater was adversely affected by heavy metals presence such as lead and mercury. They are carried by untreated wastewater and become deposited in the soil. The harmful consequence of heavy metal toxicity outweighs the importance of presence of organic nutrients (Alghobar and Suresha, 2016). Wastewater irrigation offers N and P plus organic matter to the soils, nevertheless, there is a worry about the accumulation of possibly toxic elements such as cadmium (Cd), copper (Cu), iron (Fe), manganese (Mn), lead (Pb) and zinc (Zn) from domestic and industrial sources (Kiziloglu *et al.*, 2008). Wastewater irrigation of vegetables and fodder may serve as the carrier for heavy metals in the human food chain (Scott *et al.*, 2008). Heavy metals in wastewater can pose a health threat (Carr *et al.*, 2008).

Toze (2006), however, said heavy metals are simply and efficiently eliminated during common treatment processes and the majority of concentrations in raw sewage end up in the sludge settlement fraction. This leads to very low heavy metal concentrations in the treated effluents. Consequently, heavy metals are of less concern for irrigation when using treated effluents. If the source is from an industrial source, then the influence of heavy metals need to be considered. Heavy metals from effluents used for irrigation tried to accumulate in the soils with a potential that they can become bioavailable for crops (Toze, 2006). The tolerance of plants to heavy metals from wastewater varies with type of plant and this must be considered when irrigating with treated wastewater to avoid toxicities (Pedrero *et al.*, 2010).

2.1.6 Public concern

Hartley (2003), explored the understanding of public perception and participation on reuse of treated wastewater in the United States and discovered that most people tend to become less favourable towards recycled water as it physically comes closer to them. However, they are very supportive of the irrigation of municipal open spaces in some ill-defined region, but hesitate at the use of reused water in the household or when the chance of individual physical contact increases. The extent of public disquiet about water reuse also hangs on the type of reused water and treatment levels, e.g. people have much less anxiety about using untreated arrested storm water than they have about highly treated sewage effluent.

2.1.7 Overcoming water reuse problems

Peasey *et al.* (2000), recommended pre-treatment of the recycled water to overcome any problem relating to reusing water for irrigation of crops. The risk from microbial pathogens is appreciably reduced with the treatment of water. Salt and other cations and anions are the major contaminants difficult to eliminate from used water. The only active treatment mechanism to eradicate salt molecules and ions is reverse osmosis membrane filtration. The treatment may be expensive to be economically feasible for irrigation of crops.

2.1.8 Protection for farmworkers and farmers' household

There exists a higher risk of helminth infections for farming households having close contact with wastewater compared with those without contact (Pham-Duc *et al.*, 2013) whereas van der Hoek *et al.* (2006) reported an insignificant connection between wastewater exposure and helminth infections. Restriction of crops such as those that will be eaten raw, encouragement of farmers to cultivate crops that will be cooked before eating, control of human exposure and wastewater application method (sprinkler and spray irrigations are not recommended) are some of the protection measures for farmworkers and household (Scott *et al.*, 2008). The farmworkers should use proper protecting covers like clothing, shoes, long gloves, and regular hand washing with soap. Detail health education programs and immunization against typhoid and hepatitis are worthy of attention (Scott *et al.*, 2008).

2.2 Wastewater Irrigation Management and Intercropping

Due to growing shortage of freshwater resources obtainable for irrigated agriculture and rising need of food in the world, it is paramount to make available more food with little water. The management of wastewater irrigation must consider wastewater nutrient content, nutrient requirements of crop and soil nutrient content (Mohammad and Mazahreh, 2003). The usage of treated domestic wastewater in nations that are poor in water resources is cheap and taken as an attractive irrigation water source.

2.2.1 Wastewater irrigation management

The reuse of wastewater for irrigation is rapidly growing in most countries (Rusan *et al.*, 2007). Therefore, the wastewater reuse for irrigation is encouraged (Al Salem, 1996; Mohammad and Mazahreh, 2003). The use of treated domestic wastewater as irrigation is agreed to be environmentally sound as compared with disposal directly to water bodies (Mohammad and Mazahreh, 2003). Wastewater is also a treasured source of nutrients for crops required for sustaining fertility levels in the soil (Weber *et al.*, 1996). However, wastewater may comprise unwanted chemical elements and pathogens that cause harmful environmental and health effects (Rusan *et al.*, 2007). Wastewater irrigation mismanagement can also lead to environmental and health complications to both ecosystem and human beings (Mohammad and Ayadi, 2004). The continuous use of wastewater as the only irrigation water for crops leads to unnecessary addition of nutrients and toxic elements to the soil-plant system. It results in damaging effects on productivity and yield quality of crops and soil (Vazquez-Montiel *et al.*, 1996).

2.2.2 Irrigation water management techniques

The International Rice Research Institute (IRRI) with its National Agricultural Research and Extension System (NARES) associates joined together to create and encourage the “alternate wetting and drying” (AWD) techniques of water management to deal with the increasing inaccessibility of water for agriculture. AWD is a management practice in irrigated lowland rice that saves water while maintaining yields. The practice is defined by periodic drying and re-flooding of the rice field (Lampayan *et al.*, 2015). Due to growing shortage of freshwater resources obtainable for irrigated agriculture and rising need of food in the world, it is paramount to make available more food with little water.

Farmers have accepted AWD method of irrigation to handle scarcity of water in the production of rice. The practice uses aerobic respiration instead of the rice being continuously under anaerobic soil conditions (Cabangon *et al.*, 2011). It has generally been accepted to substitute continuous flooding irrigation (CFI) for managing water and increasing productivity of water in irrigated rice systems (Ye *et al.*, 2013). CFI is when water level is allowed to maintain a constant water depth between 1 and 10 cm in the plot during growth (Yao *et al.*, 2012). The practice increases grain yield of rice when compared with continuously submerged conditions (Zhang *et al.*, 2010b). Shao *et al.* (2013) showed that irrigation water was reduced under AWD without a substantial impact on yield and it increased average productivity of water by 16.9 % when equated with conventional flood irrigation. Liang *et al.* (2013), said AWD management was an active approach to save water, reduce N and losses through runoff from rice fields, and preserve yields. Kang *et al.* (1998), showed that when the root zones were alternatively exposed to drying and wet soil of field capacity above 55% or 65%, water use was reduced by 35%, while total biomass production was only reduced by an average of 8%, if compared with the well-irrigated plants. Alternative wetting and modest drying of soil improves yield of rice grain (Yang *et al.*, 2009). AWD irrigation in rice is a developed skill that saves water by 15-30% without falling yields (Lampayan *et al.*, 2009). The controlled alternate partial root-zone irrigation (CAPRI) is a new technique of irrigation that may enhance water productivity without Substantial reduction in yield (Kang and Zhang, 2004). The WWF is a well-watered conditions with 100% water holding capacity (Ruíz-Sánchez *et al.*, 2011). WWF is maintained at 100% field capacity of soil (Farooq *et al.*, 2008).

2.2.3 Water balance

Water balance of an irrigated field refers to the equilibrium between incoming water from irrigation and/or precipitation and water leaving the field by evapotranspiration, groundwater recharge and run-off (Jasrotia *et al.*, 2009). According to Fereres and Connor (2004), crop water need is met in many agricultural zones of the universe by precipitation and when it is insufficient, irrigation is the option to meet the water requirement of crops during the growing period. The water balance over an irrigated field during and after irrigation is demonstrated in Figure 2.1. Applied water (precipitation or irrigation) is lost in four ways; transpiration, evaporation, surface run-off and deep percolation beyond the root zone of the crop. A water balance equation can be derived from Figure 3.1 affirming that the input water either alters the water content in the root zone or must exit the field.

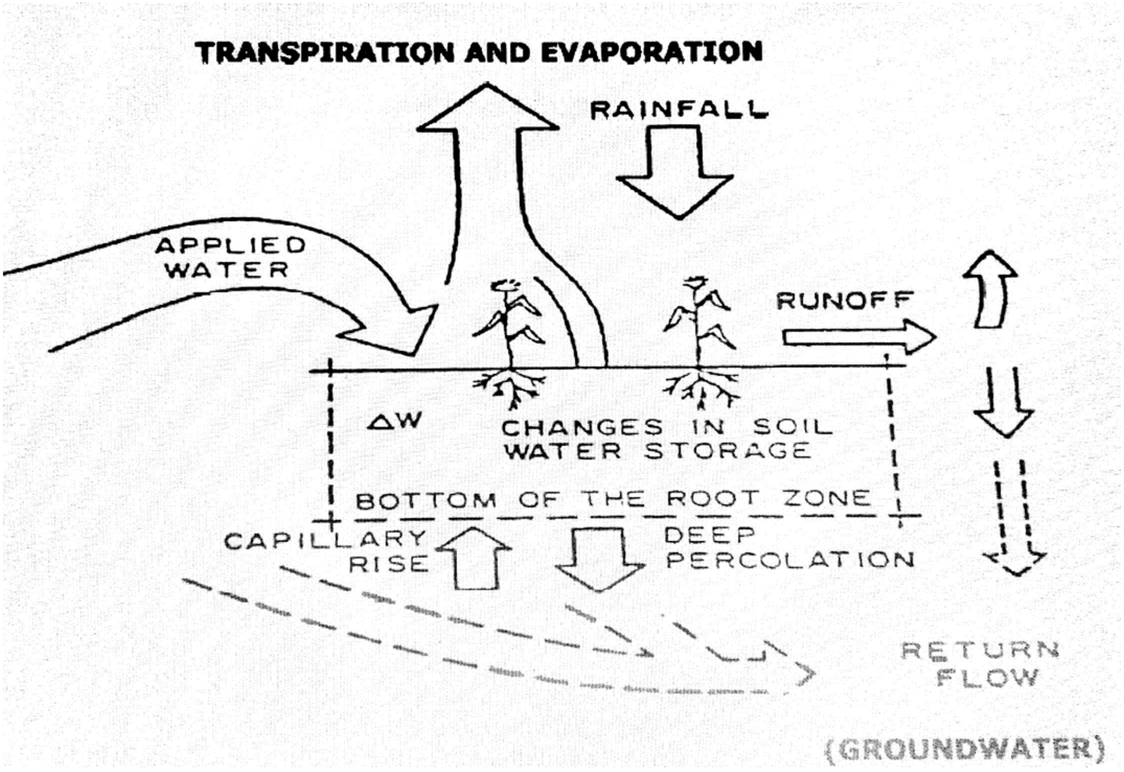

Figure 2.1 The water balance of an irrigated field (Fereres and Connor, 2004)

Mathematically, the water balance of an irrigated field is given as Equation 2.1,

$$IR + P = ET + R +/- D + W \qquad 2.1$$

where IR = applied irrigation water (mm),

P = precipitation (mm),

ET = evaporation + transpiration (mm),

R = run-off (mm),

D = drainage below the root zone (deep percolation; it may be negative if capillary rise occurs) (mm), and

W = changes in soil water content in the crop root zone (mm).

Equation 2.1 (Fereres and Connor, 2004) is as seen by both irrigation engineers and hydrologists. The farmer's concern is as expressed in Equation 2.2,

$$IR = ET - Pe + IL \qquad 2.2$$

where IR = applied irrigation water (mm),

Pe = effective precipitation (mm), and

IL = the irrigation losses from the combination of R and D, which are majorly inevitable during irrigation (mm).

2.3 Intercropping

Intercropping is the growing of two or more crop species simultaneously in the same field during a growing season (Ofori and Stern, 1987). Intercropping enhances land use maximization, steadiness in yield and profit (Erhabor and Filson, 1999). According to Hauggaard-Nielsen *et al.* (2001), intercropping is the concurrent growing of two or more crop species in the same plot. According to Ibeawuchi (2007), intercropping is practiced by most farmers in the tropical and subtropical areas of the world and most of the food from markets in these areas are produced by these set of farmers. Intercropping boosts high nutrient uptake compared to mono cropping systems and water use efficiency (WUE) is also high because of the interface between the intercrops. It promotes high soil fertility maintenance particularly when legumes are included as component crops. The legumes in the intercropping systems also offer continuous soil cover that prevents direct impact of raindrops that causes erosion. It is an inexpensive method of food production as one input like manure can be introduced once and consumed by the entire crop components on the farm thereby conserving time for the farmer. It decreases hazard of crop failure and safeguards the farmer's steady income over time. The farmer enhances best and highest use of the land at any cropping season. Factors such as spatial arrangement, plant density, maturity dates of the crops grown, plant architecture should be considered to avoid competition (Ouma and Jeruto, 2010).

2.3.1 Intercropped land productivity

Ibeawuchi (2007) presented that one of the utmost significant motives of raising two or more crops together is to increase productivity per unit of land. Scholars have designed numerous methods for evaluating intercrop performance as compared to pure stand, and the land equivalent ratio (LER) has become usual exercise in intercropping studies, because of its comparatively simple concept. LER may be well-defined as the relative land area under mono crops that is needed to produce the same yields as realised by intercropping. Usually, the "level of management" must be the same for intercropping and mono cropping. In this regard, intercrop and sole crop must be at their optimal populations as variations in population disturbs yield responses. Therefore, the LER can be used as a degree of relative yield advantage. The LER is calculated as in Equation 2.3 (Chimonyo *et al.*, 2016).

$$LER = L_A + L_B + \cdots L_N = \frac{Y_A}{S_A} + \frac{Y_B}{S_B} + \cdots \frac{Y_N}{S_N} = \sum_{I=1}^{N} \frac{Y_N}{S_N} \qquad 2.3$$

where L_A, L_B…. L_N is the LER for the individual crops,
Y_A, Y_B…. Y_N are the individual crop yields in intercropping, and
S_A, S_B….S_N is their yields as sole crops.

When LER is greater than 1 or more it signals yield advantage, and a ratio of less than 1 is a yield disadvantage.

2.3.2 Types of intercropping

There are several types of intercropping according to Ouma and Jeruto (2010). Row intercropping is the planting of two or more crops at the same time but with at least one planted in rows. Cultivating two or more crops in strips that are wide enough to separate crop production with machines, yet sufficiently close to interact is strip intercropping. Mixed cropping is planting together two or more crops in no separate row planning. Planting a second crop into an existing crop at a time when the standing plant is at reproductive stage but before harvesting is called relay intercropping. Planting two or more crops concurrently during certain part of growing season of each have more benefits over strip intercropping (Parajulee *et al.*, 1997). Relay intercropping method is worth considering utilizing resources (Homma *et al.*, 2008). It is a better way of enriching the soil-crop arrangement with nitrogen and improving weed control (Jeranyama *et al.*, 2000; Singh *et al.*, 2007; Amossé *et al.*, 2013). Relay intercropping, especially with commercial crops increases the productivity of existing natural resources and biomass which can be used as fodder without reducing the yield of the main crop (Anil *et al.*, 1998; Jeranyama *et al.*, 2000; Baldé *et al.*, 2011). *Cocoyam* and rice which are crops to be used are discussed in the next chapter. Also reviewed in the next chapter are relevant previous studies on *Cocoyam* to explore the research gaps.

2.4 *Cocoyam* and Rice Production

The two crops considered are *Cocoyam* and rice. Their distribution, origin and production level are reviewed.

2.4.1 Origin and distribution of *Cocoyam*

DAFF (2011) gave the following description and discussion on *Cocoyam*. It (*ACocoyam, Amadombie, Amadombi, Mufhongwe,* and *Taro*) is referred to as “potato of the tropics” (*Colocasia esculenta*), found globally in subtropical areas and is cooked much like a yam. It is also called Cocoyam (English) in some parts of West Africa. Edible aroids (family *Araceae*) encompass many underground food crops grown in numerous tropical and subtropical nations. They are called *aCocoyams* in many parts of the world, particularly in Africa. It originated from Oceania and South-East Asia and the American tropics. It is held that *Cocoyam* has been cultivated for over 6 000 years. It came to West Africa through America, which is now the foremost producer.

2.4.2 Production level of *Cocoyam* in South Africa

Since it is usually produced by rural farming localities for sustenance and not for trading, the level of production of *Cocoyam* in South Africa is not known**.** *Cocoyam* has been planted by villagers in KwaZulu-Natal for many generations, and is now considered as an indigenous food crop. Mpumalanga and Eastern Cape also cultivated *Cocoyam*. There are no cultivars developed in South Africa to date so far (DAFF, 2011).

2.4.3 Production level of *Cocoyam* in Africa

The production of *Cocoyam* is largely confined to the “yam zone” of Africa that comprises countries such as Cameroon, Nigeria, Benin, Togo, Ghana, and Côte d’Ivoire. About 80% of the world’s production takes place in this zone.

2.4.4 International production level of *Cocoyam*

Its limited worth in terms of total production of root and tuber crops has made it difficult to estimate data on world production and trade of *Cocoyam*. The entire world production area of *Cocoyam* alone was valued to be about 0.9 million ha in 1983, with 80% (0.7 million ha) in Africa. The remaining 20% (0.2 million ha) is what other continents contributed with Asia being the largest. The global production of *Cocoyam* then was 5.6 million tons, with Africa producing about 61.33% and Asia about 38.67%. The world production increased to 37.5 million tons in 2000 with nearly 4 million ha of land and 96% of the production from Africa. The principal producer was Nigeria with 26 million tons, trailed by Ghana with more than 3 million tons, and Côte d'Ivoire with 2.9 million tons. More than 69% of the whole area (4 million ha) was in Nigeria. The average yield was approximately 10 t.ha^{-1} (DAFF, 2011).

2.4.5 Description of *Cocoyam*

Cocoyam is a wetland perennial plant which grows up to about 2 m high. It is a tube-shaped root or corm. The corm is molded like a top with rough ridges, lumps and spindly roots and usually weighs around 0.5 to 0.9 kg, but rarely as much as 3.6 kg. The covering is brown but the flesh is white or pink depending on species. There are some varieties of *Cocoyam* that yield smaller tubers called *eddos*, which grow off the sides of the main corm. The *eddos* are usually around 2 to 4 g. It produces heart-shaped leaves which are 0.6 to 0.9 m long. Its flowers sprout between the leaves. *Cocoyam* is propagated from full tubers or carvings from corms. It possesses a central corm from which leaves grow upwards and roots grow downwards but cormels, daughter corms and runners grow laterally (Sibiya, 2015).

2.4.6 Growth cycle and development stages

The developmental stages of *Cocoyam* depend largely on the species (Mare, 2009). The rate of development is sluggish after planting but advances rapidly after 1 to 2 months. The size and shape (corm quality) are determined at various growth stages. A typical *Cocoyam* has three different growth stages; establishment, vegetative growth, and corm initiation and bulking through maturation.

2.4.7 Climatic requirements

The parameters required to produce *Cocoyam* are described (DAFF, 2011) and presented in

Table 2.3.

Table 2.3 Production parameters for *Cocoyam* (DAFF, 2011)

S/N	Parameters	Description
1	Temperature	It does great in partial shade, nonetheless endures full sun if it gets plenty of water. An ideal temperature for growth is 24° C. *Cocoyam* enjoys warm conditions because it does not survive in freezing temperatures. It grows best in the tropics at 1 500 m above sea level.

S/N	Parameters	Description
2	Water requirement	*Cocoyam* can be grown under both wetland and dry land conditions and some species perform well under both conditions. It can tolerate high-rainfall areas, if there is good drainage, but does not withstand water logging. An ideal rainfall is 1 400 – 2 000 mm for the growing season.
3	Soil requirements	*Cocoyam* thrives well in moist, heavy, well-aerated soils with good moisture holding capacity. It requires a pH value of 5.5 to 7.8. It tolerates a pH value as low as 4.8 with high yields. It also flourishes in a slightly acidic, moist or wet soil, rich in organic material.
4	Soil preparation	The land is cleared, ploughed and harrowed at 5 to 7-day intervals. Heaps or ridges can be done at 1 x 1 m apart.
5	Field layout and design	The planting row distance in commercial farming is 1.3 m apart and 40 to 50 cm between plants in a row. Planting can be done in embankments spaced at 1 x 1 m or 1.3 x 1.3 m in small farms. Plant on the apex of the heaps or ridges at 1 m apart on rows.
6	Planting	Planting is either done manually or mechanically with the help of a tractor-pulled planter. Planting depth is 15 to 20 cm deep. The root depth is within 40 cm. The safest planting period is between December and April, but plantings can be done any time during the year provided moisture is adequate.
7	Fertilization	The nutrient levels found in the soil at planting time should be supplemented with application of fertilizer. Fertile soil may not require any fertilizer but may be required if the soil has been depleted. If essential, apply N.P.K. 15:15:15 at 5 to 6 Coke bottle capfuls in a loop approximately 10 cm around the plant. The applications are done at 2, 5 and 7 months after planting. The initial fertilizer application should include 1.5% Mg, 1% Mn, and 0.1% Zn.
8	Irrigation	Irrigation can be applied at a minimum of 15 mm of water three times a week with an overhead sprinkler or drip irrigation.
9	Weed and pest control	Weeding should be done at least three times per season monitored for the first three months after planting. Weed rivalry during this

S/N	Parameters	Description
		period may negatively affect yields. Pests (white ants, rodents) are accountable for suboptimal yields as well as decline of the quality of the tuber in storage and should be controlled. Planting should be done with disease-free propagating material by closely inspecting each cutting, wash with potable water, immerse hulls in a 10% bleach solution for 30 seconds.
10	Harvesting	Most species mature in about eight to ten months from planting. The growth cycle continues from nine to eleven months. However, corms and leaves would have developed during the first six months. The foliage remains stable in the last four months, when it starts to dry, the plants are prepared for the corms to be harvested. Harvesting is by uprooting when the leaves have turned yellow and are beginning to dry.

2.4.8 Related previous studies on *Cocoyam*

The study on the effect of planting density on growth and yield of *Taro* was carried out by Sibiya (2015). The study determined the effect of water stress and density of plant on growth and yield of *Taro* landraces. The outcome of the field trial disclosed that emergence was affected by plant density, with plants developing slower at high planting density. Growth and yield responded positively to increasing plant density with yield being highest at high plant density. The research also disclosed that emergence was slow and yield reduced at 30% crop actual evapotranspiration (ETa) compared to 100% ETa. It was concluded that growth was affected negatively by water stress. The study on evaluation of growth, yield and water use of three South African landraces under changing water regimes was carried out by Mabhaudhi *et al.* (2013). The yield at 60% ETa and 30% ETa was 15% and 46% higher at optimal irrigation, respectively. Water use efficiency across varying water regimes was comparatively unaffected. The effect of irrigation regime on yield and quality of three varieties of *Taro* was evaluated by Uyeda *et al.* (2011). Their results indicated no meaningful effect of irrigation on objective measures of quality. Yet, high yield responses were discovered for all species but the extent of response of corm fresh weight to irrigation rates differ. The study conducted by Mabhaudhi and Modi (2013) revealed that growth of taro landraces as well as stomatal conductance remained lower under rain-fed when compared with irrigated situations. Some landraces showed reasonable sensitivity to restricted availability of water under rain-fed conditions.

According to Oladokun (1990), food crops such as plantain (*Musa paradisiaca*), maize (*Zea mays*), melon (*Cucumis melo*), cowpea (*Vigna unguiculata*) and pineapple (*Ananas comosus*) can be intercropped with Cocoyam. Tree crops like oil palm (*Elaeis guineensis*), kola (*Cola acuminate*), coffee (*Coffea spp.*), coconut (*Cocos nucifera*) and citrus (*Citrus medica*) can also be some intercrops. Experiments conducted by Osundare and Agboola (2003), showed a significant reduction in cassava (*Manihot esculenta*) leave area and stem girth when intercropped with Cocoyam and sweet potato (*Lopmoea batatas*). Stem height, weight of fresh cassava and number were meaningfully low by intercropping at harvest. An experiment conducted by Unamma *et al.* (1985) showed that intercropping of Cocoyam, maize and sweet potato significantly out-yielded either of the singular crop components as per experimental unit. Plantain populations had an irrelevant impact on the yields of *Colocasia esculenta*. When intercropped, perhaps the profuse suckers formed by *Colocasia* suppressed growth of plantain (Igbokwe *et al.*, 1984). Intercropping Cocoyam with maize and yam (*Dioscorea spp.*) is a very common practice (Knipscheer and Wilson, 1980). Amusa *et al.* (2011) reported that virtually all farmers intercropped Cocoyam with crops like maize, cassava and vegetables. Intercropping and mulching of Cocoyam and plantain can be strategic in decreasing weed interfering with the crops, conservation of labour, and minimising production costs and fertilizer efficiency and ensuring optimal productivity of the intercrops (Shiyam *et al.*, 2011). Intercropping Cocoyam with maize increased the marketable Cocoyam tuber yields as compared to Cocoyam sole cropping (Olasantan, 1990). Inter-cropping of taro with pepper (*Capsicum spp.*) could decrease the viral diseases occurrence rate on pepper (Fa-wan *et al.*, 2009)**.** Cocoyam-sweet potato-maize intercrop depressed yield of the component crops by 50 to 90% in the absence of weed control measures. It indicates the status of choosing a spatially and temporally well-matched intercrop grouping for control of weed and advanced yields of constituent crops in an intercrop (Weerarathne *et al.*, 2017). Mabhaudhi and Modi (2014) reported that for two seasons of intercropping *Cocoyam* with bambara nuts (*Vigna subterranean L. Verdc.*), plant height and leaf number of *Cocoyam* was negatively affected as compared with sole crop. Nevertheless, in spite of this decrease, plant height in the sole crop was similar statistically to the 1:1 intercrop. The intercrop had no substantial effect on yield of *Cocoyam* per hectare. According to Sagoe *et al.* (2004), rice reduced the length of taro petiole but increased leaf number in the intercrop.

The corm sizes were the same for all treatments, but taro yields were reduced. The average performance of the rice was the same in the intercrop

2.5 Rice

Rice, as a crop, requires sixteen (16) vital elements which must be available in optimum quantities and in forms readily available for suitable growth. Nitrogen, phosphorus, and potassium are the most usually applied elements by rice farmers as fertilizers and a significant percentage of the nutrients is used up by rice crops as they germinate to harvest magnitude (Yoon *et al.*, 2003). Rice cultivation needs enormous quantities of water and nutrients, and significant amounts of water and nutrients can be lost via surface run-off and drainage, unless there is a means for balancing between inputs and what is really consumed by the rice (Yoon *et al.*, 2003). Currently, rice is cultivated on every continent except for Antarctica (Muthayya *et al.*, 2014). According to Balasubramanian *et al.* (2007), Sub-Saharan Africa (SSA) faces numerous problems. The key one is to improve the lives of 30% of its populace that is affected by poverty and food insecurity. Above 70% of the people that live in farming areas will need to play a main part in improving the situation. Rice production in the world has increased from 200 million tons of paddy in 1960 to above 678 million tons in 2009 with China, India and Indonesia being the three largest producers (Carriger and Vallee, 2007).

According to Khush (1997), there exist two cultivated varieties of rice; *O. sativa* (Asian) that is grown worldwide and *O. glaberrima* (African) which is cultivated in West Africa on a limited scale. It belongs to the family of Gramineae or grass family. It is of superior importance for the nourishment of large spreads of the population in Asia, parts of Latin America and Caribbean and, progressively so, in Africa. It is similarly the principal source of income generation and employment for above 200 million homes in developing countries (Muthayya *et al.*, 2014). Production of rice under irrigation requires high quantities of water at about 2 500 litres for 1 kg of rice (Price *et al.*, 2013). Quantity of water application during the growing season can vary from 500 to 800 mm up to more than 3 000 mm. The root zone is between 0–20 cm for lowland rice (anaerobic) while that of upland (aerobic) rice is 0–40 cm (Bouman *et al.*, 2007).

According to the international rice research institute (IRRI), rice is typically grown in bunded fields that are continuously flooded up to 7−10 days before harvest. Continuous flooding helps to ensure sufficient water and to control weeds. Lowland rice requires a lot more water than upland rice. Before rice can be planted, the soil should be in the best physical condition for crop growth and the surface is level. Land preparation involves ploughing and harrowing to ‘till’ or dig-up, mix and level the soil. The two main practices of establishing rice plants are transplanting and direct seeding. Rice completes two distinct growth phases: vegetative and reproductive. The vegetative phase is subdivided into germination, early seedling growth and tillering the reproductive phase is subdivided into the time before and after heading, that is, panicle exertion. Harvesting can be manual or mechanical. Depending on the varieties, rice crop usually reaches maturity at around 105–150 days after crop establishment (IRRI).

2.5.1 Rice production in South Africa

Rice has never been produced commercially in South Africa. According to the IRRI, 90% of the world’s rice is cultivated in South, Southeast, and East Asia. Sub-Saharan Africa (SSA) is confronted with many problems. The main one is poverty and food insecurity. Report by Africa Rice Center (2007), showed that South Africa and Mozambique have the highest per capita consumption of rice at 14 kg/year. Production of rice in the Southern Africa region is besieged by low yield when compared with Western and Central Africa. Practically all rice consumed in South Africa is sourced from the international market (Center, 2007).

2.5.2 Related previous studies on rice

The study conducted by Oliver *et al.* (2008) to find out the effects of alternate wetting and drying (AWD) on the yield, water use and water use efficiency (WUE) of Boro rice revealed that the highest average total water used by the plant which also attributed to highest grain yield was found from conventional flood irrigation treatment, though the different in yield was not significant. The AWD treatments resulted in the highest WUE. The AWD indicated a quite large saving of 15 cm as compared with flooded irrigation. A study was carried out to compare the responses of local species of rice under different water management regime on the growth and yield (Fonteh *et al.*, 2013). The study established that the different water management regimes do not significantly affect height of plant. The WUE of AWD treatments was about 100% higher than that of continuous flooding irrigation (CFI). According to Pascual and Wang (2016), considerable higher grain yield can be achieved under the adoption of the system of rice intensification (SRI) using almost half or one quarter of the amount of irrigation water used by CFI. Grain yield of CFI was similar to AWD and it was attributed to the adoption of

SRI practices (Pascual and Wang, 2016). The result on the effect of irrigation with untreated and treated wastewater did not improve the growth and yield of rice crop (Alghobar and Suresha, 2016).

2.6 Conclusion to Literature Review

None of the literature consulted and reported has taken in to consideration the adoption of treated domestic wastewater, particularly the abundant ABR effluents, of urban and peri-urban locations in conjunction with different irrigation water management techniques. During the literature review, *Cocoyam* was not reported to have been intercropped with a water hungry crop such as rice using ABR effluent. Most of the water application approaches under review discussed AWD and CFI, but did not investigate what happens between the two, termed WWF. There is need to understand what happens if the land is made to have continuous wetting (well-watered conditions) without ponding. *Cocoyam* and rice have been carefully chosen because both of them are water and nutrient loving crops that will address the existing problems of disposing treated wastewater. The two crops are also considered to be irrigated with effluent because they are cooked before consumption, which reduces health risks on consumers. All these constituted knowledge gaps that were filled. There was no need to investigate the effect of ABR wastewater on soil properties at the experimental site because it was reported that use of treated domestic effluents for three consecutive seasons had no significant effects on the soil.

Having identified the knowledge or research gaps above, the following chapters were the main research focus of this work.

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3 EVALUATING THE EFFECT OF IRRIGATION WATER MANAGEMENT TECHNIQUES ON (TARO) *COCOYAM* (*COLOCASIA ESCULENTA* (L.) SCHOTT) GROWN WITH ANAEROBIC BAFFLED REACTOR (ABR) EFFLUENT AT NEWLANDS, SOUTH AFRICA

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3.1 Abstract

This study evaluated the effects of irrigation water management techniques on the growth and yield parameters of *Cocoyam* (*Colocasia esculenta*) irrigated with anaerobic baffled reactor (ABR) effluent. The irrigation water management treatments considered were alternate wetting and drying (AWD), continuous flooding irrigation (CFI) and wetting without flooding (WWF). It was hypothesized that irrigation techniques with ABR effluent have a significant effect on the growth and yield of *Cocoyam*. The effects of the treatments were significant ($P < 0.05$) on the number of irrigation events, amount of irrigated water and daily water balance. The treatments had no effect on the growth parameters (plant height, leaf number and leave area index (LAI) ($P > 0.05$)). The treatments effects were, however, highly significant ($P < 0.001$) on the yield components (biomass, corm mass, corm number, corm size, harvest index), corm yield and water productivity (WP). AWD treatments had the highest WP. The highest average corm yield of 7.5 and 9.84 t/ha for WWF treatments were obtained in 2017 and 2018 seasons respectively. It is concluded from this study that both AWD and CFI resulted in yield reduction as compared to WWF, and as such, not recommended in order to improve the productivity of *Cocoyam*.

keywords: alternate wetting and drying, anaerobic baffled reactor, irrigation management techniques, Cocoyam, water productivity, wetting without flooding.

3.2 Introduction

Wastewater is the only potential source of water that will rise as the population increases and the demand for freshwater rises (Heidarpour *et al.*, 2007). According to Qadir *et al.* (2010), urban and peri-urban farmers in almost all developing countries have no choice but to use wastewater. Metropolitan population growth, predominantly in developing countries, places enormous stress on water and land resources; as a result, growing volumes of wastewater is being released and most of it untreated. The rate of using wastewater for irrigated agriculture in urban and peri-urban and even in far rural settlements downstream of the new mega cities is increasing. Sustainable techniques for wastewater disposal in a way that enhances crop production will ease water shortages and recycling of nutrients also necessitates the use of treated wastewater for irrigating crops (Pedrero *et al.*, 2010).

The practice of periodic drying and re-flooding field during the lifecycle of a crop is referred to as alternate wetting and drying (AWD) irrigation management (Lampayan *et al.*, 2015). The continuous flood irrigation (CFI) maintains standing water (anaerobic conditions) every time (Yao *et al.*, 2012). The well-watered conditions with 100% water holding capacity is another irrigation management technique (Ruíz-Sánchez *et al.*, 2011). It is referred to as wetting without flooding (WWF).

The anaerobic baffled reactor (ABR) is made up of a series of compartments separated by discontinuous hanging baffles (Wang *et al.*, 2004) that separate the compartments and force the wastewater to move through the treatment train with an up flow velocity sufficiently low to prevent biomass wash-out. The flow pattern promotes improved contact between the influent wastewater and the retained biomass. According to Bame *et al.* (2014), ABR as a high rate digester (anaerobically), involves different hanging and vertical baffles premeditated for wastewater treatment. The ABR is an appropriate method for medium or short-term hygiene solutions in low-income societies (Foxon *et al.*, 2004). According to Musazura *et al.* (2015), the ABR effluent comprises nutrients (potassium, phosphorus and nitrogen) which are significant for growth of crops. Further treatment of the ABR effluent is undertaken by passing it through two consecutive beds of coarse stones (anaerobic filter - AF). The nutrients available in the effluent have economic value as a fertilizer when used for irrigation because the source of the wastewater are domestic households (Bame *et al.*, 2014).

Cocoyam (taro) *Colocasia esculenta* being one of the food security crops, is a marginalized tuber food crop, with wide distribution in the tropics. The neglect of *Cocoyam* as an indigenous crop is one of the causes of food insecurity; therefore, production of indigenous crops will play a critical role in contributing to food security (Kamwendo and Kamwendo, 2014). It is the 14th most consumed vegetable worldwide (Lebot and Aradhya, 1991; Singh *et al.*, 2008; Tumuhimbise, 2015). Despite its importance as a food and vegetable crop, it has received very limited research attention from agricultural, academic and development institutions and is therefore classified as a neglected and an underutilized crop species (Tumuhimbise, 2015). Scientific research on *Cocoyam* is scarce in South Africa (Mabhaudhi and Modi, 2013; Sibiya, 2015; Tumuhimbise, 2015). Cocoyam (*Cocoyam*) is "*an underexploited food and feed resource*" (Owusu-Darko *et al.*, 2014).

There has not been any reported work on the response of *Cocoyam* to different irrigation management techniques using decentralized wastewater treatment system (DEWATS) effluent. This study, therefore, investigated the effect of irrigation water management techniques on the growth and yield parameters of *Cocoyam*. It also investigated the number, amount of irrigation, field water balance and water productivity. The hypothesis was that irrigation water management techniques with ABR effluent have a significant effect on the growth, yield of *Cocoyam*, water balance and water productivity.

3.3 Methods

3.3.1 Description of the study site

The layout of the research site at the Agricultural Hub, Newlands Mashu Research Facility, Durban, South Africa (29° 46′ 26″ S, Longitude 30° 58′ 25″ E and altitude 14 m amsl) is shown in Figure 3.1. The climate in the study area falls under humid sub-tropical with cool, dry winters that are frost-free and hot, wet summers. It is characterized by an average annual precipitation between 800 to 1 000 mm and mean daily temperature of 20.5°C. The soil is a clay of the Sepane form (Musazura *et al.*, 2018).

Figure 3.1 The layout of the research site

3.3.2 Anaerobic baffled reactor (ABR) effluents

The effluent was sourced from a DEWATS unit constructed in 2010 as a demonstration and research plant at Newlands Mashu agricultural hub, Durban. Figure 3.2 showed the Newlands Mashu DEWATS plant in Durban. Primary treatment is facilitated in a settler consisting of two chambers which also acts as a biogas collection point and later distributes effluent evenly into three parallel anaerobic baffled reactor (ABR) trains (Figure 3.2). Trains 1 and 2 are identical consisting of seven chambers while Train 3 has four chambers (Figure 3.3), the first three being double the size of the chambers from Trains 1 and 2 while the fourth compartment is equal to the size of the last chamber in Trains 1 and 2. The DEWATS was fed with domestic wastewater from 83 households close to the research site in the eThekwini Municipality. The influent from the households settled in to the primary sedimentation compartment, where solid particles are separated by gravity. The liquid flows into the anaerobic baffle reactor, which can be considered as an improved septic tank with baffles that separated the tank. The baffles forced the wastewater to flow up and down through the chambers, this ensures good contact between the anaerobic microorganisms resulting in the degradation of the biodegradable organic constituents. The ABR effluent then passes through two anaerobic filter (AF) compartments which consists of a bed of coarse stones which allow the attached growth of the anaerobic microorganisms and the retention of suspended solids. The compartmentalized design separates the solids retention time from the hydraulic retention time, making it possible to anaerobically treat wastewater at a retention period of between 4–5 days. The microorganisms act as a scavenging section ensuring the treated wastewater has a low biodegradable carbon and suspended solids content. The concentration of other components of excreta such as potassium, phosphorus and ammonia are not changed. The AF effluent was then pumped in to a 10 000 L tank from where the effluent flows by gravity to the open field where the irrigation trials take place. Excess treated effluent was returned to the trunk sewer. The composition and characterization of the AF effluent is presented in

Table 3.1.

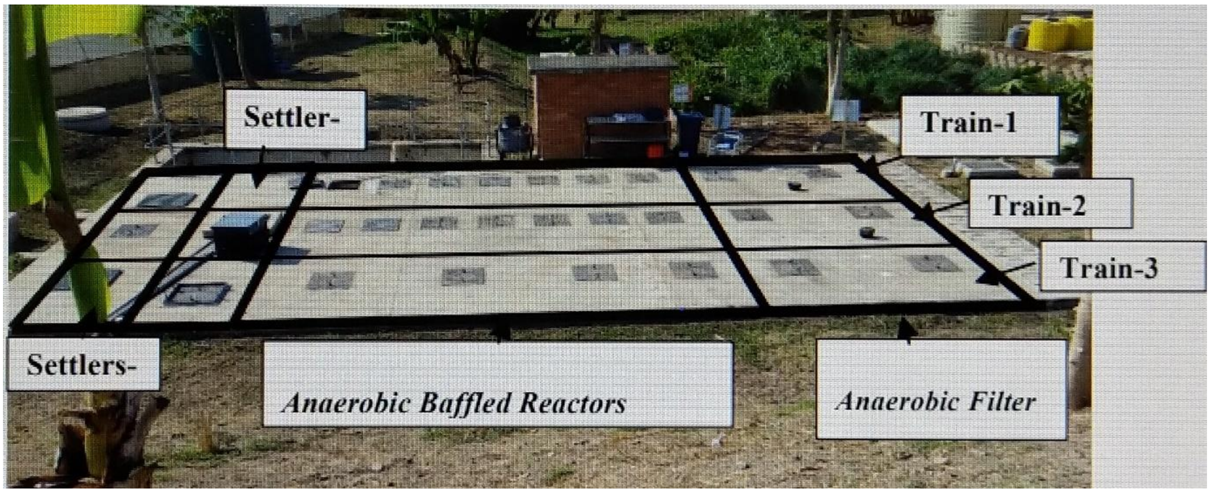


Figure 3.2 Newlands Mashu DEWATS plant

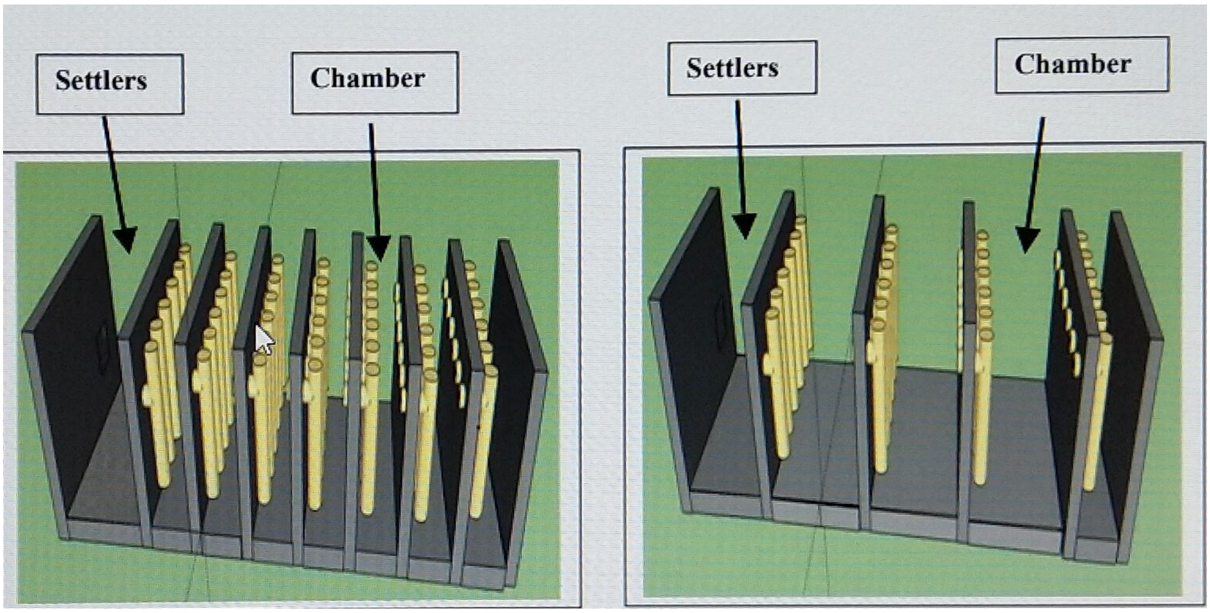


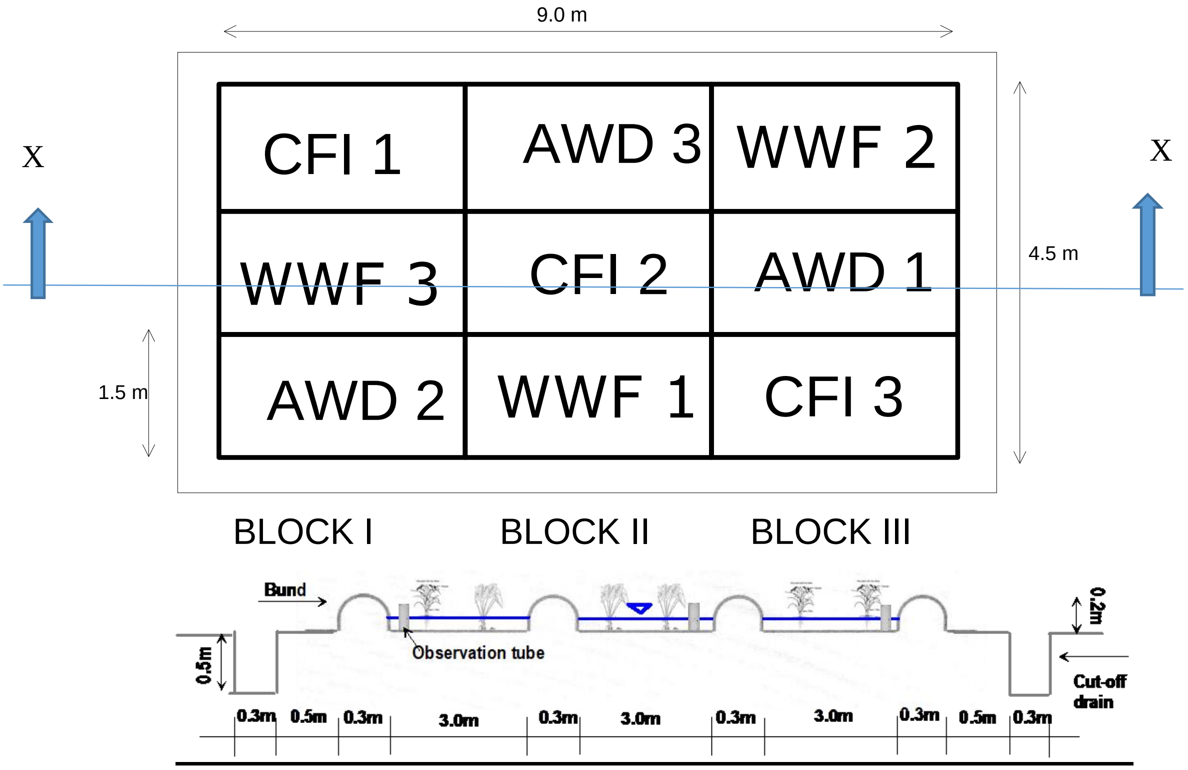
Figure 3.3 Settlers and chambers

Table 3.1 ABR effluent characteristics

Parameters	**Units**	**Mean**	**SD**	**Range**
Ammonium - N (NH_4^+ -N)	(mg/L)	58.45	± 0.89	43.73 - 67.57
Nitrite – N (NO_2^--N)	(mg/L)	0.53	± 0.01	0.18 – 1.00
Nitrate – N (NO_3^--N)	(mg/L)	0.30	± 0.07	0.10 – 0.47
Total Kjeldahl N (TKN)	(mg/L)	62.91	± 0.87	46.93 – 76.20
Total nitrogen (TN)	(mg/L)	67.67	± 1.37	53.67 – 76.00
Ortho phosphate (PO_4^{3-}**)**	(mg/L)	18.19	± 0.18	14.80 – 22.23
Chemical oxygen demand (CODt)	(mg/L)	276.60	± 5.03	222.67 – 295.00
Total suspended solids (TSS)	(mg/L)	82.00	± 2.03	67.78 – 123.33
Dissolved oxygen (DO)	(mg/L)	1.37	± 0.05	0.22 – 3.51
Alkalinity	(mg/L)	6.98	± 0.19	5.56 – 7.87
E.coli	(cfu/ml)	2600.00	± 700.00	2000.00 – 3400.00
pH		7.27	± 0.05	7.19 – 7.38
Electrical conductivity (EC)	S/m	93.22	± 0.83	71.57 – 107.90

3.3.3 Experimental design and treatments

The field trials were conducted at an open agricultural field for two seasons. The first season was from July, 2017 (cool dry winter) to February, 2018 (hot and wet summers) and the second season was from December, 2017 (hot and wet summers) to July, 2018 (cool dry winter). The trials were laid out in a randomized complete block design (RCBD) with three replications as shown in Figure 3.4. The slope of the field was considered to be the blocking effect. Randomization was done using *Kutools for Excel* software to avoid bias of both trials (Kutools, 2017). The trials consisted of a factor, irrigation management techniques with three levels of treatments, alternate wetting and drying (AWD), conventional flooding irrigation (CFI) and continuous wetting without flooding (WWF). Treatment WWF was used as a control. The whole field layout gave rise to 9 plots of 3 m by 1.5 m each. Bunds were established between plots to isolate them from adjacent plots Figure 3.4. Bunds (300 mm wide at the base and 200 mm high) were covered with plastic sheeting (250 µm) which was buried into the soil to a depth of 0.6 m to prevent run-on, run-off, lateral-in and lateral-off flow in each plot. Inserted into each plot was a 400 mm long and 110 mm diameter PVC observation tube perforated with 5 mm diameter holes at 40 mm intervals. A measuring tape (metal) was used to measure the water level in the tube. A water depth monitoring tube was inserted into each of the 9 irrigation plots (at least 500 mm away from the bund walls, 200 mm above and 200 mm below the topsoil). It was used to determine the need for water addition and monitoring the soil water depth.



Section X - X

Figure 3.4 Field trial layout showing different treatments

3.3.4 Planting material and technique

The South African *Cocoyam* landraces obtained from Umbumbulu (eddoes types) were used as planting materials. Planting materials were initially selected for uniform plant size. They were planted at an intra-row spacing of 0.5 by 0.5 m. The spacing produced 40 000 plants per hectare. All the plots were irrigated with municipal water for the first two months in order to have a successful crop establishment and to avoid biasness in the treatments. They were transplanted after two months and the irrigation management techniques with AF effluents commenced. The plants exhibited transplant shock for about a week.

3.3.5 Application of irrigation water management techniques and water productivity

The plots were surface irrigated with bunds to control run-off. There were grids of irrigation pipes (plastic materials) of 25, 20 and 15 mm diameter consisting of a ball valve and water tap at the discharge point of each plot. The CFI treatments maintained continuously an irrigation depth (pond) of 50 mm and stopped 2 weeks prior to the harvesting of all the replications. AWD treatments maintained an irrigation water depth of 50 mm when the water level in the tube has reduced to 150 mm below the soil surface (Lampayan *et al.*, 2015). A total depth of 200 mm of water was applied through the inserted tube wells as soon as the level in the tube drop to 150 mm below the soil surface in order to return to 50 mm level of ponding. The frequent of irrigation varied between minimum of 3 and maximum of 5 days depending on the prevailing conditions. The WWF plots maintained the same water level with the field (well-watered). It is a continuous process provided the level of water in the tube goes beyond the soil surface. It is almost daily and the amount added depends on the drawdown. The tube had been marked at 50 mm above the surface for ease of irrigation for both AWD and CFI. Time to irrigate was dictated by observation of water table level in the observation tube.

An automatic weather station, Campbell Scientific Automated (AWS), fitted with a CR 1 000 data logger, installed at the experimental site was used to collect weather data. It measured the total rainfall and the reference evapotranspiration (ETo mm/day) according to FAO Penman-Monteith protocol. The crop coefficient (Kc) values for *Cocoyam* were as described by Mabhaudhi *et al.* (2013) whereby Kc initial = 1.05 (2 months), Kc med = 1.15 (4 months) and Kc late = 1.1 (1 month). Using these values of Kc and ETo from the AWS. The data obtained over the period of the trials is presented in Table 3.2.

Table 3.2 Average monthly temperature, relative humidity and rainfall for the two seasons at the experimental site

Month	**Average Temp. (˚C)**			**Relative Humidity (%)**			**Rainfall (mm)**
	Max	Min	Ave.	Max	Min	Ave.	Ave.
Sept 17	25.58	14.12	19.85	94.27	48.22	71.25	30.36
Oct 17	27.03	15.35	21.19	93.99	47.31	70.65	54.10
Nov 17	26.64	16.42	21.53	94.15	50.36	72.26	70.44
Dec 17	28.27	19.39	23.83	94.93	56.96	75.95	86.61
Jan 18	29.98	20.20	25.09	94.92	54.29	74.60	123.28
Feb 18	30.10	19.73	24.91	95.33	53.35	74.34	70.79
Mar 18	29.80	19.27	24.53	96.76	54.65	75.71	88.73
Apr 18	28.19	15.98	22.09	95.92	47.05	71.49	12.53
May 18	27.41	12.67	20.04	96.99	41.88	69.44	75.35
Jun 18	26.13	9.64	17.88	95.34	33.65	64.49	2.79
July 18	24.98	7.92	16.45	93.98	29.55	61.77	2.54

3.3.6 Data collection and analysis

Data were collected fortnightly from 3 sample plants per plot at every replication. Data collected included plant height, leaf area index (LAI) and leaf number for growth parameters. The plant height was measured with the aid of collapsible metre rule, leaf numbers were counted manually and leaf area indexes (LAI) were measured using LAI-2200C Plant Canopy Analyzer (LI-COR, Inc. USA and Canada) throughout the growing season. Biomass per plant (kg), corm number, corm size (mm), corm mass per plant (kg), harvest index (%)) and total yield (t/ha) were measured and recorded at harvest. Corm yield was calculated from the harvestable plots, converted to yield per hectare and expressed as t/ha. This was done with Equation 3.1 (*Gebre et al.*, 2015).

$$Yield\ (t/ha) = \frac{Yield\ per\ net\ plot\ (kg) * 10\ 000}{Net\ area\ of\ the\ plot\ (m^2) * 1\ 000} \qquad 3.1$$

The water balance was calculated according to Fereres and Connor (2004) and water productivity calculated as the ratio of total corm yield to the total water use (El-Zohiri and AMH, 2014). Data sets generated were subjected to statistical analysis of variance (ANOVA) by one-way ANOVA using GenStat® 18th edition analytical package. Significant difference was determined at $P \leq 0.05$. Duncan's multiple range test was used to separate means at 5% level where the treatments are significant.

3.4 Results and Discussion

3.4.1 Treatments effect on irrigation

The effects of irrigation water management techniques with ABR effluent were significant on the total amount of irrigation and total water used ($P = 0.002$). The effects were highly significant ($P < 0.001$) on the number of irrigation and daily water balance (Table 3.3). A significant ($P<0.05$) reduction occurred in number of irrigation, amount of irrigation, total amount of water use and water balance between treatments AWD and WWF. However, there was no significant ($P>0.05$) difference between means of CFI and WWF for all the parameters except for number of irrigation and water balance in 2017 season. The CFI treatments used the highest quantity of water during the crop growth cycle because of the continuous application of irrigation in order to ensure flooding/ponding unlike AWD treatments that received irrigation water intermittently. The WWF was similar to CFI in terms of irrigation events and amount because water application was also continuous, though, not to ponding level. The higher the total number of irrigation events, the more the amount of irrigation and water balance. Irrigation amount and/or total water use is a very key parameters of water balance. The values of all parameters measured in Table 3.3 were higher in 2018 than 2017 season. This was a result of seasonal differences that produced less rainfall in 2018 as compared to 2017.

Table 3.3 Effects of irrigation water management techniques with anaerobic baffled reactor (ABR) effluents on number of irrigations, amount of irrigation, total water use and daily water balance for 2017 and 2018 seasons

Season	Treatments	Number of irrigation	Amount of irrigation (mm)	Total water use (mm)	Water balance (mm/day)
2017	AWD	18.00 ^{a}	847 ^{a}	1197 ^{a}	5.45 ^{a}
	CFI	66.67 ^{c}	1684 ^{b}	2034 ^{b}	12.28 ^{c}
	WWF	63.00 ^{b}	1540 ^{b}	1891 ^{b}	11.11 ^{b}
	p	***	**	**	***
2018	AWD	31.00 ^{a}	1498 ^{a}	1743 ^{a}	9.18 ^{a}
	CFI	135.00 ^{b}	3952 ^{b}	4197 ^{b}	24.67 ^{b}
	WWF	134.00 ^{b}	3290 ^{b}	3535 ^{b}	20.58 ^{b}
	p	***	**	**	***

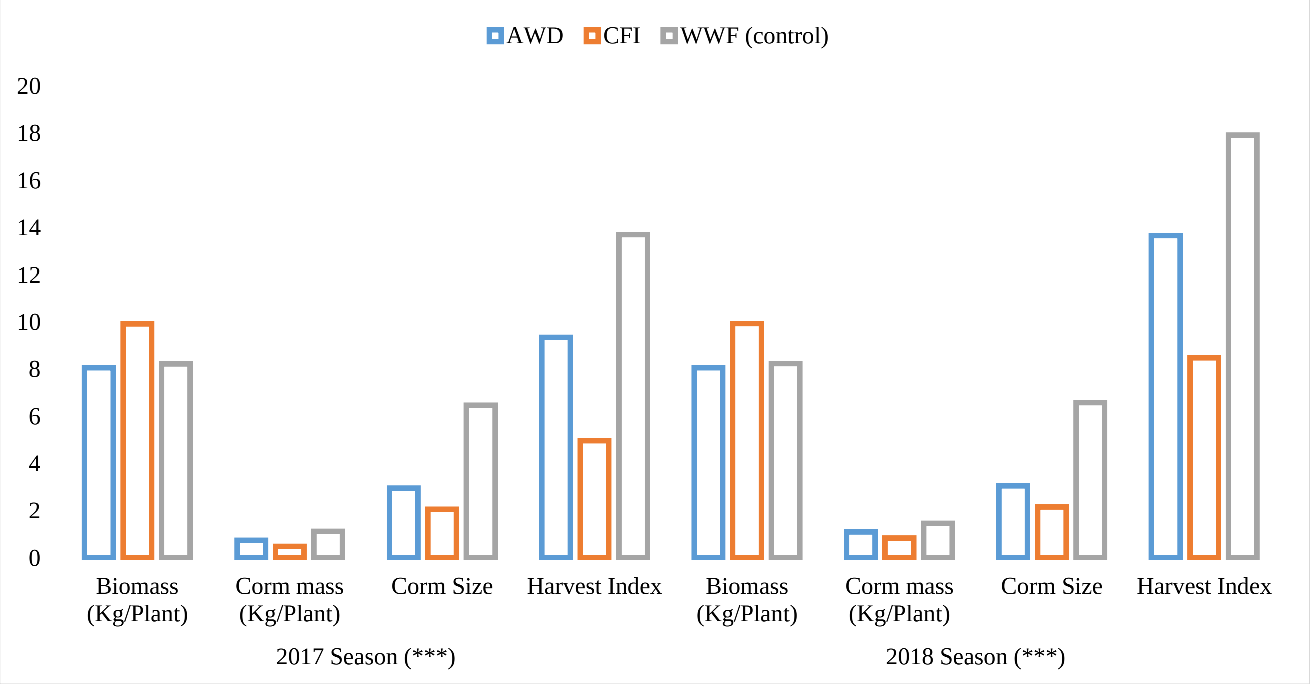
Notes: Means with same alphabets within a column in each season do not differ significantly at 5% level of probability. *p = probability*
**** = significant at 0.001 probability level, ** = significant at 0.01 probability level*

3.4.2 Treatment effects on growth of *Cocoyam*

The results for 2017 cropping season showed that irrigation water management techniques had no significant (P = 0.82) effect on plant height and LAI (P = 0.81). LAI had its highest and lowest values at AWD and WWF, respectively. The result of LAI agreed with Mabhaudhi *et al.* (2013), who reported that eddoes landrace of *Cocoyam* had its highest leave area under intermittent water stress when compared with no stress treatment. Overall, there was no significant difference (P = 0.99) in the mean number of leaves per plant. This could be as a result of turnover of leaves experienced during the life cycle of the species; newer leaves were continually emerging and the older leaves died off. The effects of the treatments were also not significant in 2018 season on plant height (P = 0.84), LAI (P = 0.88) and leave number per plants (P = 1.0). Hence, the two seasons followed the same trend in terms of growth parameters. The above results indicated that neither of the irrigation management techniques influenced growth parameters of *Cocoyam*.

3.4.3 Effect of treatments on yield components, corm yield and water productivity

The effects of the irrigation water management techniques on biomass, corm mass, corm size and harvest index of *Cocoyam* grown with AF effluent for three different techniques (AWD, CFI and WWF) are shown in Figure 3.5. The treatment effects were highly significant ($P < 0.001$) in both seasons on the biomass per plant, corm mass per plant, corm size per plant and harvest index. There was a significant ($P<0.05$) reduction between the means of corm mass per plant, corm size per plant and harvest index among in both seasons with the exception of biomass per plant. The biomass under AWD treatments revealed a significant increase from the control treatment (WWF). All the parameters in Figure 3.5 for 2018 planting seasons were higher than 2017 seasons which was probably as a result of the increase in the amount of irrigation water.



**** = significant at 0.001 probability level*

Figure 3.5 Effects of the irrigation water management techniques treatments on yield components of *Cocoyam* grown with AF effluent

Apart from the statistical result, it could be observed from Figure 3.6 that CFI treatments produced the smallest mean corm size and mass but with a higher number of corm number per plant as against the control treatment (WWF). The largest corm size and mass were found for the WWF treatments but with a fewer number of corm number per plant. The biggest corm size and weight accounted for the margin observed in the yield. *Cocoyam* does not tolerate water logging (DAFF, 2011). However, biomass was highest in the CFI treatments, which demonstrated the effect of ponding on the leafy (vegetable) part of *Cocoyam*. *Cocoyam* is both categorized as tuber and vegetable crop, it may therefore be suggested to use CFI treatments to enhance leafy part and WWF for higher *Cocoyam* corm yield. Weed infestation is reduced by flooding and this may be responsible for the highest mean value recorded for biomass at CFI treatment because large air spaces in the petiole may have permitted the submerged parts to maintain gaseous exchange with the atmosphere. Uyeda *et al.* (2011) reported similar result for biomass weight having the highest at 250% ET as compared to 50% or 100%. But standing or ponding effluent may result in a low oxygen content and may cause decaying of *Cocoyam*, thereby reduce the corm yield as found under CFI treatments (FAO, 2018).

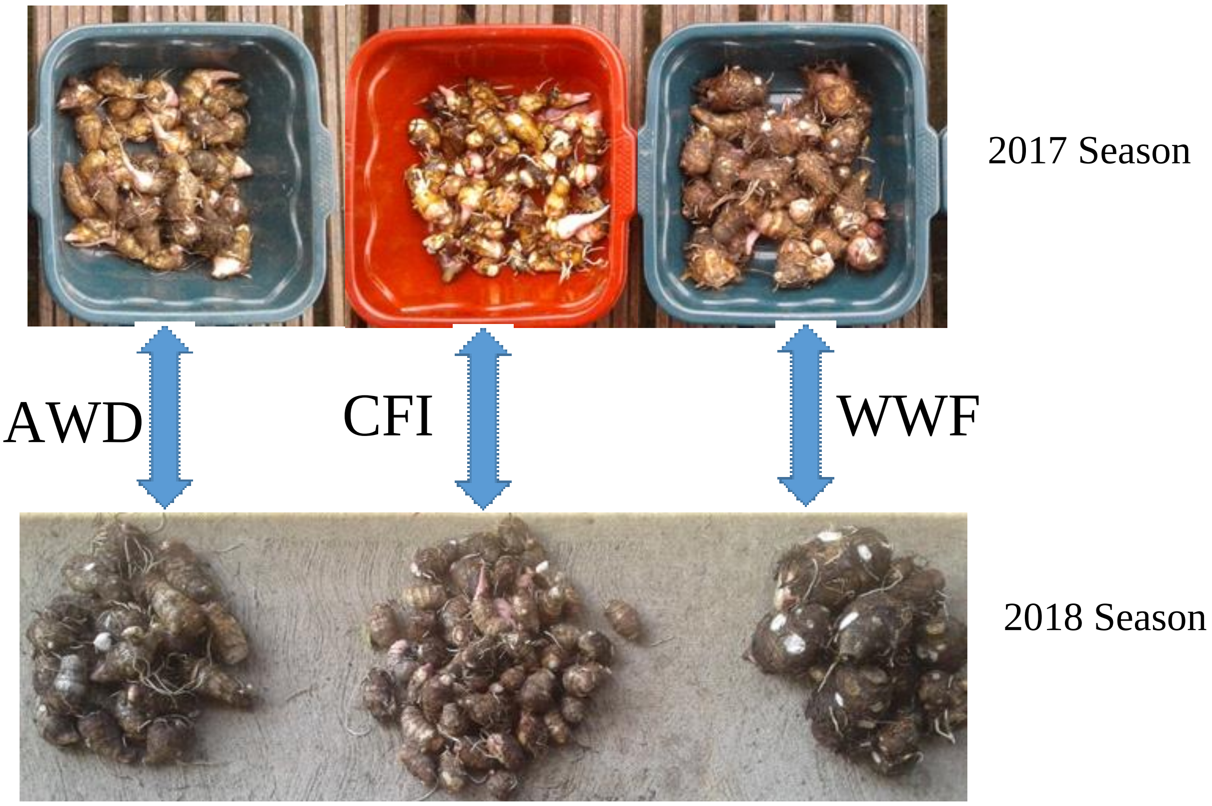


Figure 3.6 Harvested yield corm from both seasons

Table 3.4 shows the treatment effects on the corm numbers, corm yield and water productivity for both seasons. The treatment effects were highly significant ($P < 0.001$) on the corm numbers per plant, corm yield and water productivity of *Cocoyam*. The significant differences observed indicated that the performance of the *Cocoyam* landrace was influenced by different irrigation techniques. The means of corm numbers in treatments WWF were significantly different from both treatments AWD and CFI in 2017 season. However, in 2018 season, the means of corm numbers per plant among the three irrigation management techniques were significantly different from one another. The highest corm number per plant was obtained from treatments CFI. The control (WWF) produced the highest yield of 7.52 and 9.84 t/ha for 2017 and 2018 seasons, respectively. The two values obtained in this results were greater than the global average yield of 6.5 t/ha as reported by Gebre *et al.* (2015) while CFI gave the lowest mean yield. According to Muinat *et al.* (2017) temperature is the most factor that affects *Cocoyam* yield and this showed in the yield obtained from 2018 as compared with 2017 planting season. 2018 planting was done during summer while 2017 season was planted in winter. Sibiya (2015) reported 4.71 t/ha for same eddoes type of *Cocoyam* at the same spacing of 0.5 m by 0.5 m. Mabhaudhi *et al.* (2013), reported 6.1 (30% ETa), 9.31 (60% ETa) and 9.00 t/ha (100% ETa) for the same landraces during summer seasons. The difference in the yields obtained from the two seasons could be attributed to a slight delay experienced in transplanting *Cocoyam* to the trial field during 2017 season and may also be as a result of seasonal (winter vs summer) variation. The establishment stage for *Cocoyam* is 8 weeks but the *Cocoyam* in 2017 season went beyond to a part of vegetative growth (critical stage). This may have contributed to the yield reduction between seasons. *Cocoyam* was planted in 2017 winter (received more rainfall) and 2017 summer (characterized by lesser rainfall but more nutrient-rich AF effluent). This could be supported by DAFF (2011) that said *Cocoyam* prefers warm conditions (summer). WP were the highest (0.42 kg/m^3) for AWD treatments in both seasons. It was however, attached with a yield penalty (reduction). The highest WP for AWD was as a result of lower amount of water applied in the treatments. Since irrigation water productivity is the ratio of yield to amount of water/irrigation applied. There was no significant difference between the means of treatments AWD and WWF in 2017 while the means of water productivity were significantly different from one another in 2018 season. The lowest means of WP obtained in treatment CFI was as a result of maximum amount of water used (every-time ponding).

Table 3.4 Corm number, corm yield and water productivity of *Cocoyam* grown with anaerobic baffled reactor (ABR) effluent for the three irrigation water management techniques (AWD, CFI and WWF)

Seasons	Treatments	Corm number	Corm yield (t/ha)	Water productivity (kg/m^3)
2017	**AWD**	**38.78 ^{b}**	**5.02 ^{b}**	**0.42 ^{b}**
	CFI	**38.44 ^{b}**	**3.29 ^{a}**	**0.16 ^{a}**
	WWF	**28.00 ^{a}**	**7.52 ^{c}**	**0.40 ^{b}**
	P	***	***	***
2018	**AWD**	**42.11 ^{b}**	**7.34 ^{b}**	**0.42 ^{c}**
	CFI	**46.87 ^{c}**	**5.61 ^{a}**	**0.13 ^{a}**
	WWF	**32.00 ^{a}**	**9.84 ^{c}**	**0.28 ^{b}**
	P	***	***	***

Note: *Means with different alphabets within the same column differ significantly at the 5% level, p = probability, * = significant at 0.05 probability level, ** = significant at 0.01 probability level, *** = significant at 0.001 probability level.*

3.5 Conclusion

This study showed that *Cocoyam* (eddoes landraces from Umbumbulu) was susceptible to flooding (CFI). Attempts to domesticate the landrace out of its native way of irrigation (WWF) were unsuccessful as the crop failed to produce significant yield. *Cocoyam* is a wetland crop, so it performed and produced reasonable yields under continuous wetting without flooding (WWF) condition. The treatments with CFI treatments had the highest number of irrigation events and consumed the highest amount of irrigation. The highest yield of 7.52 and 9.84 t/ha were obtained for the two seasons in treatments WWF. These yields were higher than the global average yield of *Cocoyam*. The eddoes landrace under flooded condition (CFI) showed a significant reduction in corm yield as compared to WWF and alternate wetting and drying (AWD) conditions. The major effect of CFI was found under the total biomass per plant. The yield obtained in this study was mainly an effect of different irrigation water management techniques using water reuse (anaerobic baffled reactor (ABR) effluent) without application of additional (organic or inorganic) fertilizer. The adoption of irrigation management technique such as WWF using AF effluent could therefore be concluded as relatively a cheaper way of enhancing food security and sanitation especially in urban and peri-urban settlement. The hypothesises on water balance, water productivity and yield were accepted while that of growth parameters was rejected.

3.6 Acknowledgements

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4 IRRIGATION WATER MANAGEMENT TECHNIQUES WITH ANAEROBIC BAFFLED REACTOR (ABR) EFFLUENTS: EFFECT ON RICE GROWTH, YIELD AND WATER PRODUCTIVITY

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4.1 Abstract

The study evaluated the effect of irrigation water management techniques using anaerobic baffled reactor (ABR) effluent on the growth and yield of rice. It was hypothesized that irrigation techniques with ABR effluent have a significant effect on the growth, yield of rice, water productivity (WP) and water balance (WB). The experimental setup was a randomized complete block design for 2017 and 2018 cropping seasons, three treatments each with three replications. The treatments were alternating wetting and drying (AWD), continuous flooding irrigation (CFI) and wetting without flooding (WWF). The effects of irrigation treatments were significant ($P < 0.05$) on number of irrigation, amount of irrigation, total water use and daily field WB. The effect of irrigation water management techniques was significant ($P < 0.05$) for 2017 season but insignificant ($P > 0.05$) in 2018 on the yield. Effect of irrigation treatments on WP was significant ($P < 0.05$). The effects were not significant ($P > 0.05$) on the plant height, leave area index (LAI) and number of tilers per plant. However, the effect was significant ($P < 0.05$) on the number of panicles per plant. In conclusion, the result proved the acceptability of the hypothesis. AWD irrigation with ABR effluent should be encouraged among rice farmers.

keywords: alternate wetting and drying, anaerobic baffled reactor, continuous flood irrigation, effluent, water productivity and wetting without flooding.

4.2 Introduction

Water is a valuable resource yet; it is an insufficient resource in many nations. Consequently, there is a need to preserve, protect and conserve fresh water and access lower quality water for irrigation (Al-Rashed and Sherif, 2000). According to Renner (2012), surface irrigation is the application of water to the surface of the field. The entire field might be flooded (basin irrigation), the water might be fed into minor channels (furrows) or strips of land (borders), and it is the most common irrigation method. It is usually applied when conditions such as sufficient or abundant supply of water are favourable, mild slopes, soil type is clayey-loam with medium to low infiltration rate. Basins are surrounded by low bunds. The bunds avert water from moving to the end-to-end fields (Renner, 2012).

4.2.1 Urban wastewater reuse

Recycling of urban wastewater in agriculture has become public practice for a number of reasons, part of it being water scarcity, nutrient worth and environmental safety (Tamoutsidis *et al.*, 2009). The need for irrigation, since rainfall is not readily available throughout a season, and the need for water are constantly growing; therefore, water of higher quality is conserved for domestic use while that of lesser quality is suggested for irrigation purposes. Farming households having close contact with wastewater contaminated surface water had a higher risk of helminth infections compared with those without contact (Pham-Duc *et al.*, 2013) while van der Hoek *et al.* (2006) reported no significant association between wastewater exposure and helminth infections. Crop restriction such as crops that will be cooked before consumption, human exposure control and choice of wastewater application method (spray and sprinkler irrigation not recommended) are some of the ways to protect farmworkers and household (Scott *et al.*, 2008). The farmworkers must use appropriate protective covers such as clothing, long gloves, shoes and hand washing with soap. Rigorous health education programs and vaccination against typhoid and hepatitis are worthy of consideration (Scott *et al.*, 2008). The risks of ground water contamination due to irrigation with treated excess wastewater have a long-term effect and are challenging to estimate **(Shakir *et al.*, 2017).** Groundwater pollution is considerably more problematic to stop than surface pollution since groundwater can travel a far distance through invisible aquifers but impervious aquifers like clays partly decontaminate water of pathogen by simple filtration inform of adsorption and absorption, or chemical and biological activity. Musazura *et al.* (2015) found that dense peri-urban settlements in developing countries like South Africa need a cost effective systems such as decentralized waste water treatment systems (DEWATS) to be developed. These involve the use of anaerobic baffled reactors (ABR). Wang *et al.* (2004) defined the ABR as a closed tank with series of hanging and standing baffles which allow wastewater to flow under and over them from inlet to outlet in the absence of oxygen. DEWATS increases wastewater reuse opportunities. The nutrients in the effluent from DEWATS got economic value as a fertilizer and it has potential to be used in irrigated agriculture and since communal ABRs receive input from mainly domestic sources, the probability of heavy metals is very low and negligible. Thereby making ABR effluent from a DEWATS a very promising source of irrigation. Major elements like Ca and Mg required for plant growth can accrue in soils thereby improving the pH especially of acidic soils (Bame *et al.*, 2014)

4.2.2 Rice and its distribution

Rice (*Oryza sativa L.)* is the main food for more than half of the world population, plus thousands of families in Sub-Saharan Africa (SSA). Rice is grown in almost 115 nations in the world and is only next to wheat in terms of production globally. Approximately 40% of the rice consumed in Africa is imported (Seck *et al.*, 2010). Rice cultivation needs enormous quantities of water and nutrients; it requires 16 vital elements optimally. The root zone is between 0–20 cm for lowland rice (anaerobic) while that of upland rice (aerobic) is 0–40 cm (Bouman *et al.*, 2007). According to the International Rice Research Institute (IRRI), rice is typically grown in bunded fields that are continuously flooded up to 7−10 days before harvest. Currently, rice is cultivated on every continent except for Antarctica (Muthayya *et al.*, 2014). According to Balasubramanian *et al.* (2007), Sub-Saharan Africa (SSA) faces numerous problems. The key one is to improve the lives of 30% of its populace that is affected by poverty and food insecurity. Report by Africa Rice Center (2007), formerly referred to as West Africa Rice Development Association - WARDA, reported that South Africa and Mozambique have the highest per capita rice consumption at 14 kg/year. Rice production in the Southern Africa region is inundated by low yield as against Western and Central Africa. Rice importations characterize more than 90% of domestic consumption requirements excluding Zambia and Mozambique. Practically all rice consumed in South Africa is sourced from the international market (Center, 2007).

4.2.3 Irrigation technologies

For rice, irrigation water-saving technologies comprise alternate wetting and drying (AWD) and saturated soil culture-wetting without flooding (WWF) (Bouman *et al.*, 2007). The well-watered conditions with 100% water holding capacity is another irrigation management technique (Ruíz-Sánchez *et al.*, 2011). However, AWD is the most commonly practiced water-saving irrigation management technologies. Generally, AWD irrigation increased water productivity with respect to total water used because the yield reduction compared with CFI was smaller than the amount of water saved (Yao *et al.*, 2012).

The abundancy of municipal treated wastewater at the experimental site is a problem that must be addressed in terms of reuse and disposal. There has not been any reported use or adoption of anaerobic baffled reactor (ABR) effluent with irrigation management techniques in Republic of South Africa (RSA) and other parts of the world. The beneficial use of ABR effluents is more general research activity undertaken by the Pollution Research Group (PRG). The study, therefore aimed to investigate the effect of ABR effluent irrigation management techniques on the growth, yield parameters of rice, water balance (WB) and water productivity (WP). The hypothesis stated that irrigation water management techniques with ABR effluent have a significant effect on the growth, yield of rice, WB and WP.

4.3 Methods

4.3.1 Study site

The experimental site and ABR effluents treatment plant are located at the Agricultural Hub, Newlands Mashu research facility, Durban, South Africa. The site map is displayed in Figure 4.1.

Figure 4.1 General overview of the study area

The site is on Latitude 29^0 46′ 26″ S and Longitude 30^0 58′ 25″ E. It is characterized by an average annual precipitation of 1 000 mm and mean daily temperature of 20.5 ^{0}C. The soil classification was a clayey-loam. The mean monthly temperature, relative humidity and rainfall obtained from the on-site weather station for the growing period are presented in Table 4.1.

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Table 4.1 Average monthly temperature, relative humidity and rainfall for the two seasons at the experimental site

Seasons	Month	Average Temp. (^{0}C)			Relative Humidity (%)			Rainfall (mm)
		Max	Min	Ave.	Max	Min	Ave.	Ave.
Season 1	Oct 17	27.03	15.35	21.19	93.99	47.31	70.65	54.10
	Nov 17	26.64	16.42	21.53	94.15	50.36	72.26	70.44
	Dec 17	28.27	19.39	23.83	94.93	56.96	75.95	86.61
	Jan 18	29.98	20.20	25.09	94.92	54.29	74.60	123.28
Season 2	Feb 18	30.10	19.73	24.91	95.33	53.35	74.34	70.79
	Mar 18	29.80	19.27	24.53	96.76	54.65	75.71	88.73
	Apr 18	28.19	15.98	22.09	95.92	47.05	71.49	12.53
	May 18	27.41	12.67	20.04	96.99	41.88	69.44	75.35
	Jun 18	26.13	9.64	17.88	95.34	33.65	64.49	2.79

The ABR effluent was from domestic source comprising about 83 households within the site. It was a purely domestic unlike industrial effluent which contain heavy metals. Therefore, the issue of heavy metals presence is negligible for irrigation when using treated effluent (Toze, 2006). Table 4.2 below shows the chemical composition of the effluent. Bedbabis *et al.* (2014) reported that treated effluent does not significantly affect some properties of soil and Musazura *et al.* (2015) observed insignificant changes in the physical and chemical properties of soil after irrigation with ABR effluent.

Table 4.2 ABR effluent characteristics

Parameters	Units	Mean	SD	Range
Ammonium - N (NH_4^+ -N)	(mg/L)	58.45	± 0.89	43.73 - 67.57
Nitrite – N (NO_2^--N)	(mg/L)	0.53	± 0.01	0.18 – 1.00
Nitrate – N (NO_3^--N)	(mg/L)	0.30	± 0.07	0.10 – 0.47
Total Kjeldahl N (TKN)	(mg/L)	62.91	± 0.87	46.93 – 76.20
Total nitrogen (TN)	(mg/L)	67.67	± 1.37	53.67 – 76.00
Ortho phosphate (PO_4^{3-}—P)	(mg/L)	18.19	± 0.18	14.80 – 22.23
Chemical oxygen demand (CODt)	(mg/L)	276.60	± 5.03	222.67 – 295.00
Total suspended solids (TSS)	(mg/L)	82.00	± 2.03	67.78 – 123.33
Dissolved oxygen (DO)	(mg/L)	1.37	± 0.05	0.22 – 3.51
Alkalinity	(mg/L)	6.98	± 0.19	5.56 – 7.87
Ecoli	(cfu/ml)	2600.00	± 700.00	2000.00 – 3400.00
pH		7.27	± 0.05	7.19 – 7.38
Electrical conductivity (EC)	S/m	93.22	± 0.83	71.57 – 107.90

Note: cfu is colony forming unit and S/m is Siemens per metre

4.3.2 Experimental design and layout

Experiments were conducted in 2017 and 2018 at two adjacent Fields. Experimental design was randomized complete block design (RCBD) with three replications in both years. The experiments consist of a factor, irrigation water management techniques with three levels of treatments, alternate wetting and drying (AWD), conventional flooding irrigation (CFI) and continuous wetting without flooding (WWF). CFI treatments were used as control for both seasons. Cut-off drains were trenched around the perimeter of the field to prevent surface run-off entering the whole field. The drain collected all the runoff coming from the field, and channelled it to a stilling basin that was dug at the outlet of the cut-off drain. The stilling basin prevented the scouring effect that could cause damage to the adjacent land. The experimental design gave rise to 9 plots of equal size measuring 3 m by 1.5 m each (Figure 4.2). Bunds were established between plots to isolate them from adjacent plots. Bunds (30 cm wide at the base and 20 cm high) were covered with plastic sheeting (250 µm grade) which was buried into the soil with the aid of metal sheeting to a depth of 0.6 m to prevent run-on, run-off, lateral-in and lateral-off in each plot for a proper water balance analysis. Zhang *et al.* (2010b), Tan *et al.*

(2013), Pascual and Wang (2016) suggested 0.5 m, Ye *et al.* (2013) used 0.3 m, while Yao *et al.* (2012) suggested 0.2 m as the depth of inserting plastic sheeting. Inserted in each plot was a 400 mm long and 110 mm diameter PVC observation tube perforated with 5 mm diameter holes at 40 mm intervals. About the half side of the tube was inserted into the field (at least 500 mm away from the bund, 200 mm above and 200 mm below the topsoil) for the monitoring of water table and to instruct when to irrigate as per general recommendations (Bouman *et al.*, 2007; Ye *et al.*, 2013; Lampayan *et al.*, 2015). A measuring tape (metal) was used to measure the water level in the tube.

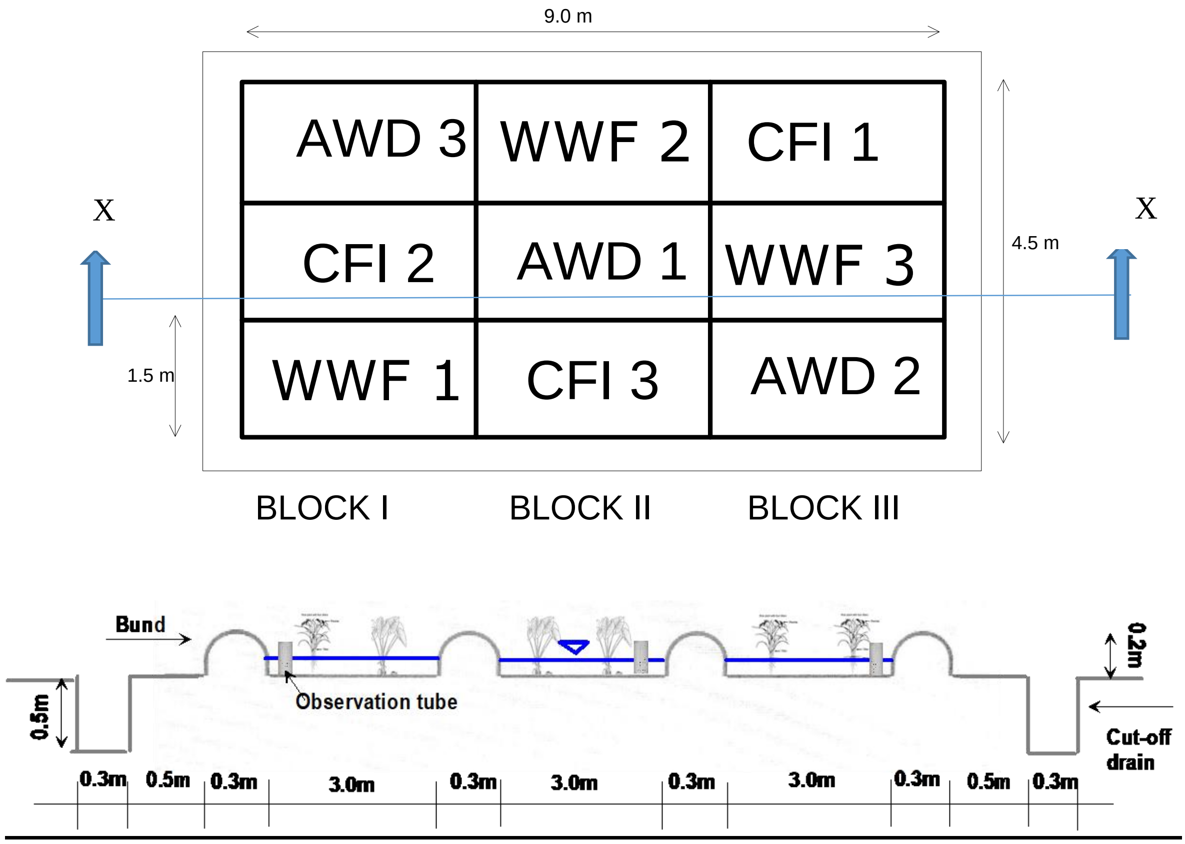


Figure 4.2 Field layout and cross-section X-X

4.3.3 Crop management

The rice variety used for the experiments was FARO 44 lowland adaptation, takes between 110 to 120 days to maturity, has a maximum plant height of 110 cm and average yield of 4.5 to 6.5 t ha^{-1}. Rice was considered for irrigation with the effluent because of its water, nutrients requirement and the need to be cooked before consumption, which reduces health risks on consumers. Prior to sowing, rice seeds were washed and soaked for 24 hours in salty water, following which they were incubated at 30^{O}C for another 24 hours to stimulate strong germination (Mulbah, 2010). Seeds were raised at the seedbed with sowing date of 21

September in 2017 and 19 January in 2018. Transplanting of 3 seedlings was done at age 2 weeks for the 2 seasons at a hill spacing of 25 x 25 cm inter and intra plant spacing. It had 3 rows of 6 plants per row (18 plants per plot) for a plant population of 160,000 plants per hectare. Four inner plants were selected for sampling leaving the border plants. Thinning was done at minimum of 7 and maximum of 14 days after planting to replace dead seedlings. Neither fertilizer nor insecticide were applied but periodic weeding was done.

4.3.4 Irrigation

The field trials were irrigated by basin/flood method with bunds to control run-off. There were networks of PVC pipes (main, lateral and field) with a ball gate control valve and water tap at each plot. Scouring protection (boulders and granites) was placed at the point of discharge into the plots. The depth of irrigation water (pond) was continuously maintained at a depth of 50 mm and stopped at 2 weeks before harvesting for all CFI replications. AWD treatments also maintained an irrigation water pond of 50 mm whenever the ponded water level in the tube has dropped to 150 mm below the surface (Lampayan *et al.*, 2015). The level of water in the tube for WWF plots was the same with the field (well-watered). Measurement of depth and when to irrigate were dictated by observation of water table level in the water observation tube with the aid of an improvised light weight foams (polystyrene). A Campbell Scientific automated weather station (AWS), with a CR 1 000 data logger (Utah, USA) mounted about 12.7 m away from the field trial was used to collect weather data. The AWS measured the total rainfall, reference evapotranspiration (ETo in mm/day) according to FAO Penman-Monteith equation and crop evapotranspiration, ETc, was calculated as a product of ETo and crop coefficient factor, Kc. Figure 4.3 and Figure 4.4 presented the graph of duration of planting versus *ET*o, Kc and ETc throughout the trials for season 1 and 2 respectively. Kc for rice is divided as initial (1.15 for 30 days), development (1.23 for 30 days), mid (1.14 for 60 days) and late stage (1.02 for the last 30 days) for a 150-day rice variety (Tyagi *et al.*, 2000).

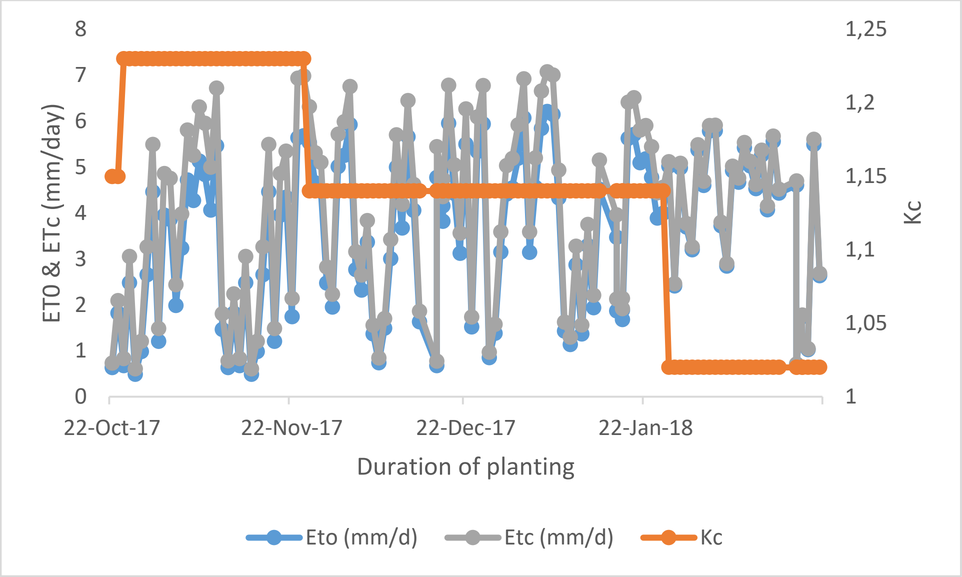


Figure 4.3 Graph of duration of planting versus ETo, Kc and ETc for 2017 planting season

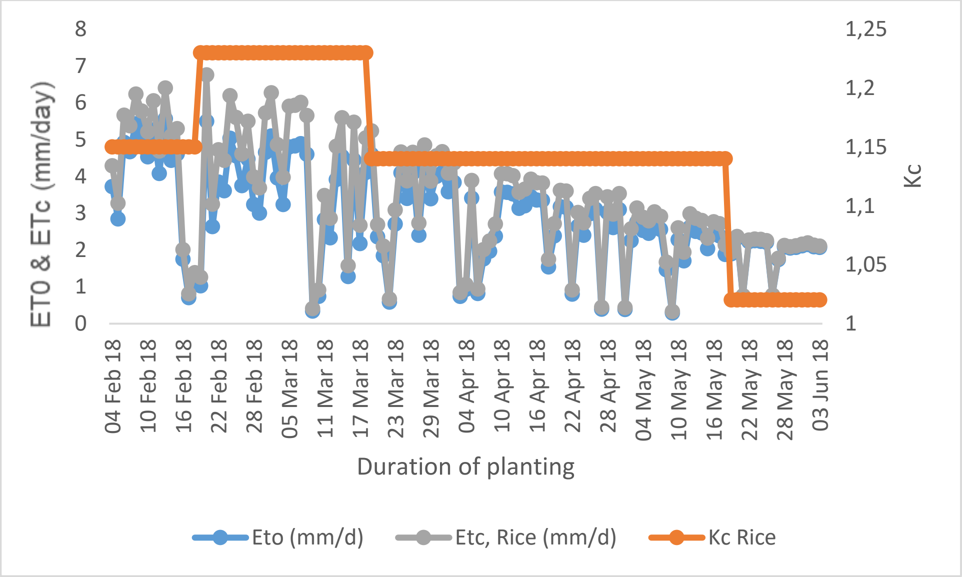


Figure 4.4 Graph of duration of planting versus ETo, Kc and ETc for 2018 planting season

4.3.5 Water saving, water balance and water productivity

Water saving was determined with reference to a particular irrigation water management technique (CFI – control and conventional irrigation for lowland rice) and calculated as Equation 4.1

$$Water\ saving\ at\ AWD\ = \frac{CFI(t)-AWD(t)}{CFI(t)} * 100\% \qquad (4.1)$$

$$Water\ saving\ at\ WWF = \frac{CFI(t) - WWF(t)}{CFI(t)} * 100\% \qquad (4.2)$$

where, water AWD (t), CFI (t) and WWF (t) were the total water used by different treatments (mm).

The water balance in the root zone of the irrigated soil in a given time interval (t) was given as Equation 4.3:

$$\Delta Wt = (I + P + RON + LATON + CR)t - (ET + ROFF + LATOFF + DP)t \qquad (4.3)$$

where ΔWt = changes in soil water storage (mm) over time, t (day),
I = applied irrigation water (mm),
P = precipitation (mm),
RON = run-on to field (mm),
$LATON$ = lateral or seepage flow into the field (mm),
CR = capillary rise from the water table (mm),
ET =evapotranspiration (mm),
$ROFF$ = run-off leaving field (mm),
$LATOFF$ = lateral or seepage leaving field (mm), and
DP = deep percolation below the root zone (mm).

The effect of plastic sheeting between plots changed the equation to Equation 4.4:

$$\Delta Wt = (I + P + CR)t - (ET + DP)t \qquad (4.4)$$

According to Fereres and Connor (2004), deep percolation is negative if capillary rise occurs and Mermoud *et al.* (2005) said rising capillary movement into the root zone results in negative value of deep percolation. Hence, the resultant water balance equation became Equation 4.5

$$\Delta Wt = (I + P)t - (ET)t \qquad (4.5)$$

According to Yao *et al.* (2012), water productivity was defined as the grain yield per unit of total water input including irrigation and precipitation and was calculated as Equation 4.6:

$$Water\ productivity\ = \frac{Grain\ yield}{Water\ use} \tag{4.6}$$

4.3.6 Data collection

Data on the growth parameters were measured weekly from 4 sample plants in each of the 3 replications for all treatments. The height of the individual plant was measured as the distance (m) from the ground level to the shoot apex. The number of tillers and panicles for each plant were determined by direct counting of functional tillers and panicles, respectively. Leaf area indices (LAI) were measured using the LAI-2200C Plant Canopy Analyzer (LI-COR Environmental) throughout the growing seasons. Yield components such as number of filled grains per panicle, weight of 1000 filled grains and grain yield were measured at harvest.

4.3.7 Statistical analysis

Data collected were subjected to normality test using Skewness and Kurtosis for numerical and Normal Q-Q plots for graphical outputs. The two methods showed that data were approximately normally distributed. The Data sets for both seasons were then subjected to statistical analysis of variance (ANOVA) with a least significant difference (LSD) test at the 0.05 probability level using GenStat® 18th edition analytical package of 2016. Where differences in treatment means were significant, means were separated using the Duncan LSD test.

4.4 Results and Discussion

4.4.1 Irrigation

The effects of irrigation water management techniques with ABR effluent were highly significant ($P<0.001$) on numbers of irrigation, amount of irrigation, total water use and daily water balance for both seasons as shown in Table 4.3. There was a significant ($P<0.05$) reduction with respect to number of irrigation events under AWD treatments but an insignificant ($P>0.05$) reduction in treatments WWF when compared with the control (CFI). The amount of irrigation, total water use and WB on the other hand were significantly ($P<0.05$) reduced by both AWD and WWF treatments. AWD and CFI treatments had the lowest and highest values respectively in all the variables measured for both seasons (Table 4.3). The highest quantity of water was recorded under CFI treatments because of the continuous ABR effluent application in order to achieve ponding unlike intermittently application characterised by AWD treatments. The WWF was similar to CFI since water application was also continuous, nevertheless, not to ponding level. The higher the total number of irrigation events, the greater the amount of irrigation and water balance. Irrigation amount or total water use is a key parameters of water balance. The total water use for all the treatments were higher in 2018 season than 2017 season. AWD produced water saving of 38% and 52% for 2017 and 2018 season respectively when compared with CFI without any yield penalty. WWF treatments also saved water but with significant yield reduction The resultant water saving was as a result of intermittent flooding and drying of the rice field. This agreed with the study of Pascual and Wang (2016) which reported water savings of between 50% to 72% for flooded to intermittent drying conditions. Tan *et al.* (2013) reported 16% saving as compared with CFI, Yao *et al.* (2012) noted savings of between 24% and 38% using AWD when compared with CFI, while Bouman *et al.* (2007) reported savings of 200 – 900 mm. The daily water balance showed that the total water used (rainfall and irrigation) was higher than the crop evapotranspiration. The results also showed that the amount of irrigation in 2018 season was higher than 2017 season. The difference compensated the total amount of rainfall that was higher in 2017 season.

Table 4.3 Effects of irrigation water management techniques with ABR effluents

Season	Treatments	Number of irrigation	Amount of irrigation (mm)	Total water use (mm)	Water balance (mm/day)
2017	AWD	18.00 ^{a}	888 ^{a}	1238 ^{a}	5.72 ^{a}
	CFI	63.00 ^{b}	1638 ^{c}	1988 ^{c}	11.85 ^{c}
	WWF	61.00 ^{b}	1468 ^{b}	1819 ^{b}	10.48 ^{b}
	p	***	***	***	***
2018	AWD	21.33 ^{a}	1040 ^{a}	1281 ^{a}	7.17 ^{a}
	CFI	95.00 ^{b}	2453 ^{b}	2694 ^{b}	19.36 ^{c}
	WWF	92.00 ^{b}	2363 ^{b}	2604 ^{b}	18.65 ^{b}
	p	***	***	***	***

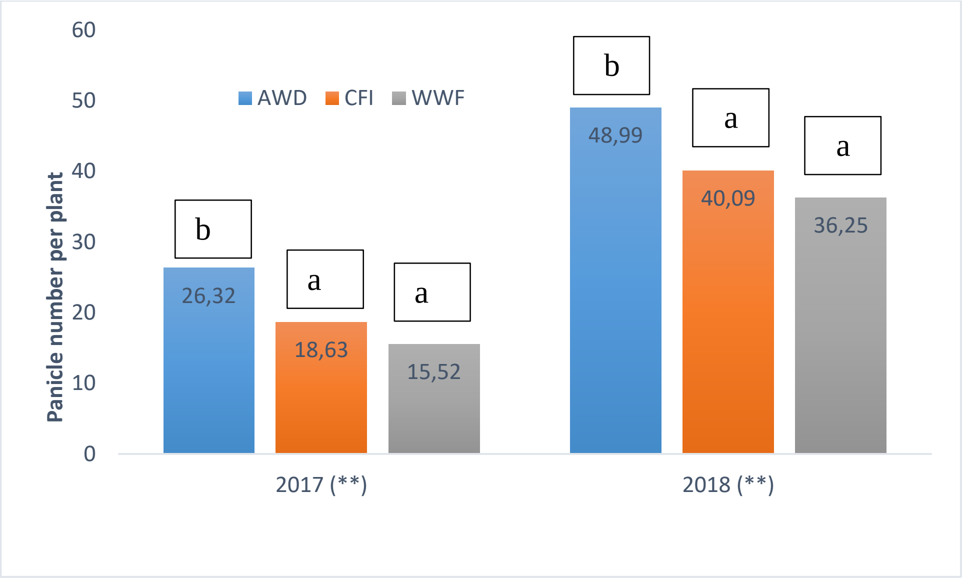
Notes: Means with same alphabets within a column in each season do not differ significantly at 5% level of probability.

p = probability

**** = significant at 0.001 probability level*

4.4.2 Growth parameters

The effects of irrigation water management techniques with ABR effluents on growth parameters of rice are shown in Figure 4.5 and Table 4.4. The effect of irrigation treatments on the number of panicles per plant was significant (P = 0.003) in 2017 and also significant (P = 0.007) in 2018. Further analysis to separate the means showed that means from CFI and WWF treatments were significantly different from means of AWD treatments as shown in Figure 5. The average number of panicles per plant were higher in 2018 than 2017 season. This may be as a result of early birds' invasion at the trial in 2017 before combination of scarecrows were provided.



Notes: Means with same alphabets within a season do not differ significantly at 5% level of probability

*** = significant at 0.01 probability level*

Figure 4.5 Graphical representation of the effects of treatments on growth parameters of rice

Irrigation water management techniques did not significantly affect the plant height in 2017 (P = 0.37) and 2018 (P = 0.65). The plant heights for every treatment were higher in 2018 than in 2017. The lowest heights found in AWD agreed with the study of Fonteh *et al.* (2013), who found that reduced depth of ponding and drying enhances emergence of weed which significantly reduces the height of rice plant. LAI was also not significantly affected with the effects of irrigation treatments in both 2017 (P = 0.69) and 2018 (P = 0.79) seasons. The LAI was higher in treatment AWD than CFI in 2018 and this agreed with the study of Pascual and Wang (2016), who found that LAI under intermittent irrigation is higher than flooded condition. The maximum number of tilers produced per plant was observed in treatments AWD in both seasons. The effect of irrigation water management techniques however had no significant difference (P = 0.41 for 2017 and P = 0.79 for 2018) in number of tillers per plant. The physical inspection of rice at the field did not displayed any sign of growth disorder even at high fertilization rate from ABR effluent. This could be attributable to the fact that irrigated lowland rice like FARO 44 is characterised by a relatively low N-fertilizer efficiency because inorganic N applied is rapidly lost from the field of soil-flood water through volatilization and denitrification (Cassman *et al*., 1996).

Table 4.4 Effects of irrigation water management techniques with ABR effluents on growth parameters of rice for 2017 and 2018 seasons

Season	Treatments	Height (cm)	Leave area index (LAI)	Tiller numbers per plant
2017	AWD	66.32 ^{a}	3.57^{a}	58.51 ^{a}
	CFI	75.53 ^{a}	3.62 ^{a}	52.13 ^{a}
	WWF	70.58 ^{a}	3.32 ^{a}	50.98 ^{a}
	p	*ns*	*Ns*	*ns*
2018	AWD	94.58 ^{a}	4.14 ^{a}	59.36 ^{a}
	CFI	100.94 ^{a}	3.92 ^{a}	56.33 ^{a}
	WWF	97.17 ^{a}	4.15 ^{a}	55.79 ^{a}
	p	*ns*	*Ns*	*ns*

Notes: Means with same alphabets within a column in a season do not differ significantly at 5% level of probability

p = probability

ns (not significant)

4.4.3 Yield components

Table 4.5 present the effects of irrigation water management techniques on the yield components of rice. The effect of irrigation management techniques was significant (P = 0.001 and 0.05) on the number of filled grains per m^2 for both seasons. Further analysis to separate the means of each treatment revealed that the means of number of filled grains per m^2 for treatments AWD and CFI were not significantly different from each other but significantly different from treatment WWF. The effect of irrigation treatments was not significant (P = 0.08) in 2017 and (P = 0.13) in 2018 on number of panicles per m^2. The treatments did not have significant effect, P = 0.70 in 2017 and P = 0.57 in 2018 on the weight of 1000 filled grains. The yield components for both seasons followed the same trend with the exception of number of filled grains per panicle that was significant (P = 0.05) in 2017 but not significant (P = 0.13) in 2018 trials.

Table 4.5 Effects of irrigation water management techniques with ABR effluents on yield components of rice

	Treatments	Number of filled grains per m^2	Number of filled grains per panicle	Number of panicles per m^2	Weight of 1000 filled grains (g)	Grain yield (t/ha)	Water productivity (kg/m^3)
2017	AWD	23556 ^{b}	77.33 ^{b}	305.30 ^{b}	24.13 ^{a}	5.68 ^{b}	0.46 ^{c}
	CFI	21662 ^{b}	80.67 ^{b}	268.70 ^{ab}	24.90 ^{a}	5.39 ^{b}	0.27 ^{b}
	WWF	14990 ^{a}	62.67 ^{a}	240.70 ^{a}	25.69 ^{a}	3.86 ^{a}	0.21 ^{a}
	p	***	*	*ns*	*ns*	**	***
2018	AWD	24862 ^{b}	81.00 ^{a}	307.30 ^{a}	25.63 ^{a}	6.38 ^{a}	0.50 ^{b}
	CFI	23620 ^{b}	84.33 ^{a}	280.00 ^{a}	26.87 ^{a}	6.36 ^{a}	0.24 ^{a}
	WWF	15231 ^{a}	61.33 ^{a}	248.30 ^{a}	26.93 ^{a}	4.12 ^{a}	0.16 ^{a}
	p	*	*ns*	*ns*	*ns*	*ns*	**

Notes: Means with same alphabets within a column do not differ significantly at 5% level of probability, ns (not significant).

** = significant at 0.05 probability level*

*** = significant at 0.01 probability level*

**** = significant at 0.001 probability level*

4.4.4 Grain yield

The effects of irrigation water management techniques on the grain yield of rice for both seasons trials are presented in Table 4.5. The effect of irrigation treatments was found to be significant (P = 0.01) in 2017 but insignificant (P = 0.12) in 2018 season. There was a significant (P<0.05) reduction in the yield of WWF treatments as compared with CFI (control) treatments. However, there was an increase in the yield of rice grain under AWD treatments, though, the effect was not significant (P>0.05). The treatments AWD produced the highest grain yields of 5.68 in 2017 and 6.38 t/ha in 2018 season. Rice grown using AWD irrigation techniques can show higher yield than continuously flooded irrigation (Yang and Zhang, 2010; Zhang *et al.*, 2010b). The higher grain yield in 2018 season could be attributed to the higher amount of nutrients-rich effluent applied to the rice field as compared to 2017 season. Early attack of birds in 2017 before a combination of scarecrows were provided could also contributed to the low yield. The flood and dry cycles experienced under AWD irrigation enhanced air exchange between the soil and the atmosphere, enough oxygen is supplied to the root system to accelerate soil organic matter, which may have contributed to higher and more LAI, tiller numbers, panicle numbers and eventually grain yield experienced in this study. This was in consonant with the findings of Ye *et al.* (2013). AWD promoted higher LAI compared with CFI because continuous or prolonged flooding resulted in lower LAI and crop growth rate (Pascual and Wang, 2016). The result of yield components such as number of filled grains per panicle and 1000 grain weight agreed with the work of Pascual and Wang (2016) and Zhang *et al.* (2010b). FARO 44 (same rice variety with this study) has potential grain yield between 4.0 and 6.0 t/ha (Akintayo *et al.*, 2011). The grain yield of rice produced with the ABR effluent irrigation was averagely good when compared with that of the usual cultivation with fertilizer and rain-fed (FARO 44 varieties) that produced 3.2 t/ha as reported by Akintayo *et al.* (2011). An average yields of 5.86 to 6.86 t/ha and 5.7 to 6.5 t/ha were reported by Oliver *et al.* (2008) and Fonteh *et al.* (2013) respectively. These grain yields were in the range of yields obtained by this study with the application of only ABR effluent without additional organic or inorganic fertilizer. This showed the effect of ABR effluent in the grain yield since they were basically same irrigation methods, similar plant spacing, though different rice varieties and irrigation water. Pascual and Wang (2016) cultivated a fertilized rice field with same irrigation methods and reported higher average yields of 7.46 to 10.46 t/ha. This could be attributable to the effects of fertilizer concentration of 270 kg/ha of NPK (Pascual and Wang, 2016) as against 150 kg/ha applied by Fonteh *et al.* (2013). Nitrogen is the most extensively used input by rice farmers to improve production but over application may reduce potential yield or delaying maturity (Ata-Ul-Karim *et al.*, 2017). The recommended crop nutrient requirements is N 120 kg/ha (Mohammad *et al.*, 2018). The minimum (AWD treatments) N supplied to the rice crop by the effluent amounted to 519 kg/ha which was higher to the N requirements, hence there is no need for extra fertilizer. All the above N fertilizer input recommendation are lesser than that of ABR effluent for this study. The high fertilization of ABR effluent in this study may be responsible for the delay in maturity of the crop and the yield obtained. This was evidenced in this study because FARO 44 was supposed to mature for harvest in 4 months according to the seed supplier but the crop matured at age 5 months. The effects of ABR effluent may have been affected by rainfall at the field trails since it was not covered from receiving rainfall. WP is one of the most important criteria to justify AWD irrigation technology. The effect of irrigation water management techniques was highly significant (P < 0.001) in 2017 and also significant (P = 0.002) in 2018. Each of the treatments were significantly different from one another in 2017. There was no significant different between means of CFI (control) and WWF treatments in 2018, they (CFI and WWF), however, different significantly from the means of AWD as shown in Table 4.5. The features of total water use and WP came out clearly in the study showing the highest WP in treatments AWD for both seasons as compared to treatments CFI. This result was supported by the work of Ye *et al.* (2013).

4.5 Conclusions

The results of this study have shown the effects of ABR effluent irrigation water management techniques on growth and yield of rice crop. The growth and yield parameters of lowland rice crop were improved as a result of irrigation management techniques with ABR effluent. The number, amount of irrigation and total water use were lower in AWD as compared to either CFI and WWF treatments. AWD irrigation was able to save 38 and 52% of water use as compared to treatments CFI in 2017 and 2018 respectively. The value of the water saved by this technique would itself be sufficient to address justification for its adoption in cultivating lowland rice because the saved irrigation water may be used for irrigating other crops or fields. In spite of using much less amount of ABR effluent for irrigation, AWD gave the highest yields of 5.68 in 2017 and 6.38 t/ha in 2018. These yields were obtained with the use of ABR effluent that was free of any additional fertilizer. This could be concluded that submerged paddy field is not necessarily the only solution to optimum rice production. Rice, can therefore, be grown in an anaerobic and aerobic conditions. The daily water balance revealed that the total amount of water (rainfall and irrigation) was in excess of the water lost through evapotranspiration. AWD was found to be the most suitable because of the highest water productivity at both seasons. The hypothesis of having a significant difference on the grain yield, panicle number per plant, water balance, water productivity, number of irrigation, water use should be accepted but rejected on the effect of irrigation water management techniques on plant height, LAI and number of tiller per plant. Rice has been regarded for a very long time as an aquatic plant, but, this conviction has been repeatedly challenged, as rice is known to be capable of growing under both flooded and non-flooded conditions as evidenced in this study and past related studies. Finally, with the effects of climate change and growing competitions for water in this region, therefore, AWD offers an opportunity worth adopting in South Africa, however, further study to investigate the effect of percolation and nitrogen leaching in paddy fields.

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5 THE IMPACT OF IRRIGATION WATER MANAGEMENT TECHNIQUES ON THE PERFORMANCE OF POTTED-RICE USING TREATED WASTEWATER REUSE IN DURBAN, SOUTH AFRICA

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5.1 Abstract

The need to cultivate effluent-irrigated rice is paramount and synonymous to treated wastewater reuse, recycling and water resources management. A trial in a peri-urban set-up with a low-cost decentralized wastewater treatment system (DEWATS) was carried out in 2017 and 2018 cropping seasons to assess the effect of irrigation water reuse management techniques on the yield and water productivity of rice. It was hypothesized that anaerobic baffled reactor (ABR) irrigation water management techniques do not have an effect on the yield of a peri-urban grown rice. The AWD treatments had the highest yields of 2.32 and 3.21 t/ha for 2017 and 2018 seasons, respectively. The effects of irrigation management techniques were highly significant ($P < 0.001$) on number of irrigation, amount of irrigation and daily water balance. However, the effect was not significant ($P > 0.05$) on the number of tillers per plant but significant ($P < 0.05$) on the number of panicles per plant. The effects were not significant ($P > 0.05$) on the plant height but significant ($P < 0.05$) on the yield rice for both trials. The effect was also significant ($P < 0.05$) on water productivity. The result proved that the hypothesis be rejected. It could be concluded that significant potential exists for applying wastewater reuse for non-drinking applications such as irrigation.

keywords: anaerobic baffled reactor (ABR), DEWATS, effluent, peri-urban agriculture, reuse

5.2 Introduction

Several communities in the Republic of South Africa struggle to get dependable and sufficient quantities of fresh water for various water requirements, hence, interest is increasing in the reuse of wastewater for non-drinking water requirements such as irrigation (Adewumi *et al.*, 2010). The push to use less water in agriculture is because of increasing demand generated by the growing population. To counter the continually growing food and fibre requirements of an increasing populace, it is imperative to enhance irrigation water efficiency and also use alternative water sources (water reuse) so as to guarantee sustainable agriculture (Hari *et al.*, 2016). One of the low-cost hygiene technologies which has been effectively used in developing countries is the decentralized wastewater treatment system (DEWATS) that includes an anaerobic baffled reactor (ABR) (Adhanom *et al.*, 2018). Irrigating crops with effluent is important for water reuse, recycling nutrients and which is better than direct discharge into rivers (Musazura *et al.*, 2018). Irrigation with treated sewage effluents constitutes an environmentally sound way of disposing effluents into the environment (de Carvalho *et al.*, 2012). When using domestic treated effluents, heavy metals are of less concern for irrigation because they are basically and effectively removed during common treatment processes. The majority of concentrations in raw sewage end up in the sludge settlement partition (Toze, 2006). No significant effect of treated wastewater on some soil properties (Bedbabis *et al.*, 2014). Musazura *et al.* (2015) also confirmed no significant changes of soil physico-chemical properties over three consecutive seasons after irrigation with ABR effluent. Irrigation water management techniques include alternate wetting and drying (AWD (Bouman *et al.*, 2007). The well-watered conditions with 100% water holding capacity is another irrigation management technique (Ruíz-Sánchez *et al.*, 2011). It is referred to as wetting without flooding (WWF). The continuous flood irrigation (CFI) ensures ponded/flooded field at any time (anaerobic conditions). Rice *(Oriza stiva L.)* is a main staple food for majority of the world’s populace. South Africa has one of the highest per capita rice consumption at 14 kg/year. Basically, international market is the source of all rice consumed in South Africa (Center, 2007). This study therefore aimed at evaluating the performance, in terms of growth, yield and water productivity, of lowland rice grown under different irrigation water management techniques with treated wastewater reuse and recycling (ABR effluent) in a peri-urban environment. It was hypothesized that irrigation water management techniques do not have an effect on the yield of rice grown with treated wastewater reuse.

5.3 Methods

5.3.1 Description of study site

The study area is located at the Agricultural hub, Newland Mashu research facility, Durban, South Africa where the ABR effluent plant is located. The site is on 29^0 46′ 26″ S and 30^0 58′ 25″ E and characterized by mean annual precipitation of 1 000 mm and mean daily temperature of 20.5 ^{0}C. The site description is displayed in Figure 5.1. Eighty-three (83) households were contributing domestic wastewater to the DEWATS. The ABR effluent generated from the DEWATS was allowed to pass through another filter compartments called anaerobic filter (AF). The continuous effluent was stored in a storage tank from which it was piped to the tunnel. The 30 m (L) X 8 m (W) X 4 m (H) tunnel Figure 5.1 was meant to serve as a means of achieving zero effective rainfall on trials.

Figure 5.1 Tunnel house and potted rice plant

5.3.2 Experimental design and layout

The pot trials were conducted from September, 2017 to February, 2018 for first trial (Season 1) and January, 2018 to June, 2018 for trial 2 (Season 2). The trial was laid out in a randomized complete block design (RCBD) with three irrigation water management regimes treatments and three replications each in both years. The three treatments were alternate wetting and drying (AWD), conventional flooding irrigation (CFI) and continuous wetting without flooding (WWF). The CFI treatment was used as control for both seasons. The pots were randomized periodically in the tunnel and blocked with respect to direction of sunlight. The pots used were 20 litres capacity plastic pots, each filled with a 24.8 kg of clayey-loam soil from the adjacent field. Each of the pots served as an experimental unit (EU). A PVC observation tube 400 mm long, 50 mm diameter and perforated with 5 mm diameter holes at 40 mm intervals was inserted in each pot. Half side of the tube was inserted into the pot to monitor water table and instruct when to irrigate (Bouman *et al.*, 2007; Ye *et al.*, 2013; Lampayan *et al.*, 2015). The water level in the tube was measured with the aid of a measuring tape.

5.3.3 Crop management

FARO 44 lowland adaptation rice variety was used for the experiments. It has mean yield of 4.5 to 6.5 t/ha according to the specification from supplier. Seedlings were washed and soaked in salty water for a day. They were then incubated at 30^{O}C for another 24 hours to stimulate strong germination, according to Mulbah (2010). Seedlings were raised in a seedbed with sowing dates of September 21st in 2017 (Season 1) and January 19th in 2018 (Season 2). Transplanting was done on October 8, 2017 (Season 1) and February 4, 2018 (Season 2) at a hill spacing of 35.5 cm x 35.5 cm inter and intra plant spacing, respectively. Thinning was done between age 7 to 14 days after planting to replace dead seedlings. Periodic weeding was done and no additional fertilizer was added. There were no plant diseases identified during the trials, hence, no insecticides were applied. Consideration was given to rice for irrigation with domestic ABR effluent because of its water, nutrients requirement and the need to be cooked before eating, which reduces health risks on consumers.

5.3.4 Water application

The pot trials were irrigated by flood method with a 70 mm freeboard to control run-off. There were networks of PVC pipes and ball gates and water tap at each pot. Splash erosion was prevented by placing a small bowl-shaped container at the point of discharge. The pots were lined with double-plastic black bags (25 µm) to keep water from seeping out of drainage holes at the bottom of the pots. The depth of irrigation was constantly maintained at a depth of 50 mm for all CFI replications. AWD treatments maintained an irrigation depth of 50 mm once the ponded water level in the tube had dropped to 150 mm below the surface (Lampayan *et al.*, 2015). The level of water in the tube was the same with the field (well-watered) pots with WWF treatments. Measurement of depth and when to irrigate were dictated by manual observation of water table level in the water observation tube with the aid of an improvised light weight foams (polystyrene). A Campbell Scientific automated weather station (AWS), with a CR 1 000 data logger (Utah, USA) mounted about 30 m away from the tunnel was used to collect reference evapotranspiration (ETo in mm/day) according to FAO Penman-Monteith equation and actual crop evapotranspiration, ETc, was calculated as a product of ETo and crop coefficient factor, Kc. Kc for rice is divided as initial (1.15 for 30 days), development (1.23 for 30 days), mid (1.14 for 60 days) and late stage (1.02 for the last 30 days) for a 150-day rice variety (Tyagi *et al.*, 2000).

5.3.5 Pot experiments water balance, saving and productivity

The water balance was calculated from Equation 5.1 (adapted from Fereres and Connor (2004))

$$\Delta Wt = (I + P + RON + LATON + CR)t - (ET + ROFF + LATOFF + DP)t \quad (5.1)$$

where ΔWt = changes in soil water storage (mm) over time, t (day),

I = applied irrigation water (mm),

P = precipitation (mm),

RON = run-on to field (mm),

$LATON$ = lateral or seepage flow into the field (mm),

CR = capillary rise from the water table (mm),

ET =evapotranspiration (mm),

$ROFF$ = run-off leaving field (mm),

$LATOFF$ = lateral or seepage leaving field (mm), and

DP = deep percolation below the root zone (mm).

The effect of the tunnel set-up (zero effective rainfall) and pots as medium for planting rice changed the equation to Equation 5.2:

$$\Delta Wt = (I)t - (ET)t \qquad (5.2)$$

Water productivity was defined according to Yao *et al.* (2012) as the grain yield per unit of total water input including irrigation and precipitation, and was calculated as in Equation 5.3;

$$WP = \frac{Y}{TWU} \qquad (5.3)$$

Where, *Y* is the actual harvestable yield in kg/ha and

TWU is the total seasonal water use in m^3.

Water saving was determined with reference to the conventional way of irrigating rice (control treatment in this study) and calculated as in Equation 4:

$$WS_{AWD} = \frac{CFI(t) - AWD(t)}{CFI(t)} * 100\% \qquad (5.4)$$

$$WS_{WWF} = \frac{CFI(t) - WWF(t)}{CFI(t)} * 100\% \qquad (5.5)$$

where,

WS_{AWD} = *water saving for AWD,*
WS_{WWF} = *water saving for WWF,*
AWD (t) = total water applied in treatment AWD (mm),
CFI (t) = total water applied in treatment CFI (mm) *and*
WWF (t) = total water applied in treatment WWF (mm).

5.3.6 Data collection and analysis

Data were collected weekly in each of the 3 replications for all treatments on the growth parameters. The individual plant height was measured as the distance (m) from the base of the plant to the shoot apex. The number of panicles and tillers for each plant were determined by direct counting of functional panicles and tillers, respectively. Leaf area index (LAI) was measured using the LAI-2200C Plant Canopy Analyzer (LI-COR Environmental) throughout the growing seasons. Yield components like number of filled grains per panicle, weight of 1000 filled grains and grain yield were measured. Three samples of harvested grains were randomly taken from each replicate and initial weights were recorded, the final weights were also recorded after oven drying at 70 °C for 72 h; thereafter the grain yield was adjusted to 16% seed moisture content. Three samples of 1000 grains were randomly selected from the harvested grains in each replicate for 1000-grain weight determination. Data were subjected to normality tests (Skewness and Kurtosis and Normal Q-Q plots) and analysis of variance (ANOVA) for a randomized complete block design using GenStat 18th edition (2016) and the Duncan multiple range test at 5% was used to determine differences between treatment means.

5.4 Results and Discussion

5.4.1 Characterization of anaerobic baffled reactor (ABR) effluent

The ABR effluent does not meet the minimum standards for the disposal of wastewater into the environment and water bodies in terms of the chemical oxygen demand (COD) (<400 mg/l), total N (5 – 30 mg/l), EC (0 – 3 dS/m) and the total coliforms. It however met the minimum standard such as in TSS, pH. The chemical oxygen demand test procedure is based on the chemical decomposition of organic and inorganic contaminants, dissolved or suspended in water. This can indicate the ability of water to deplete oxygen and reduce other compounds such as nitrates. The ABR is capable of reducing COD by 86 % (Foxon *et al.*, 2004). Average pH in the ABR was 7.27 and this allows the activity of bacteria to act on the degradation of the organic waste. The minimum pH requirement for irrigation water is 6.5 – 8.4 (Bame *et al.*, 2014). The pH in irrigation water is important as it affects availability of nutrients, irrigation pipes corrosion and quality of crops, especially in sensitive species (Bame *et al.*, 2014). TSS within a water sample is an indication of water that has been reduced in quality. It can be plant debris or soil particles. ABR can reduce about 50% of total solids in the first compartment of DEWATS called sedimentation chamber. TSS can affect soil physical properties, clogging and salinity problems and less than 100 mg/l is recommended.

5.4.2 Water application

The treatment effects of irrigation water management techniques were highly significant ($P<0.001$) on the amount of irrigation water applied, numbers of irrigations and daily water balance for both seasons, as shown in Table 5.1. Further analysis for both seasons showed that the means of each treatments were significantly different from one another on the amount of irrigation water and daily water balance. However, the difference between means of AWD and CFI were not significant on the number of irrigations for both seasons (Table 5.1). The highest and lowest values in all the variables measured for both seasons were for CFI and AWD treatments, respectively. The amount of irrigation water applied for all the treatments were higher in 2018 season than 2017 season. Water saved from AWD treatments were in order of 27% and 22% for 2017 and 2018 season, respectively, as compared to CFI without any significant yield penalty. The WWF treatments also saved water but this was accompanied by significant yield reduction.

Several studies have also reported water savings between intermittent flooding and drying as compared to continuous flooding. Bouman *et al.* (2007) reported savings of 200 – 900 mm, Yao *et al.* (2012) noted savings of between 24% and 38%, Tan *et al.* (2013) reported 16% saving and Pascual and Wang (2016) reported 50 to 72% savings. The subsequent saving was as a result of intermittent flooding and drying of the rice field. The daily water balance showed that the amount of irrigation applied was higher than the crop evapotranspiration. The difference between irrigation applied in 2017 and 2018 was as a result of seasonal difference.

Table 5.1 Effects of irrigation water management techniques on number, amount of irrigation and daily water balance for 2017 and 2018 seasons

Treatments	Number of irrigation		Amount of irrigation (mm)		Water balance (mm/day)	
	2017	2018	2017	2018	2017	2018
AWD	11.00 ^{a}	12.00 ^{a}	498.70 ^{a}	548.00 ^{a}	15.52 ^{a}	15.34 ^{a}
CFI	28.00 ^{b}	31.00 ^{b}	680.00 ^{c}	701.00 ^{b}	21.91 ^{c}	20.87 ^{c}
WWF	27.00 ^{b}	30.00 ^{b}	642.70 ^{b}	660.30 ^{b}	18.87 ^{b}	18.04 ^{b}
p	***	***	***	***	***	***

Notes: Means with same alphabets within a column in each season do not differ significantly at 5% level of probability. *p = probability,* *** *= significant at 0.001 probability level*

5.4.3 Growth parameters

The treatment effects (Table 5.2) did not significantly affect the plant height in 2017 (P = 0.24) and 2018 (P = 0.15). The plant heights were higher in 2018 than in 2017 for all the treatments. The finding was in agreement with the study of Fonteh *et al.* (2013), who found that reduced depth of ponding and drying enhances emergence of weeds significantly which eventually reduces the height of rice plant. AWD treatments have the lowest plant height during both seasons. The effect of irrigation water management techniques was also not significant (P = 0.40) on the LAI in 2017 but was significant (P = 0.02) in 2018. This was deduced from statistical analysis result in Table 5.2. The difference in LAI with reference to the three irrigation management techniques occurred at age 14 and 8 weeks for 2017 and 2018 seasons respectively. These weeks corresponded with the weeks of panicles initiation, respectively, for both seasons. This could be attributed to plant canopies and the atmosphere. Seasonal difference (2017 winter and 2018 summer) could also add to the effect. This translated to the consumption of more nutrient-rich effluent for irrigation in 2018 than 2017. The LAI was higher in AWD treatments than CFI in both potted seasons and this was in consonant with the study of Pascual and Wang (2016), who discovered that LAI under alternating irrigation is higher than under inundated condition. The effect of treatments on the number of panicles per plant was significant (P = 0.004) in 2017 and (P = 0.02) in 2018. The panicles initiation commenced late (13 weeks after transplanting) for 2017 winter season while early (8 weeks after transplanting) in 2018 summer season. The initiations commenced first in AWD treatments at both seasons. The average number of panicles per plant were higher in 2018 than 2017 potted season. The maximum number of tilers produced per plant was observed in treatments AWD in both seasons. However, the effects of potted irrigation water management techniques had no significant difference (P = 0.32 for 2017 and P = 0.09 for 2018) on number of tillers per plant. The flood and dry cycles experienced under AWD improves air exchange between soil and the atmosphere and may have attributed to more tiller and panicle numbers.

Table 5.2 Effects of irrigation water management techniques on growth parameters of rice for 2017 and 2018 seasons

Treatments	Height (cm)		Leaf area index (LAI)		Number of panicles per plant		Number of tilers per plant	
	2017	2018	2017	2018	2017	2018	2017	2018
AWD	70.17^{a}	92.62^{a}	1.40^{a}	2.60^{b}	22.79^{b}	31.92^{b}	36.12^{a}	44.67^{a}
CFI	80.91^{a}	102.22^{a}	1.17^{a}	1.91^{a}	18.38^{a}	27.22^{ab}	34.97^{a}	43.09^{a}
WWF	75.10^{a}	97.84^{a}	1.35^{a}	2.49^{b}	15.75^{a}	24.75^{a}	29.92^{a}	35.53^{a}
p	*ns*	*ns*	*ns*	*	**	*	*ns*	*ns*

Notes: Means with same alphabets within a column in a season do not differ significantly at 5% level of probability. *p = probability, ns (not significant), * = significant at 0.05 probability level, ** = significant at 0.01 probability level*

5.4.4 Yield components

The effect was significant (P = 0.009 and 0.003) on the number of filled grains per m^2 for both seasons (Table 5.3). Comparison test to separate the means of each treatment revealed that the means of treatments AWD and CFI were not significantly different from each other but significantly different from treatment WWF. The effect of irrigation treatments in potted rice was significant (P = 0.02) in 2017 and (P = 0.03) in 2018 on number of filled grains per panicles. The effect was also significant (P = 0.002) in 2017 and (P = 0.001) in 2018 on the number of panicles per m^2. However, the treatments did not have significant effect (P = 0.65) in 2017 and (P = 0.57) in 2018 on the weight of 1000 filled grains. The yield components for both seasons followed the same trend. The yield obtained from the same species of rice (FARO 44) may not be comparable with the result of this study since this was planted in pots though with effluent as fertilizer unlike field result from the seeds supplier. None of the yields obtained were up to the range given by the supplier.

Table 5.3 Effects of effluent irrigation water management techniques on yield components, yield and water productivity of rice for 2017 and 2018 seasons

	Treatments	Number of filled grains per m^2	Number of filled grains per panicle	Number of panicles per m^2	Weight of 1000 filled grains (g)	Grain yield (t/ha)	Water productivity (kg/m^3)
2017	AWD	10295^{b}	48.00^{a}	214.30^{c}	22.55^{a}	2.32^{b}	0.47^{c}
	CFI	9794^{b}	55.67^{b}	175.60^{b}	23.32^{a}	2.28^{b}	0.34^{b}
	WWF	5399^{a}	41.67^{a}	129.30^{a}	24.25^{a}	1.30^{a}	0.20^{a}
	p	**	**	**	*ns*	**	**
2018	AWD	13665^{b}	62.67^{b}	218.30^{b}	23.54^{a}	3.21^{b}	0.59^{c}
	CFI	13026^{b}	63.67^{b}	204.30^{b}	24.78^{a}	3.22^{b}	0.46^{b}
	WWF	6683^{a}	49.67^{a}	134.30^{a}	24.84^{a}	1.65^{a}	0.25^{a}
	p	**	*	***	*ns*	**	***

Notes: Means with same alphabets within a column do not differ significantly at 5% level of probability, *ns* (not significant). * = *significant at 0.05 probability level, ** = significant at 0.01 probability level, *** = significant at 0.001 probability level*

5.4.5 Grain yield and water productivity

The treatment effect (Table 5.3) was found to be significant (P = 0.009) in 2017 and (P = 0.002) in 2018 season. Duncan multiple comparison analysis showed that AWD and CFI were not significantly different from each other but were significantly different from the means of WWF in both seasons. Rice grown using AWD irrigation techniques can show higher yield than continuously flooded irrigation (Yang and Zhang, 2010; Zhang *et al.*, 2010b). The difference in yield obtained could be as a result of higher amount of nutrients-rich effluent applied in 2018. The pond and alternate dry rotations practiced under AWD irrigation boosted air exchange between the soil and the atmosphere, adequate oxygen is supplied to the root system to accelerate soil organic matter, which may be responsible for higher and more tiller numbers, panicle numbers, LAI and eventually grain yield experienced in this study. This was consistent with the results of Ye *et al.* (2013). The result of yield components such as number of filled grains per panicle and 1000 grain weight agreed with the work of Pascual and Wang (2016) and Zhang *et al.* (2010b). The grain yields obtained in both seasons were very low when compared with the yield obtained by other researchers (Oliver *et al.*, 2008; Yang and Zhang, 2010; Fonteh *et al.*, 2013; Pascual and Wang, 2016). This was largely attributed to the use of pots. The yield obtained also was justified with water productivity. The effects of treatment on water productivity was significant (P = 0.005) in 2017 and (P < 0.001) in 2018 season. WP is one of the most important justification for AWD irrigation technology. Each of the treatments were significantly different from one another. The features of WP came out evidently in the study with the highest WP in treatments AWD for both seasons as compared to treatments CFI. This agreed with the findings of Ye *et al.* (2013).

5.5 Conclusions

The results of this study have shown the effects of irrigation water management techniques on growth and yield of rice crop using treated wastewater reuse and recycling. The amount and number of irrigation were higher in CFI and WWF as compared to AWD treatments. AWD saved water compared to treatments CFI in 2017 and 2018 respectively. The yields obtained from AWD and CFI treatments in both seasons were not significantly difference from each other. The yields were obtained with the use of ABR effluent that was free of any additional fertilizer. This could be concluded that submerged rice field is not necessarily the only solution to optimum rice production. Rice can also be grown in a combination anaerobic and aerobic conditions within a peri-urban environment where there is availability of treated wastewater for reuse. AWD irrigation technique proved to be the most appropriate irrigation technology because of its highest water productivity in both seasons without significant yield loss penalty. The hypothesis was rejected. Finally, peri-urban farmers should be encouraged to adopt the use of AWD with ABR effluent because of its water saving advantage without yield penalty.

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5.7 References

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6 ASSESSING THE IMPACT OF INTERCROPPING *COCOYAM* (*COLOCASIA ESCULENTA*) AND RICE (*ORYZA SATIVA L.)* ON YIELD AND LAND PRODUCTIVITY UNDER DIFFERENT IRRIGATION WATER MANAGEMENT TECHNIQUES WITH ANAEROBIC BAFFLED REACTOR (ABR) EFFLUENT WATER IN DURBAN, SOUTH AFRICA

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6.1 Abstract

The need for the optimal use of land without a yield penalty in urban and peri-urban (UP) settlements is vital. The volume of anaerobic baffled reactor (ABR) effluent generated by a decentralized wastewater treatment system (DEWATS) of UP will increase with increasing population, urbanization and improved living conditions. Hence, there is a need to utilize the continuous flow of nutrients-rich effluents productively. This study investigated the effect of intercropping *Cocoyam* (Colocasia esculenta) and rice (Oryza sativa l.) with respect to yield and land productivity when irrigated with ABR effluent under different irrigation water management techniques. It was hypothesized that intercropping with irrigation water management techniques using ABR effluent have no effect on the yield and land productivity of a *Cocoyam*/rice intercrop. Field trials were conducted in 2017 and 2018 cropping seasons with ABR effluent (without fertilizer) at the Newlands Mashu Experimental Site, Durban, South Africa. The experiments were set up in randomized complete block designs with three replications. The cropping treatments were sole *Cocoyam*, sole rice and *Cocoyam* + rice (intercrop). The three irrigation treatments were alternate wetting and drying (AWD), continuous flood irrigation (CFI) and wetting without flooding (WWF). Growth and yield parameters at harvest were determined. Thereafter, land equivalent ratio (LER) was calculated to evaluate productivity of the intercrop. The yields of Cocoyam under intercropping were 4.96 and 6.96 t/ha for 2017 and 2018 seasons while grain yields under intercropping were 0.84 and 1.0 t/ha for 2017 and 2018 seasons. The effect of intercropping was significant ($P<0.05$) on the total number of irrigation and total water use. There was a significant reduction ($P<0.05$) on the plant heights of both *Cocoyam* and rice under intercrop. However, the effect on plant height for treatment CFI was positive but not significant ($P>0.05$) for both seasons. A significant ($P<0.05$) reduction also occurred on the number of *Cocoyam* leaves per plant, number of panicles per plant and number of tillers per plant for rice. Intercropping significantly reduced ($P<0.05$) the *Cocoyam* corm and rice grain yield over the two seasons as compared to sole cropping. The LER showed that intercropping *Cocoyam* with rice was not productive ($LER < 1$) than sole cropping of *Cocoyam*. It was concluded that over the two season period, intercropping *Cocoyam* and rice was not productive under any of the three irrigation management techniques applied and the study hypothesis is thus rejected.

Keywords: ABR effluent, intercropping, irrigation management techniques, land equivalent ratio (LER), Cocoyam, wetting without flooding (WWF).

6.2 Introduction

Agriculture in the future must produce more food from a reduced area of land through more effective use of resources with a negligible effect on the environment so as to satisfy the demand and need of the growing population (Hobbs *et al.*, 2008). Intercropping is an old practice that is placed on the fringes of a 'modern agriculture' controlled by large areas of sole-cultured, resource-consuming and high-yielding crops (Zhang *et al.*, 2010a; Yang *et al.*, 2011; Brooker *et al.*, 2015). Intercropping is when two or more crop varieties are planted concurrently in a field during a growing season. Nevertheless, intercropping could be a means of addressing some of the main problems related to modern farming, such as, reasonable yield, pathogen and pest accumulation, environmental deterioration and degradation of soil (Rusinamhodzi *et al.*, 2012; Brooker *et al.*, 2015) thereby promoting more sustainable and productive agriculture (Dordas *et al.*, 2012). Crops with low yields caused by continuous sole-cropping and declining soil status in smallholder agricultural fields of sub-Saharan Africa have resulted in a search for sustainable production practices accompanied with better resource use efficiency (Ngwira *et al.*, 2012). This does not necessarily mean that crops can be planted simultaneously, but for two or more crops to be together in one field, throughout their growing season or in a timeframe. It is therefore possible to plant at different times (Dariush *et al.*, 2006; Mousavi and Eskandari, 2011). The intercropping strategy could consist of a combination of annuals-annual, annuals-perennial, or perennials-perennial crops (Eskandari, 2012). According to Mousavi and Eskandari (2011), intercropping is categorized as row, mixed, strip and relay. The advantages of intercropping over the sole-cropping include conservation of soil, promotion of resistance to lodging, yield advantage and control of weeds (Takim, 2012). Successful intercropping must take into consideration the maturity date of crop, plant compatibility, planting density (plant architecture) and time of planting (Seran and Brintha, 2010).

6.2.1 Wastewater in irrigation

The adoption of wastewater for irrigation is gradually being considered as a technical solution to reduce degradation of soil and for restoration of nutrient content of soils. The demand for fresh water is increasing, therefore, higher quality water is conserved for domestic use whereas that of lesser quality is suggested for irrigation. Municipal wastewater is considered an attractive source for irrigation because it is less expensive and is considered a sound way of wastewater disposal practice which helps to reduce pollution (Al-Rashed and Sherif, 2000). Furthermore, it is a valuable source of organic matter and plant nutrients necessary for maintaining fertility and productivity. Nevertheless, water reuse for irrigation may possibly generate environmental problems when not properly managed (Kiziloglu *et al.*, 2008). Appropriate water management for irrigation is of utmost importance to preserve water resources both quantitatively and qualitatively in order to make more food with the available water (Mermoud *et al.*, 2005). Anaerobic baffled reactor (ABR) play a role in wastewater treatment and recycling by its creative construction and outstanding performance (Zhu *et al.*, 2015). The decentralize wastewater treatment systems (DEWATS) is widely used in both developing and developed countries. It works with little or no energy, is reliable, robust and buffers shock loads, it produces limited sludge, the operation and maintenance (O & M) do not require highly skilled personnel, the O & M is low, the risks associated with system failure is reduced and it increases wastewater reuse opportunities (Singh *et al.*, 2009). ABR effluent contains mineral elements such as phosphorus and nitrogen, which are significant for plant growth and there could be eutrophication and loss of aquatic life when the effluent is emptied into water bodies. Effluents from ABR have proved to meet the requirements for irrigation with regard to the removal of organics such as BOD or COD for reuse (recycling) in agriculture. The rich contents of nutrients such as ammonia and phosphorous present in the effluents may be suggested as a valuable resource from an agricultural perspective (Musazura *et al.*, 2015). Heavy metals are of lesser concern for irrigation when using treated domestic effluent as a source of recycled water because they are basically and effectively removed during common treatment processes. The majority of concentrations in raw sewage end up in the sludge settlement partition (Toze, 2006).

6.2.2 Irrigation water management techniques

Irrigation water management techniques such as alternate wetting and drying (AWD) is a water-saving irrigation techniques which aim to reduce the total amount of irrigation applied in a season. This is done by optimizing the frequency, duration and intensity of irrigation applications in a way that crop productivity is not endangered by the decrease in total irrigation water (Moya *et al.*, 2004). Irrigated fields with a ponding water layer of between 5 to 15 cm during the growing season is referred to as conventional flood irrigation (Bindraban *et al.*, 2006). The 100 % saturated conditions is another irrigation management techniques (Ruíz-Sánchez *et al.*, 2011). It is referred to as wetting without flooding (WWF).

Cocoyam is a relegated tuber food crop. Its neglect resulted in food insecurity; consequently, its production will play an important role in contributing to food security (Kamwendo and Kamwendo, 2014). It occupied 14th position as the most consumed vegetable globally, yet, it received very inadequate scientific research attention from either agricultural or academic institutions and is therefore classified as a neglected and an underutilized crop species (Kamwendo and Kamwendo, 2014; Tumuhimbise, 2015). Rice, family of gramineae (grass), is the major source of food for half of the world's populace, this includes thousands of families in Sub-Saharan Africa (SSA) and it is also the principal water user in agriculture (Lampayan *et al.*, 2015). Importation takes about 40% of rice consumed in Africa. This exposed Africa seriously to global market shock or food crisis (Seck *et al.*, 2010).

There are no reported studies investigating the effect of irrigation water management techniques using ABR effluent on the growth and yield of either *Cocoyam* or rice. There is also no report of an intercrop of *Cocoyam* with rice under irrigation water management techniques in terms of yield and land productivity using abundant treated domestic effluent. Hence, the need for this study. This study therefore, evaluated the impact of intercropping *Cocoyam* and rice on the growth, yield and land productivity under different irrigation water management techniques with ABR effluent water. It was hypothesized that irrigation water management techniques with ABR effluent do not have an effect on the yield and land productivity of intercropped *Cocoyam* and rice.

6.3 Methods

6.3.1 Site description

Field trials were carried out at Newlands-Mashu Research site (29° 46′ S and 30° 58′ E), located at Newlands East, Durban, KwaZulu-Natal Province, Republic of South Africa (Figure 6.1).

Figure 6.1 Description of the study area

The trials were carried out over two seasons (2017 winter and 2018 summer). The soil classification was a clayey-loam. It is a humid subtropical climate with hot and humid summers and pleasantly warm and dry winters, which are snow- and frost-free. It has an annual rainfall of 1009 mm. The average temperature in summer ranges around 24°C, while in winter the average temperature is 17°C (Table 6.1).

Table 6.1 Average temperature, relative humidity and rainfall at the experimental site

Month	Average Temp. (°C)			Relative Humidity (%)			Rainfall (mm)
	Max	Min	Ave.	Max	Min	Ave.	Ave.
Sept., 2017	25.58	14.12	19.85	94.27	48.22	71.25	30.36
Oct., 2017	27.03	15.35	21.19	93.99	47.31	70.65	54.10
Nov., 2017	26.64	16.42	21.53	94.15	50.36	72.26	70.44
Dec., 2017	28.27	19.39	23.83	94.93	56.96	75.95	86.61
Jan., 2018	29.98	20.20	25.09	94.92	54.29	74.60	123.28
Feb., 2018	30.10	19.73	24.91	95.33	53.35	74.34	70.79
Mar., 2018	29.80	19.27	24.53	96.76	54.65	75.71	88.73
Apr., 2018	28.19	15.98	22.09	95.92	47.05	71.49	12.53
May, 2018	27.41	12.67	20.04	96.99	41.88	69.44	75.35
June, 2018	26.13	9.64	17.88	95.34	33.65	64.49	2.79
July, 2018	24.98	7.92	16.45	93.98	29.55	61.77	2.54

6.3.2 Planting material

The *Cocoyam* landrace from Umbumbulu rural district (29°36′S; 30°25′E) in KwaZulu-Natal Province, South Africa and rice seeds, FARO 44 were planted. *Cocoyam* was planted in July 2017 (season 1) and in December 2017 (season 2) while rice was planted in September 2017 and February 2018 for season 1 and 2, respectively. *Cocoyam* seedlings raised with freshwater for two months, were later transferred and transplanted into the prepared field. Seedlings were washed and soaked in salty water for a day. They were then incubated at 30^{O}C for another 24 hours to stimulate strong germination, according to Mulbah (2010). Seedlings were raised in a seedbed for fourteen days. The rice seeds were later transplanted to join standing *Cocoyam* on the same plots at two weeks after planting. Relay intercropping was adopted in order not to allow for competition since *Cocoyam* has large heart-shaped leaves that may affect the growth of a grass family crop like rice. The intercropping was 1:1 (1 row of *Cocoyam* to 1 row of rice). The intercrop spacing was 0.5 m while intra-crop spacing was 0.5 for *Cocoyam* and 0.25 m for rice. This gave rise to population of 40,000 plants per hectare for rice and for *Cocoyam*. Periodic weeding was done and no additional fertilizer was added since ABR effluent contains nutrients such as ammonia and phosphorous. There were no plant diseases identified during the trials, hence, no insecticides were applied. Different scarecrows were used in order to prevent birds' invasion against rice.

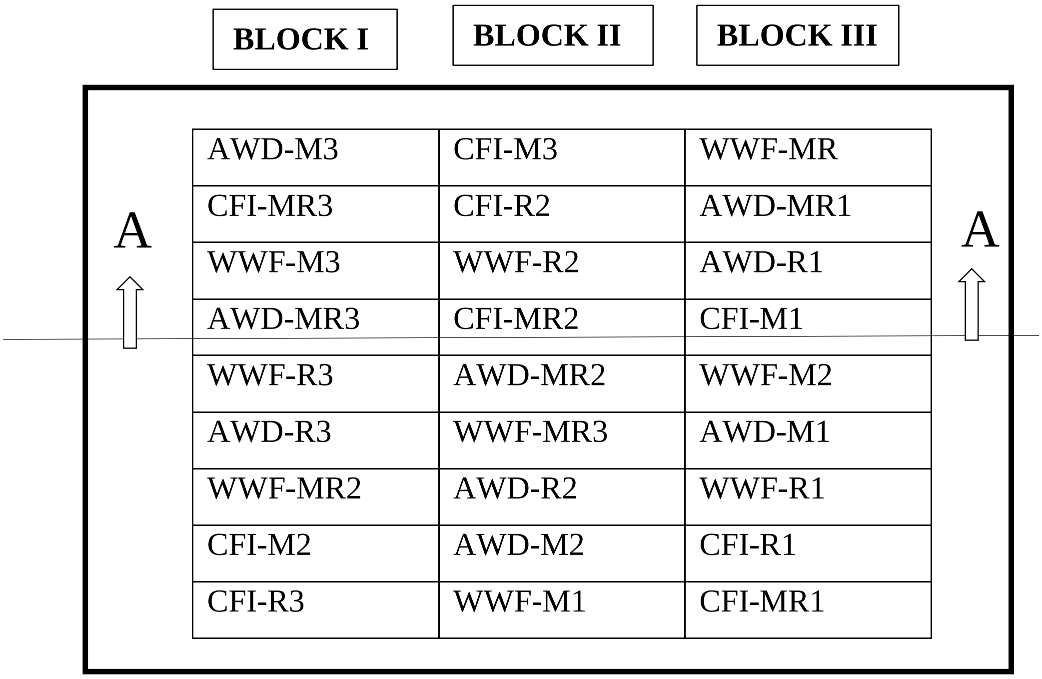
6.3.3 Experimental design

The experiments (both seasons) were laid out in a randomized complete block design (RCBD), replicated three times. Randomization was done using *Kutools for Excel* software to avoid bias (Kutools, 2017). The component crops were *Cocoyam* and rice. The treatments included *Cocoyam* and rice sole crops each, and intercrop. The treatments combination is presented in Table 6.2.

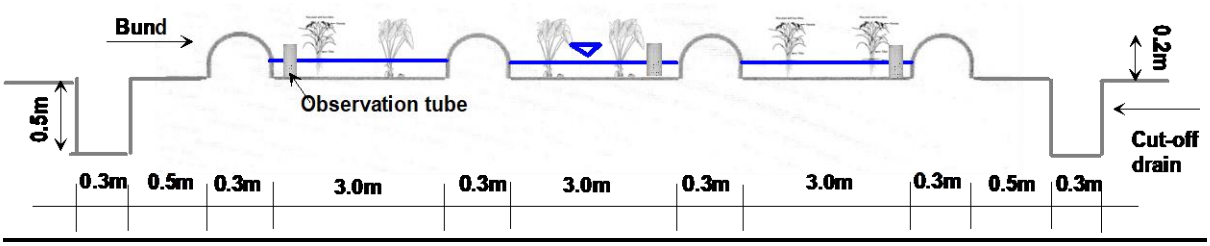
Table 6.2 Treatments combination

S/N	Treatment Code	Treatments Detail
1	AWD-M	Alternate wetting and drying with *Cocoyam*
2	AWD-R	Alternate wetting and drying with Rice
3	AWD-MR	Alternate wetting and drying with *Cocoyam* and Rice
4	CFI-M	Continuous flooding with *Cocoyam*
5	CFI-R	Continuous flooding with Rice
6	CFI-MR	Continuous flooding with *Cocoyam* and Rice
7	WWF-M	Wetting without ponding with *Cocoyam*
8	WWF-R	Wetting without ponding with Rice
9	WWF-MR	Wetting without ponding with *Cocoyam* and Rice

The experimental plots were 3 m×1.5 m. This resulted in a total of 27 plots (Figure 6.2) in the field with 9 plots in a row (block). Each of the plots was separated by bunds (30 cm wide at the base and 20 cm high) to isolate them from adjacent plots and to prevent run-on, run-off, lateral-in and lateral-off in each plot. To prevent seepage, polythene sheets (250 µm thickness) were pushed into the soil to a depth of 0.6 m and also covered the bund. The 0.6 m depth was adopted given consideration to the root zone depth of *Cocoyam* (0.5 m) and rice (0.2 m), though, Tan *et al.* (2013), Zhang *et al.* (2010b), Pascual and Wang (2016) suggested 0.5 m, Ye *et al.* (2013) used 0.3 m, while Yao *et al.* (2012) suggested 0.2 m as the depth to bury the plastic sheeting.



BLOCK I	**BLOCK II**	**BLOCK III**
AWD-M3	CFI-M3	WWF-MR
CFI-MR3	CFI-R2	AWD-MR1
WWF-M3	WWF-R2	AWD-R1
AWD-MR3	CFI-MR2	CFI-M1
WWF-R3	AWD-MR2	WWF-M2
AWD-R3	WWF-MR3	AWD-M1
WWF-MR2	AWD-R2	WWF-R1
CFI-M2	AWD-M2	CFI-R1
CFI-R3	WWF-M1	CFI-MR1



Cross-section A - A

Figure 6.2 Layout of the field trials (above) and cross-section A-A (below)

PVC pipes of 110 mm in diameter and 400 mm in length were installed in the field keeping 200 mm above the soil and the remaining 200 mm which was perforated with 16 mm diameter holes at 40 mm intervals (Figure 6.3) underneath to measure the depletion of irrigation water in the field and to instruct when to irrigate (Oliver *et al.*, 2008; Cabangon *et al.*, 2011; Price *et al.*, 2013; Ye *et al.*, 2013; Lampayan *et al.*, 2015). Irrigation water was applied through a network of pipes that was installed in the trial field to facilitate easy irrigation application and measurement. The network contained PVC pipes and fittings of different diameter sizes ranging from 15 to 25 mm. Water applied in each plot was measured by the level of water inside the observation tube wells (Figure 6.3) inserted in each plot. This is dictated by manual observation of water level in the water observation tube with the aid of an improvised light weight foams (polystyrene). The amount of rainfall was obtained from the on-site weather station. Irrigation water was applied when depleting water table inside the pipe reached a certain level. The CFI was continuous submergence (50 mm standing water), AWD stood for an application of 50 mm irrigation water depth when water level in the pipe fell 150 mm below the ground level. WWF maintained the same water level in the observation pipe with the ground level of the field plots.

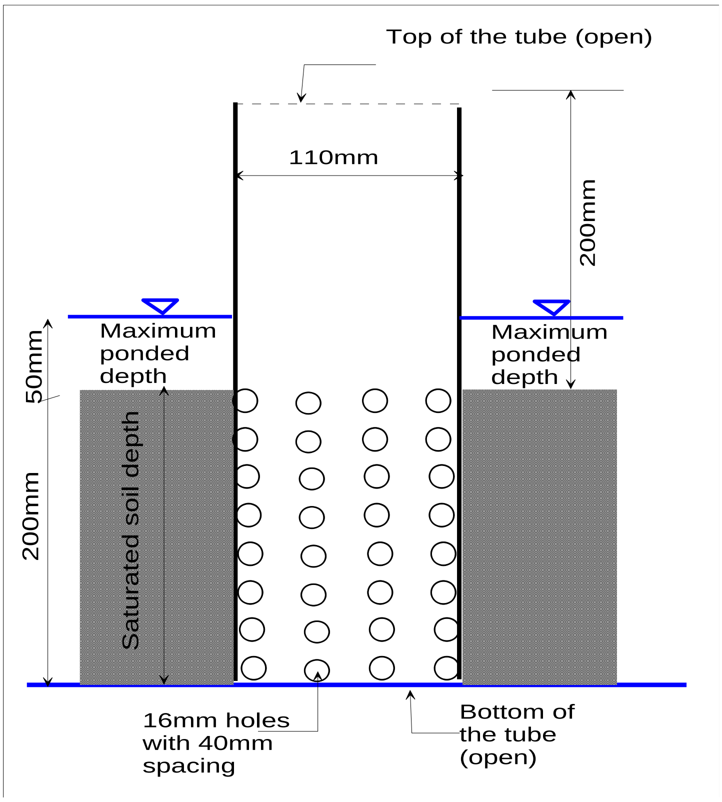


Figure 6.3 Field water tube/observation well (adopted from Lampayan *et al.* (2015))

6.3.4 Data collection and analyses

Quantitative information related to number of irrigation time events, amount of irrigation applied (mm), total water use (irrigation plus rainfall - mm), plant height (cm), number of leaves per plant, corm yield (t/ha) for *Cocoyam*, plant height (cm), number of tillers per plant, number of panicles per plant at harvest, grain yield (t/ha) for rice were collected and analyzed for both seasons to obtain the effect intercropping and irrigation water management techniques with the use of ABR effluent as irrigation water. The plant height for both crops were measured with the aid of a scale rule while leave number, tillers and panicles number per plant were counted manually. Yield of *Cocoyam* was determined according to the method described by Gebre *et al.* (2015). Three samples of harvested rice grains were randomly obtained from each replication; initial weights were recorded. The final weights were recorded after oven drying at 70°C for 72 h; subsequently, the grain yield was then adjusted to 16% seed moisture content. Land productivity of the intercrop was determined using the Land Equivalent Ratio (LER) as described by Mead and Willey (1980), Ibeawuchi (2007) and Chimonyo *et al.* (2016):

$$LER = L_A + L_B = \frac{Y_A}{S_A} + \frac{Y_B}{S_B} \qquad (6.1)$$

Where L_A and L_B are the partial LERs of *Cocoyam* and rice, respectively, Y_A and Y_B are the intercrop yields of *Cocoyam* and rice, respectively, and S_A and S_B are their respective sole crop yields. When the LER is greater than one, it signals yield advantage, and a ratio of less than one is a yield disadvantage. Data were subjected to normality test using both Skewness and Kurtosis for numerical outputs and Normal Q-Q plots for visual outputs. The two methods showed that the variables are within the limits of the confidence interval, which is an indication that they were approximately normally distributed. The data was then analyzed using the analysis of variance (ANOVA) algorithm in GenStat® (Version 18) (VSN International Ltd, UK). Duncan's Multiple Range Test (DMRT) was used for mean separation at the 5% level of significance.

6.4 Results and Discussion

6.4.1 Characterization of anaerobic baffled reactor (ABR) effluent

ABR effluent does not meet the minimum standards for its disposal into the environment and water bodies with reference to chemical oxygen demand (COD) (<400 mg/l), total N (5 – 30 mg/l), EC (0 – 3 dS/m) and the total coliforms. It however, proved to be constantly meeting the required standard for irrigation with regard to the removal of organics such as COD for reuse in agriculture. The COD indicates the ability of water to deplete oxygen and reduce other compounds such as nitrates. The average pH in the ABR was 7.27 and allows the activity of bacteria to act on the degradation of the organic waste. The range of 6.5 to 8.4 is the minimum pH requirement for irrigation water. The pH level in irrigation water is important because it affects nutrients availability, corrosiveness on irrigation pipes and crop quality, especially in sensitive species (Bame *et al.*, 2014). Total soluble solids (TSS- plant debris or soil particles) within a water sample is a symptom of water with reduced quality. TSS can affect physical properties of soil, salinity problems and clogging. The concentration was 82 mg/l and concentration less than 100 mg/l is recommended.

6.4.2 Irrigation and water use

The effect of intercropping was significant (P<0.05) on the number of irrigation events, amount of irrigation and total water use for both 2017 and 2018 growing seasons (Table 6.3). The effect of irrigation water management techniques was also significant (P<0.05) on the number of irrigation events, amount of irrigation and total water use for both seasons (Table 6.3). The number of times of irrigation were more in intercropping as against sole cropping. Number of times of irrigation increased from sole to intercropping by 28% for AWD, 15% for CFI and 17% for WWF in 2017 while it increased by 21% (AWD), 6% (CFI) and 2% for WWF in 2018 season. Treatments AWD had the lowest number of irrigation and total water use (irrigation and rainfall) and CFI had the highest number of irrigation and total water use for both seasons. There was increase in the total water use when comparing sole with intercropping. This was also confirmed with reference to different irrigation management techniques.

Table 6.3 Effect of intercropping on number of irrigation events, amount of irrigation and total water use under different irrigation water management techniques using ABR effluent.

Season	Treatments	Number of irrigation events	Amount of irrigation (mm)	Total water use (mm)
2017	AWD-M	18.00a	847.00a	1197.00a
	AWD-MR	25.00b	1194.00b	1544.00b
	CFI-M	66.67d	1684.00c	2034.00c
	CFI-MR	78.67f	2221.00e	2571.00e
	WWF-M	63.00c	1540.00c	1891.00c
	WWF-MR	75.67e	2004.00d	2354.00d
2018	AWD-M	31.00a	1498.00a	1743.00a
	AWD-MR	39.00b	1949.00a	2194.00a
	CFI-M	135.00cd	3952.00cd	4197.00cd
	CFI-MR	143.00e	4414.00d	4659.00d
	WWF-M	134.00c	3290.00b	3535.00b
	WWF-MR	137.30d	3745.00bc	3990.00bc

Numbers with different letters in the same column and treatment within a season differ significantly at the 5% level of significance.

6.4.3 Growth of *Cocoyam*

The plant height of *Cocoyam* for both seasons was negatively affected significantly (P<0.05) by intercropping. However, the effect on plant height at harvest for treatment CFI was positive, though, not significant (P>0.05) for both seasons (Table 6.4). The number of leaves per plant was also negatively affected significantly (P<0.05) by intercropping. The plant height at harvest for *Cocoyam* under intercropping resulted in about 17% reduction for AWD and 6% reduction for WWF in 2017 season while it was 24% reduction for AWD and 14% reduction for WWF in the 2018 planting season as against the result of sole cropping. However, there was an exception for treatment CFI, where there were 11% and 2% increases in 2017 and 2018, respectively. This could be attributed to continuous ponded condition plus intercropping which do not permit weed growth (Takim, 2012). *Cocoyam* is sensitive to weed competition over most of its growing cycle (Gurnah, 1985). The effect of intercropping also reduced the number of leaves per plant (*Cocoyam*) when compared with sole cropping. The reductions were in the order of 21% (AWD), 13% (CFI) and 6% (WWF) in 2017 planting season. There was a slight difference in 2018 when the reductions were in order of 18% (AWD), 17% (CFI) and 25% (WWF). The two seasons exhibited similar trend under same irrigation technique. The results obtained in this study are consonant with the findings of Mabhaudhi and Modi (2014).

Table 6.4 Effect of intercropping on growth of *Cocoyam* under different irrigation water management techniques using ABR effluent.

Season	Treatments	Plant height (cm)	Number of leaves/plant
2017	AWD-M	99.80bc	14.44bc
	AWD-MR	82.90a	11.72a
	CFI-M	101.80bc	14.78c
	CFI-MR	115.30c	13.38b
	WWF-M	103.70bc	14.89c
	WWF-MR	98.30b	14.05bc
2018	AWD-M	114.70bc	11.44b
	AWD-MR	87.40a	9.38a
	CFI-M	116.80c	11.56b
	CFI-MR	118.80c	9.71a
	WWF-M	118.30c	11.56b
	WWF-MR	101.30ab	9.16a

Numbers with different letters in the same column and treatment within a season differ significantly at the 5% level of significance

6.4.4 Growth of rice

Intercropping had a negative significant effect ($P<0.05$) on plant height, panicles number per plant and tillers number per plant, rice in the intercrop was shorter and had fewer panicle and tiller numbers compared with the sole crop (Table 6.5). The plant height of rice had an about 38.5% reduction when compared with the plant height of rice as a sole crop at harvest for both seasons. The reduction in number of tillers per plant ranges between average of 75% (2017) to 64% (2018 season). The number of panicles per plant at harvest reduced by 78% in 2017 and 84% in 2018 season due to intercropping. Intercropping in this study resulted in shorter plant heights, fewer leaf numbers per plant, tiller numbers per plant and number of panicles per plant compared with sole cropping. The work of Sagoe *et al.* (2004), to the contrary, found that rice plant height and tillers were higher in the rice-taro intercrop under tropical (Ghana) climate characterized with wet and dry season of a typical West African country. This could be as a result of so many factors such as species of components crops, types of intercropping, seasons, method of irrigation, nature of soil, and nutrients contents in the water. The results of the present study may have suggested inter-species competition for resources such as space, light and nutrients (Mabhaudhi and Modi, 2014). There could also be possible effect of leaf architecture (shading) on rice from the adjacent *Cocoyam* plants with broad-heart shaped leaves.

Table 6.5 Effect of intercropping on growth of rice under different irrigation water management techniques using ABR effluent.

Season	Treatments	Plant height (cm)	Number of tillers/plant	Number of panicles/plant
2017	AWD-R	107.08b	113.08d	38.75c
	AWD-MR	67.08a	28.50b	8.67a
	CFI-R	121.33c	91.58c	29.08b
	CFI-MR	74.08a	26.42b	6.67a
	WWF-R	110.33b	90.83c	24.75b
	WWF-MR	69.75a	20.33a	5.25a
2018	AWD-R	122.80b	83.42c	61.42c
	AWD-MR	72.60a	33.69b	11.03a
	CFI-R	131.00b	79.75c	51.75b
	CFI-MR	77.50a	29.53b	7.92a
	WWF-R	125.30b	79.50c	47.42b
	WWF-MR	74.20a	22.96a	6.55a

Numbers with different letters in the same column and treatment within a season differ significantly at the 5% level of significance.

6.4.5 Yield and intercrop productivity

Intercropping had significant reduction ($P<0.05$) with respect to corm yield and grain yield of both component crops in both seasons (Table 6.6).

Table 6.6 Effect of intercropping on the yield of *Cocoyam*/rice under different irrigation water management techniques using ABR effluent.

Season	Treatments	*Cocoyam* corm yield (t ha^{-1})	Rice grain yield (t ha^{-1})
2017	AWD	5.02c	5.62c
	AWD-MR	4.20b	1.20a
	CFI	3.96b	5.39c
	CFI-MR	3.29a	1.18a
	WWF	7.52d	3.86b
	WWF-MR	4.96c	0.84a
2018	AWD	7.34e	6.38c
	AWD-MR	4.46b	1.67a
	CFI	5.61c	6.36c
	CFI-MR	2.73a	1.51a
	WWF	9.84f	4.12b
	WWF-MR	6.96d	1.00a

Numbers with different letters in the same column and treatment within a season differ significantly at the 5% level of significance.

The study showed that mono cropping of either component crops consistently yielded higher than intercropping. This study showed that mono cropping of *Cocoyam* consistently yielded more than *Cocoyam*-rice intercrop, this is in agreement with the research of Sagoe *et al.* (2004) that found that final taro yields were reduced in the rice-taro intercrop. There was no competition for resources such as ABR effluent-water, space and light in the *Cocoyam* sole cropping as compared to intercrop. The two crops (tuber and grass family) are both water and nutrients loving crops, which could lead to resource competition, hence, may be the reason for the negative effect on the yield of both crops at intercrop. One of the criteria for intercropping is to determine if the yield of the main crop will not be affected (Mabhaudhi and Modi, 2014). This criterion assumed that any yield from the second crop is acceptable. This study sought to determine if intercropping *Cocoyam* with rice would not affect *Cocoyam* yield, therefore, any yield of rice achieved would be considered acceptable. The yield of rice obtained in all cases in the intercrop (Table 6.6) were not comparable to results of rice as a stand-alone crop. The results are in tandem with the result of Sagoe *et al.* (2004) that reported reduced yield of rice in the rice-taro intercrop. Introducing rice reduced total taro yield by about 24%-32% (Sagoe *et al.*, 2004). Row intercropping adopted by Okwuowulu *et al.* (2000) enhanced higher relative yield totals of Cocoyam (*Cocoyam*) for the two varieties used but reduced the yield of rice in combinations. The result of this study was also consonant with the work of Enesi *et al.* (2018), that said intercropping of tuber (yam) with grass (maize) reduced tuber yield by an average of 40% over three years across all yam densities. Maize grain yield was greater in mono crop but reduced in intercropping.

The productivity of the intercrop was evaluated using the LER and the result are presented in Table 6.7. This study showed that intercropping *Cocoyam* with rice does not signify a better combination option since the average LER over the two seasons was less than one. This was unlike the LER obtained by Sagoe *et al.* (2004) which signified a better choice in terms of land resource use. When LER is greater than 1 or more it signals yield advantage, and a ratio of less than 1 is a yield disadvantage (Ibeawuchi, 2007). Other benefit of intercropping, such as less weeding as compared to mono cropping, were more visible at the site during the experimental trials.

Table 6.7 LER under different irrigation management techniques using ABR effluent.

Treatments	LER 2017	LER 2018	Average LER
AWD	1.05	0.87	0.96
CFI	1.05	0.72	0.89
WWF	0.88	0.95	0.92

6.5 Conclusions

Cocoyam and rice each at sole cropping performed better as compared with intercrop. The number of irrigations and total amount of water used were more and higher in intercropping. Intercropping *Cocoyam* with rice resulted in significant reduction in all parameters measured at different irrigation treatments with the exception of *Cocoyam* plant heights at CFI treatments, though, not significant. There was a consistent yield reduction in both components crop at intercropping. The result of LER that was less than 1 signified a yield disadvantage in the intercropping. It could therefore be concluded that *Cocoyam*/rice intercrop was not productive over the two trial seasons considered, hence, not recommended with regard to the outcome of this study and the hypothesis should be rejected.

6.6 Acknowledgements

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7 IMPACTS OF IRRIGATION WATER MANAGEMENT TECHNIQUES ON THE GROWTH, YIELD AND WATER PRODUCTIVITY OF POTTED *COCOYAM* (*COLOCASIA ESCULENTA (L.) SCHOTT)* GROWN WITH ANAEROBIC BAFFLED REACTOR (ABR) EFFLUENT

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7.1 Abstract

The use of domestic treated wastewater in agriculture can aid river pollution reduction, and make available water and nutrients for plants. This study investigated the effects of irrigation management techniques using anaerobic baffled reactor (ABR) effluent on growth and yield parameters of *Cocoyam (Colocasia esculenta***)**. The irrigation water management treatments considered were alternate wetting and drying (AWD), continuous flooding irrigation (CFI) and wetting without flooding (WWF- control). It was hypothesized that the effect of irrigation management techniques with ABR on growth and yield are not significant. The control treatments produced the highest yields of 4.97 and 6.40 t/ha for 2017 and 2018 seasons, respectively for pot trials. Significant differences ($P < 0.05$) were observed between treatments with respect to number of irrigation events, amount of irrigated water and daily water balance. However, the treatments did not differ significantly with respect to plant height, leaf number and leave area index (LAI) ($P > 0.05$). The treatments effects were significant ($P < 0.05$) on the yield components (corm mass, corm number and corm size), corm yield and water productivity

(WP). WWF treatments had the highest WP without any yield penalty because it also produced the highest yield. The highest average corm yield of 4.97 and 6.40 t/ha for WWF treatments for 2017 and 2018 seasons were obtained. The hypothesis on the growth parameters was accepted while that of yield was rejected. This study concluded that both AWD and CFI resulted in yield reduction and WP as compared to WWF, and as such, not suggested for *Cocoyam* production in order to improve productivity.

keywords: alternate wetting and drying, anaerobic filter, Cocoyam, pot, tunnel, water productivity, wetting without flooding.

7.2 Introduction

The worldwide increasing need for water has caused the emergence of application of wastewater for general agriculture and landscaping (Heidarpour *et al.*, 2007). Peri-urban farming could actually perform a role of an environmentally sound disposal of continuous organic waste through the re-use of nutrients–rich, low quality and affordable wastewater as fertilizers (Van Der Merwe, 2011). While urban residents have long grown edible crops in backyard plots, modern micro-gardening such as tunnel makes use of containers such as plastic pots, wooden crates, custom-built tables and even old car tyres. It integrates horticulture production techniques with environmentally friendly technologies suited to cities household waste management. Crops in simple containers assist low-income families meet their daily requirements for fresh, nutritious food in the cities. Like most other developing nations, South Africa is becoming urbanized at rates never witnessed before (Van Der Merwe, 2011).

Decentralized wastewater treatment system (DEWATS) that includes an anaerobic baffled reactor (ABR) is a low-cost technology which has been used efficiently in developing nations (Adhanom *et al.*, 2018). The use of ABR effluent for irrigation is important for treated wastewater reuse, recycling because of its nutrients contents and is better than direct discharge into rivers (Musazura *et al.*, 2018). Heavy metals are not considered when using treated domestic wastewater for irrigation (Toze, 2006). According to Bedbabis *et al.* (2014) treated wastewater does not affect some soil properties significantly. Changes in soil physico-chemical properties over three uninterrupted seasons after irrigation with ABR effluent was not significant (Musazura *et al.*, 2015). The practice of intermittent flooding and drying is referred to as alternate wetting and drying (AWD) irrigation management (Lampayan *et al.*, 2015). The continuous flood irrigation (CFI) maintains anaerobic conditions (Yao *et al.*, 2012). The well-watered conditions with 100% water holding capacity is another irrigation management technique (Ruíz-Sánchez *et al.*, 2011). It is referred to as wetting without flooding (WWF).

Cocoyam is widely distributed in the tropics. Notwithstanding, its importance as both food and vegetable crop, it has received little research attention from agricultural, academic and development institutions, hence, categorised as a neglected and an underutilized crop species (Tumuhimbise, 2015). Research on *Cocoyam* is limited in South Africa (Mabhaudhi and Modi, 2013; Sibiya, 2015; Tumuhimbise, 2015). There has not been any reported literature on the response of *Cocoyam* growth and yield to different irrigation water management techniques using ABR effluent in a pot trial. This study, therefore, examined the effect of irrigation water management techniques on the growth and yield parameters of *Cocoyam* in pots using ABR effluent. The number, amount of irrigation, field water balance and water productivity were also considered. The hypothesis was that the treatments (AWD, CFI and WWF as irrigation management techniques) has no effect on both growth and yield of *Cocoyam*.

7.3 Methods

7.3.1 Study area

The experimental setup was located at the research site, Agricultural Hub, Newlands Mashu Research Facility, Durban, South Africa and is shown in Figure 7.1. The 30 m (L) X 8 m (W) X 4 m (H) tunnel (Figure 7.1) was meant to serve as a means of achieving zero effective rainfall on trials and was covered with clear, plastic UV-absorbing film. Side panels were transparent nets to facilitate air movement and temperature control. The study area falls under humid sub-tropical and agro-ecological region of South Africa with cool, dry winters that are frost-free and hot, wet summers. It has an average annual precipitation of 800 to 1 000 mm and mean daily temperature of 20.5°C. The soil is a clay of the Sepane form (Musazura *et al.*, 2018).

Figure 7.1 Newlands Mashu Research Facility (Tunnel house) and potted Cocoyam

7.3.2 Trial design

Eddoes landrace of *Cocoyam* from Umbumbulu, Kwazulu-Natal Province, South Africa was transplanted. Beds were raised for *Cocoyam* and irrigated with municipality tap water for two months, prior to transplanting for each season. The first season was from July, 2017 (cool dry winter) to February, 2018 (hot and wet summers) and the second season started from December, 2017 (hot and wet summers) to July, 2018 (cool dry winter). The pot trial was laid out in a randomized complete block design (RCBD) with three irrigation water management regimes treatments and replicated three times during the two-year period. The treatments were alternate wetting and drying (AWD), continuous flood irrigation (CFI) and wetting without flooding (WWF). The WWF treatment was used as control for both seasons. The pots were randomized periodically in the tunnel and blocked with respect to direction of sunlight. The pots used were 20 litres capacity plastic pots, each filled with a 25 kg of clayey-loam soil from the adjacent field. Each of the pots served as an experimental unit.

7.3.3 Irrigation

The trials were irrigated by flooding with a 70 mm freeboard to avoid over flowing of irrigation water. There were grids of PVC pipes with ball gates and water tap at each pot of different diameter sizes ranging from 15 to 25 mm. The trial plastic pots were lined with two layers of black plastic bags (25 µm thickness). The lining was to keep irrigation water from leaking out of drainage holes provided at the bottom of the pots. A PVC observation tube 400 mm in length, 50 mm in diameter and perforated with 5 mm diameter holes at 40 mm intervals was installed in each pot. The perforated length (200 mm) of the tube was inserted into the pot to monitor water table and instruct when to irrigate (Bouman *et al.*, 2007; Ye *et al.*, 2013; Lampayan *et al.*, 2015). The water level in the tube was measured with the aid of a measuring tape. Irrigation water was measured by the level of water inside the observation tube wells inserted in each pot. This is dictated by manual observation of water level in the water observation tube with the aid of an improvised light weight foams (polystyrene). Water was applied when water table inside the observation tube reached a certain level. The CFI was continuously flooded with 50 mm standing water, AWD allowed application of water to a depth of 50 mm when water level in the observation tube fell 150 mm (Lampayan *et al.*, 2015) below the top surface of the soil in the pot. WWF maintained the same water level in the observation tube with the soil surface level in the pot. A Campbell scientific automated weather station (AWS), with a CR 1 000 data logger (Utah, USA) mounted about 30 m away from the tunnel was used to collect reference evapotranspiration (*ET*o in mm/day) according to FAO Penman-Monteith equation and actual crop evapotranspiration, *ET*c, was calculated as a product of *ET*o and crop coefficient factor, Kc. Kc for *Cocoyam* is divided as Kc initial (1.05 for 60 days), Kc med (1.15 for 120 days) and Kc late (1.1 for 30 days) for a 210-day (7 months) *Cocoyam* land race (Mabhaudhi *et al.*, 2013). With values of Kc and ETo from the AWS, ETc was then calculated according to Mabhaudhi *et al.* (2013).

7.3.4 Water balance and water productivity

The daily water balance (WB) was calculated with the use of Equation 7.1 because of the effect of the tunnel set-up (zero effective rainfall) and pots as a planting medium for *Cocoyam*:

$$WBt = (I)t - (ET)t \tag{7.1}$$

where

WBt = water balance (mm) over time, t (day),
I = applied irrigation water (mm),
ET =evapotranspiration (mm),

Water productivity(WP) was calculated according to El-Zohiri and AMH (2014).;

$$WP = \frac{y}{WU} \tag{7.2}$$

Where, y is the actual harvestable yield in kg/ha and

WU is the total seasonal water use in m^3.

7.3.5 Data collection and analysis

The plant height (cm), leave number per plant and the leaf area index (LAI) were collected every two weeks (fortnightly) in each of the replicates for all the irrigation treatments. The plant height was measured as from the base of the plant to the apex. The number of leaves per plant were determined by direct counting of green leaves. LAI was measured using the LAI-2200C Plant Canopy Analyser (LI-COR Environmental) for the two seasons. Yield components (biomass/plant (kg), corm mass/plant (kg), corm number, corm size (mm) and harvest index (%) were measured and recorded. Corm yield (t/ha) was calculated from the harvestable yield per plot (Gebre *et al.*, 2015) and equated to yield per hectare (Equation 7.3).

$$Yield\ (t/ha) = \frac{Yield\ per\ net\ plot\ (kg) * 10\,000}{Net\ area\ of\ the\ plot\ (m^2) * 1\,000} \qquad (7.3)$$

The water balance was calculated according to Fereres and Connor (2004) and water productivity calculated as the ratio of total corm yield to the total water use (El-Zohiri and AMH, 2014).

7.3.6 Statistical analyses

Normality test was carried out before analysis using the combination of method of Skewness & Kurtosis and Normal Q-Q plots. The two methods proved that the data collected were normally distributed. The statistical analyses were performed using the GenStat 18th edition (2016). The data were subjected to analysis of variance (ANOVA) and treatment means compared using the Duncan Multiple Range Test, considering at the 5% level of significance.

7.4 Results and Discussion

7.4.1 Irrigation and water balance

Responses in number of irrigations events following irrigation management techniques with application of ABR effluent on *Cocoyam* are presented in Table 7.1. The number of irrigation events increased significantly (P<0.05) from 28 (control-WWF) to 30.33 (CFI) and reduced significantly ($P<0.05$) from 28 (control) to 11.67 (AWD) in 2017 planting season, however, the number of irrigation events reduced insignificantly ($P>0.05$) from 32 (control) to 29 (CFI) and reduced significantly ($P<0.05$) from 32 (control) to 15 (AWD) in 2018 planting season. This was basically as a result of the frequency of irrigation. Both WWF (control) and CFI were continuously irrigated, though to different levels unlike AWD that was alternating. There was no significant ($P>0.05$) difference between the control (WWF) and CFI and this could be attributed to one of the leaked pots in a replicate during 2018 growing season. The effects of amount of irrigation was significant ($P=0.03$ for 2017 planting season and $P=0.001$ for 2018). The effect of irrigation water management techniques with ABR on daily water balance was highly significant ($P<0.001$) for both 2017 and 2018 seasons. The AWD treatments have the least daily water balance while CFI treatments have the highest WB. This is an indication that the more the number of irrigation and amount of irrigation the higher the WB since it was a pot experiment where there were no other factors affecting the input (irrigation) and the output (evapotranspiration).

Table 7.1 Effects of irrigation water management techniques with ABR on number of irrigations events, amount of irrigation and daily water balance for 2017 and 2018 seasons

Season	Treatments	Number of irrigation	Amount of irrigation (mm)	Water balance (mm/day)
2017	AWD	11.67 ^{a}	546.3 ^{a}	15.47 ^{a}
	CFI	30.33 ^{c}	716.3 ^{b}	22.25 ^{c}
	WWF	28.00 ^{b}	681.7 ^{b}	21.17 ^{b}
	p	***	**	***
2018	AWD	15.00 ^{a}	698.0 ^{a}	16.66 ^{a}
	CFI	29.00 ^{b}	781.0 ^{b}	19.18 ^{b}
	WWF	32.00 ^{b}	817.3 ^{b}	20.29 ^{b}
	p	***	**	***

Notes: Means with same alphabets within a column in each season do not differ significantly at 5% level of probability. *p = probability*
**** = significant at 0.001 probability level, ** = significant at 0.01 probability level*

7.4.2 Plant height, leave number and leaf area index (LAI)

The results for both 2017 and 2018 cropping seasons showed that irrigation water management techniques had no significant ($P>0.05$) effect on plant height, leave number per plant and LAI. Hence, the two seasons followed the same trend in terms of growth parameters. The result agreed with Busari *et al.* (2018) that reported same result though under a different planting medium. This confirmed that neither the treatments (AWD, CFI and WWF) nor the ABR effluent have effect on growth parameters of *Cocoyam*. *Cocoyam* under ABR plus rain-fed and *Cocoyam* under only ABR have no difference under any of the irrigation managements techniques in terms of plant height, number of leave per plant and LAI.

7.4.3 Corm yield, its components and water productivity

The effects of irrigation management techniques with application of ABR effluent on corm mass per plant, corm number per plant, corm size, yield and water productivity are presented in Table 7.2. The effect of irrigation treatments was highly significant ($P<0.001$) on the mass of corm per plant. The corm mass was reduced significantly ($P<0.05$) from control treatments (WWF) in both seasons. The control had the highest corm mass in both seasons as compared with other treatments (AWD and CFI). The effect of irrigation treatments was also significant ($P<0.001$) on the number of corm per plant. The number of corm per plant was significantly higher ($P < 0.05$) in the CFI treatment than control and AWD. The trend was the same over both seasons. The effect of treatments was significant ($P=0.006$ for 2017 and $P=0.005$ for 2018 season) with respect to corm sizes. The sizes were significantly ($P<0.05$) reduced when both treatments (AWD and CFI) were compared with the control (WWF). The control had the highest corm size followed by AWD, however, there was no significant difference between means of AWD and CFI in both seasons. The treatment effects were highly significant ($P<0.001$) with respect to corm yield in 2017 and 2018 seasons. The effects were significantly different from one another among the three irrigation management techniques (treatments). The highest corm yield in t/ha was obtained from the control treatment (WWF) while the least was from CFI treatments. The same trend was observed in both seasons.

The influence of irrigation management techniques was significant ($P=0.001$) on the water productivity. The effect reduced significantly ($P<0.001$) the water productivity of AWD and CFI from control (WWF). The number of corm, size and mass have influence on the yield of *Cocoyam*. The above results showed that the highest number of corm was recorded by treatment CFI but with lowest size and mass. This was probably responsible for the lowest corm yield obtained from treatments CFI. It could also be attributed to the stagnant effluents that can results in a low oxygen content, and causes basal rotting of the *Cocoyam*. According to FAO (2018), it is imperative that *Cocoyam* is grown in a cool and continuously flowing water in order to have a maximum of dissolved oxygen. *Cocoyam* does not tolerate water logging (DAFF, 2011). The yields difference from season 1 to season 2 could be attributed to a delay encountered in transplanting *Cocoyam* to the pots trial in 2017. The establishment stage proposed for *Cocoyam* was 2 months but the *Cocoyam* in 2017 season went beyond to a part of vegetative growth (critical stage). The highest yield results obtained at treatments WWF were lower than the global mean yield of 6.5 t/ha Gebre *et al.* (2015) and this could be attributed to the medium of planting (pot against field), species of planting materials, weather locations and irrigation methods. Temperature is a major factor that affects corm yield of *Cocoyam* (Muinat *et al.*, 2017) and this probably took effect on the result because 2018 planting was done during summer while 2017 season was planted in winter. The yield of same eddoes type of *Cocoyam* at the same spacing of 0.5 m by 0.5 m was 4.71 t/ha (Sibiya, 2015) and that was higher than any of the yield result presented in this study. The results of water productivity revealed that WWF was found to be more effective and suitable way of irrigating *Cocoyam* because of its highest WP without any reduction in corm yields. WWF produced the highest yields and WP.

Table 7.2 Effects of irrigation water management techniques using ABR on the yield, yield components and water productivity

Season	Treatments	Corm number per plant	Corm size (cm)	Water productivity	Corm yield (t/ha)
2017	AWD	9.67 ^{b}	1.33 ^{a}	0.49 ^{b}	2.65 ^{b}
	CFI	16.67 ^{c}	0.87 ^{a}	0.26 ^{a}	1.91 ^{a}
	WWF	8.00 ^{a}	4.03 ^{b}	0.74 ^{c}	4.97 ^{c}
	p	***	**	***	***
2018	AWD	12.67 ^{b}	1.43.^{a}	0.59^{b}	4.08 ^{b}
	CFI	19.67 ^{c}	0.94 ^{a}	0.43 ^{a}	3.33 ^{a}
	WWF	11.00 ^{a}	4.24.^{b}	0.78 ^{c}	6.40 ^{c}
	p	***	**	***	***

Notes: Means with same alphabets within a column in each season do not differ significantly at 5% level of probability. *p = probability* *** = *significant at 0.001 probability level, ** = significant at 0.01 probability level.*

7.5 Conclusions

The results of this study have shown the impacts of irrigation water management techniques using ABR effluent on growth and yield of *Cocoyam*. The total number of irrigation events, amount of irrigation and daily water balance were lower in AWD as compared with CFI and WWF. The results also indicated that the use of different irrigation water management techniques with ABR effluent do not have any significant effect on the growth parameters (plant height, leave number per plant and LAI). The yields obtained from WWF treatments in both seasons were the highest and the yields were obtained with the use of ABR effluent that was free of any additional fertilizer. The same treatments (WWF – control) also gave the highest WP. This could be concluded that flooded or intermittent flooding and drying of *Cocoyam* with ABR effluent is not the best solution to optimum *Cocoyam* production. It is recommended that the use of pot with treatments CFI or AWD should be discouraged. The hypothesis was accepted for growth parameters but rejected for yield components.

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8 CONCLUSION AND RECOMMENDATION

The research focused on investigating the effect of irrigation water management techniques on crop production using anaerobic baffled reactor (ABR) effluent during the 2017 and 2018 planting seasons. The irrigation water management techniques used were AWD, CFI and WWF. The trials were carried out concurrently at field and tunnel house (pot). The research had five different manuscripts as presented in chapters 3 to 7. Each of the chapters was independent on its own.

This study concluded that *Cocoyam* (eddoes landraces from Umbumbulu) was susceptible to flooding (CFI). Attempts to domesticate the landrace out of its native way of irrigation (WWF) were unsuccessful as the crop failed to produce significant yield. *Cocoyam* is a wetland crop, so it performed and produced reasonable yields under continuous wetting without flooding (WWF) condition. The yields obtained from WWF treatments in both experiments (field and pot) were the highest and the yields were obtained with the use of ABR effluent that was free of any additional fertilizer. The same treatments (WWF – control) also gave the highest WP. This could be concluded that flooded or intermittent flooding and drying of *Cocoyam* with ABR effluent is not the best solution to optimum *Cocoyam* production. The adoption of irrigation management technique such as WWF using ABR effluent could therefore be concluded as relatively a better way of enhancing food security and sanitation especially in urban and peri-urban settlement.

The results of this study have shown that the yield of lowland rice crop was improved as a result of irrigation management techniques with ABR effluent. AWD irrigation was able to save water as compared to treatments CFI at the field and pot trials. The value of the water saved by this technique would itself be sufficient to address justification for its adoption in cultivating lowland rice because the saved irrigation water may be used for irrigating other crops or fields. In spite of using much less amount of ABR effluent for irrigation, AWD gave the highest grain yields and water productivity. This could be concluded that submerged paddy field is not necessarily the only solution to optimum rice production. Rice, can therefore, be grown in an anaerobic and aerobic conditions. Rice has been regarded for a very long time as an aquatic plant, but, this conviction has been repeatedly challenged, as rice is known to be capable of growing under both flooded and non-flooded conditions as evidenced in this study and past related studies.

It is therefore recommended that the use of irrigation management techniques with ABR effluent (especially for WWF treatments) be encouraged among Cocoyam farmers while AWD is recommended for rice farmers at both field and tunnel trials. Intercropping Cocoyam with rice is not recommended because of its yield disadvantage. In all, AWD treatments are recommended with reference to irrigation or total water productivity and water saving technology.

8.1 Challenges/Problems Encountered

The trials were not held without some challenges faced especially at the experimental site. Some of the challenges were:

(a) Blockage of the inlet chamber: The influent in to the chamber from the 83 households connected to the DEWATS was supposed to be a combination of greywater (sinks, showers, baths, clothes washing machines or dish washers) and blackwater (faeces, urine, water and toilet paper from flush toilets) but boulders, bigger broken blocks, broken bottles and the likes found their ways in to the sewer through the connected houses especially on weekends. These debris were gotten from building rehabilitation or party ceremony. They eventually found their way to block the inlet chamber, thereby impaired the flow of influent as expected. This eventually reduced the quantity of effluent expected down the field.

(b) Bird’s infestation: There was a slight birds attack on rice grain at the stage of panicles initiation. This was discovered at the first week of panicles initiation.

8.2 Solution Proffered

Some solutions were proffered to eradicate the challenges faced above and some of them were listed below:

(a) Bi-weekly chamber inspection through the manhole: The blockage was discovered to occur during weekend, therefore the services of two field assistants were employed to check and clean the inlet on Mondays and Fridays.

(b) Combination of different scarecrows were used to prevent bird’s attack. Some of these scarecrows included net, a statue of human head with shirt and red tapes popularly called danger tape.

8.3 Future Lesson and Research Possibilities

Future lesson must consider the use of irrigation water management techniques using both freshwater and ABR effluent, this will allow comparable differences since the irrigation treatments will be the same except that one will be ABR and the other will be tap water. The research could also be further improved by joining an irrigation engineer with probably an honour student of microbiology to look in to the edibility test on the harvested products. The yield quality of both crops and food safety issues should be considered in future research. This will have a complete knowledge of the research. Modelling could form part of the future research possibilities in order to complement and validate the findings of the field experiments and apply the information at local and regional level. Finally, further study to investigate the effect of percolation and nitrogen leaching in paddy fields is recommended.

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