Evaluating the effect of irrigation water management techniques on (taro) madumbe (*Colocasia esculenta* (L.) Schott) grown with anaerobic filter (AF) effluent at Newlands, South Africa

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ABSTRACT

This study evaluated the effects of irrigation water management techniques on the growth and yield parameters of madumbe (*Colocasia esculenta*) irrigated with anaerobic filter (AF) 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 anaerobic baffled reactor (ABR) effluent have a significant effect on the growth and yield of madumbe. 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 leaf 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 yields of 7.5 and 9.84 t/ha for WWF treatments for 2017 and 2018 seasons were obtained. It is concluded from this study that both AWD and CFI resulted in yield reduction compared with WWF, and as such, is not recommended to improve the productivity of madumbe.

Key words | alternate wetting and drying, anaerobic filter effluent, irrigation management techniques, madumbe, water productivity, wetting without flooding

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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, a growing volume of wastewater is being released and most of it untreated. The rate of wastewater usage for irrigated agriculture in urban and peri-urban and even in far rural settlements downstream of the new megacities is increasing. Sustainable techniques for wastewater disposal 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 of fields 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

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standing water at all times (anaerobic conditions) (Yao *et al.* 2012). Well-watered conditions with 100% water holding capacity is another irrigation management technique (Ruíz-Sánchez *et al.* 2011). This 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 upflow 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 is domestic households (Bame *et al.* 2014).

Madumbe (taro) (*Colocasia esculenta*), one of the food security crops, is a marginalized tuber food crop, with wide distribution in the tropics. The neglect of madumbe 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 & Kamwendo 2014). It is the 14th most consumed vegetable worldwide (Lebot & 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 underutilized crop species (Tumuhimbise 2015). Scientific research on madumbe is scarce in South Africa (Tumuhimbise 2015; Sibiya 2015; Mabhaudhi & Modi 2016). Cocoyam (madumbe) is 'an underexploited food and feed resource' (Owusu-Darko *et al.* 2014).

There is no reported work on the response of madumbe 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 madumbe. It also investigated the number, amount of irrigation, field water balance and water productivity. The (alternative) hypothesis was that irrigation water management techniques with ABR effluent have a significant effect on the growth, yield of madumbe, water balance and water productivity.

METHODS

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, 30° 58′ 25″ E and altitude 14 m amsl) is shown in Figure 1. The climate in the study area falls under the humid sub-tropical and agro-ecological region of South Africa with cool, dry winters that are frost-free and hot, wet summers. It is characterized by an average annual precipitation between 800 and 1,000 mm and mean daily temperature of 20.5 °C. The soil is a clay of the Sepane form (Musazura *et al.* 2018).

Anaerobic baffled reactor and anaerobic filter 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 2(a) shows the Newlands Mashu DEWATS plant. 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 ABR trains (Figure 2(a)). Trains 1 and 2 are identical, consisting of seven chambers, while train 3 has four chambers (Figure 2(b)), 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.

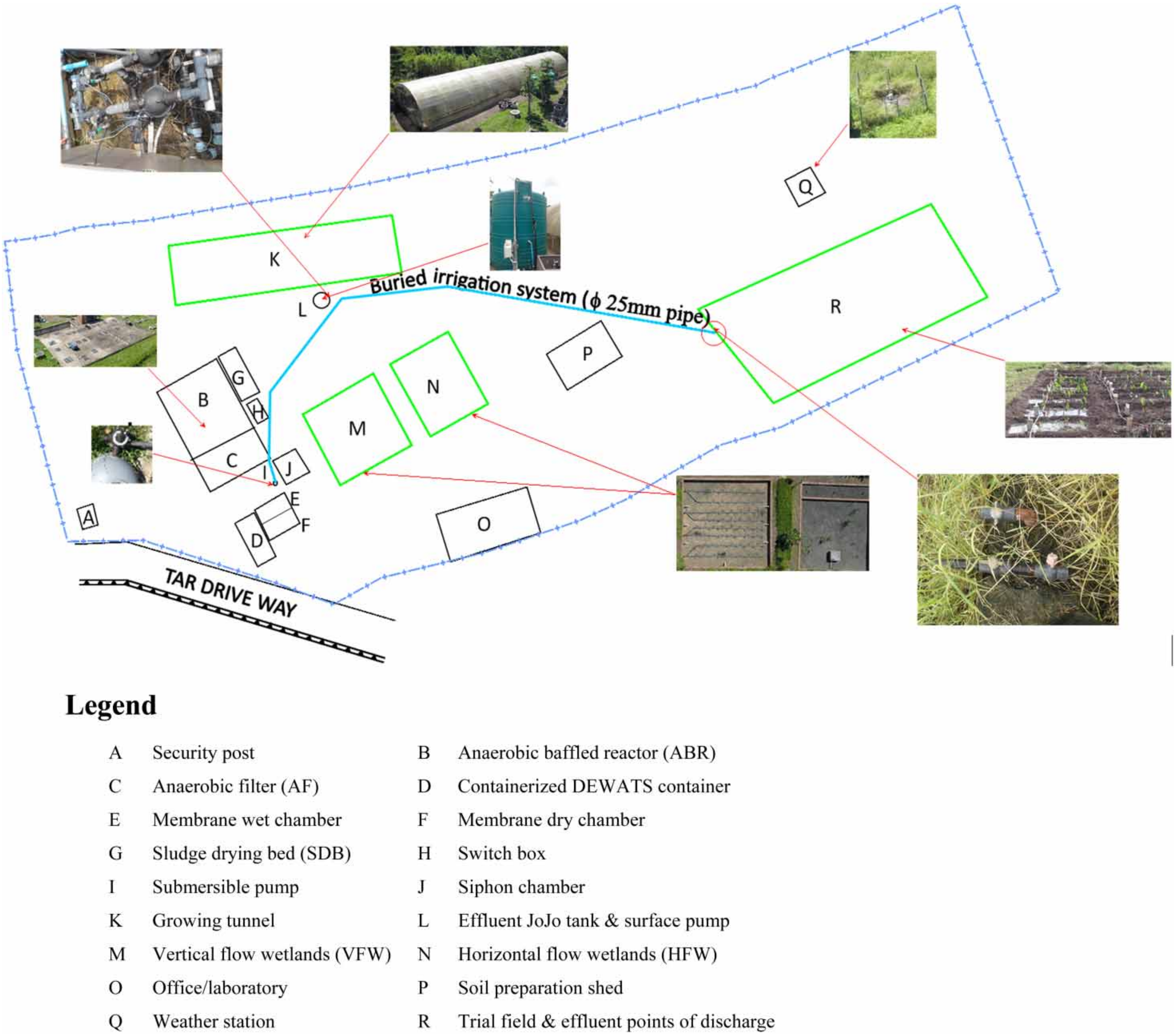

Figure 1 | Layout of the experimental area.

The liquid flows into the ABR, which can be considered as an improved septic tank with baffles that separate the tank. The baffles force 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 AF compartments which consist 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 and 5 days with a flow rate between 25 and 35 m^3/day. 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 is then pumped into a 10,000 L tank from where the effluent flows by gravity to the open field

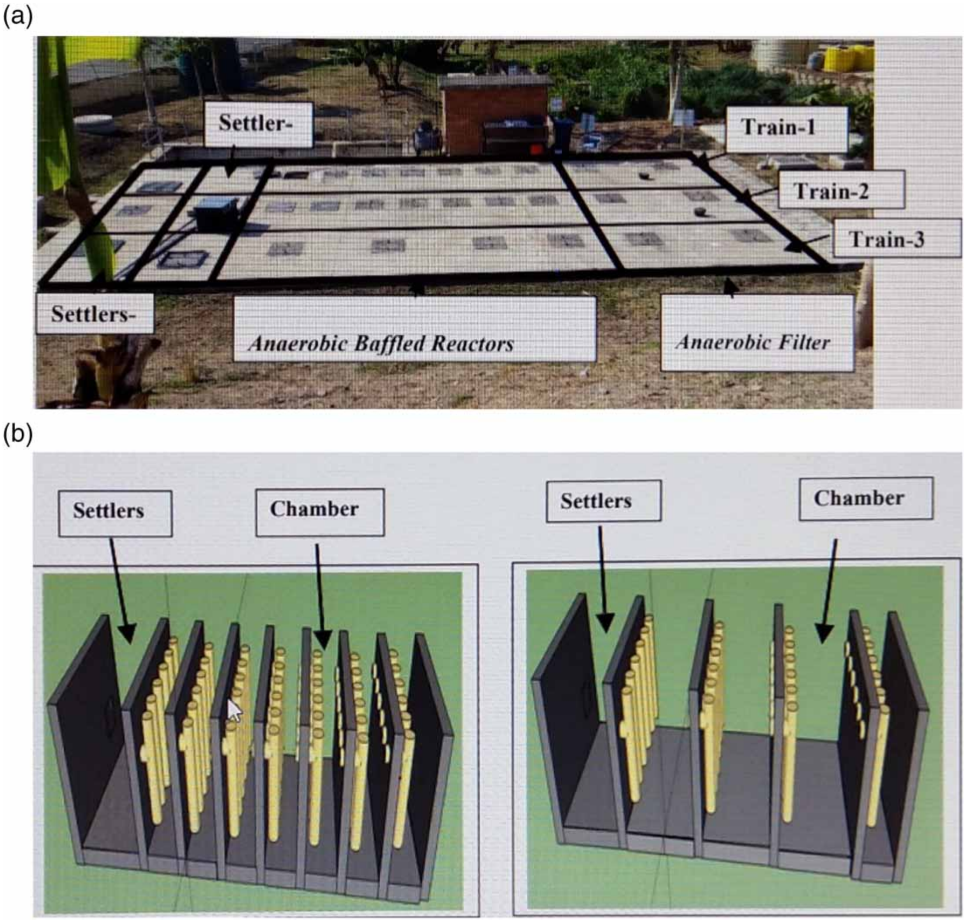

Figure 2 | Layout of compartments of anaerobic baffled reactor.

where the irrigation trials take place. Excess treated effluent is returned to the trunk sewer. The composition and characterization of the AF effluent is presented in Table 1.

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 summer) and the second season was from December 2017 (hot and wet summer) 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. 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 nine plots of 3 m by 1.5 m each. Bunds were established between plots to isolate them from adjacent plots (Figure 2). 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

Table 1 | AF effluent characteristics

Parameter	Unit	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
Escherichia coli	(cfu/ml)	2,600.00	±700.00	2,000.00–3,400.00
pH		7.27	±0.05	7.19–7.38
Electrical conductivity (EC)	S/m	93.22	±0.83	71.57–107.90

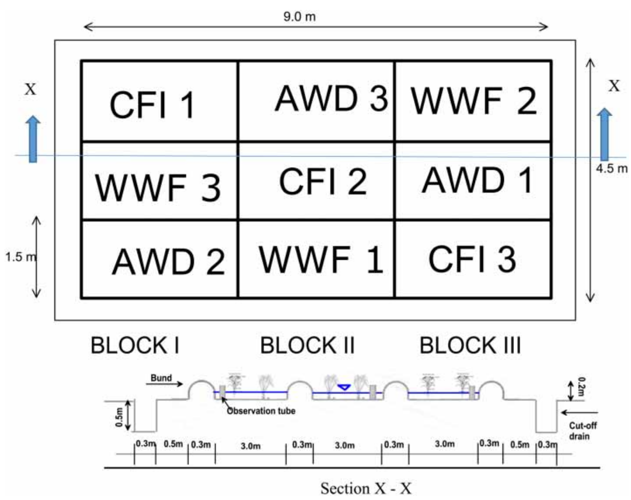

Figure 3 | Experimental layout of the trials showing different treatments and cross-section.

nine 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 to monitor the soil water depth.

Planting material and technique

The South African madumbe 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 m by 0.5 m. The spacing produced 40,000 plants per hectare. All the plots were irrigated with municipal water for the first 2 months for successful crop establishment and to avoid bias in the treatments. They were transplanted after 2 months and the irrigation management techniques with AF effluents commenced. The plants exhibited transplant shock for about a week.

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 in 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 reduced 150 mm below the soil surface (Lampayan *et al.* 2015). The WWF plots maintained the same water level with the field (well-watered). 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 madumbe 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 crop water requirement (ETc) was then calculated according to Mabhaudhi *et al.* (2013). The data obtained over the period of the trials is presented in Table 2.

Data collection and analysis

Data were collected fortnightly from three 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 a collapsible metre rule, leaf numbers were counted manually and leaf area indexes (LAI) were measured using a LAI-2200C Plant Canopy Analyzer (LI-COR, Inc., USA and Canada) throughout the growing season. Biomass/plant (kg), corm number, corm size (mm), corm mass/plant (kg), harvest index (%) and total yield (t/ha) were measured and recorded. Corm yield was calculated from the harvestable plots, converted to yield per hectare and expressed as t/ha. This was done with Equation (1) (Gebre *et al.* 2015).

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

The water balance was calculated according to Fereres & Connor (2004) and water productivity calculated as the ratio of total corm yield to the total water use (El-Zohiri & 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 the 5% level where the treatments are significant.

RESULTS AND DISCUSSION

Effect of water application

The effects of irrigation water management techniques with AF 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 events and daily water balance (Table 3). A significant ($P < 0.05$)

Table 2 | Average monthly temperature, relative humidity and rainfall for the two seasons at the experimental site

	Average temp. (°C)			Relative humidity (%)			Rainfall (mm)
Month	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

Table 3 | Effects of irrigation water management techniques with anaerobic filter (AF) effluents on number of irrigation events, amount of irrigation, total water use and daily water balance for the 2017 and 2018 seasons

Season	Treatment	Number of irrigations	Amount of irrigation (mm)	Total water use (mm)	Water balance (mm/day)
2017	AWD	18.00^{a}	847^{a}	$1,197^{a}$	5.45^{a}
	CFI	66.67^{c}	$1,684^{b}$	$2,034^{b}$	12.28^{c}
	WWF	63.00^{b}	$1,540^{b}$	$1,891^{b}$	11.11^{b}
	p	***	**	**	***
2018	AWD	31.00^{a}	$1,498^{a}$	$1,743^{a}$	9.18^{a}
	CFI	135.00^{b}	$3,952^{b}$	$4,197^{b}$	24.67^{b}
	WWF	134.00^{b}	$3,290^{b}$	$3,535^{b}$	20.58^{b}
	p	***	**	**	***

Notes: Means with same letter 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. Superscripts a, b and c denote means which are significantly different.

reduction occurred in number of irrigations, amount of irrigation, total amount of water use and water balance between treatments WWF and AWD. However, there was no significant ($P > 0.05$) difference between means of CFI and WWF for all the parameters except for number of irrigations and water balance in the 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 higher the amount of irrigation and water balance. Irrigation amount and/or total water use are key parameters of water balance. The values of all parameters measured in Table 3 were higher in 2018 than in 2017. This was a result of seasonal differences that produced less rainfall in 2018 compared with 2017.

Treatment effects on growth of madumbe

The results for the 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 with AWD and WWF, respectively. The result of LAI agreed with Mabhaudhi *et al.* (2013), who reported that eddoes landrace of madumbe had its highest leaf 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 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 the 2018 season on plant height ($P = 0.84$), LAI ($P = 0.88$) and leaf number per plant ($P =$ 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 madumbe.

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

The effects of the irrigation water management techniques on biomass, corm mass, corm size and harvest index of madumbe grown with AF effluent for three different techniques (AWD, CFI and WWF) are shown in Figure 4. 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 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 4 for the 2018 planting season were higher than those in the 2017 season, which was probably a result of the increase in the amount of irrigation water.

Apart from the statistical results, it can be observed from Figure 5 that CFI treatments produced the smallest mean corm size and mass but with a higher number of corms per plant as against the control treatment (WWF). The largest corm size and mass were found for the WWF treatments but with fewer corms per plant. The biggest corm size and mass accounted for the margin observed in the yield. Madumbe does not tolerate waterlogging (DAFF 2011). However, biomass was highest in the CFI treatments, which demonstrated the effect of ponding on the leafy (vegetable) part of madumbe. Madumbe is categorized as both a tuber and a vegetable crop; it may therefore be suggested to

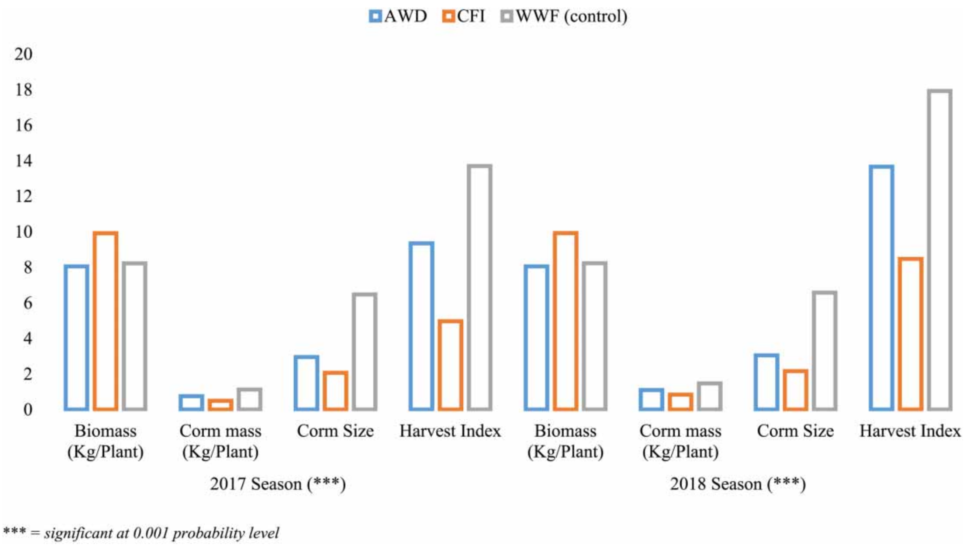

Figure 4 | Effect of treatments on the yield components.

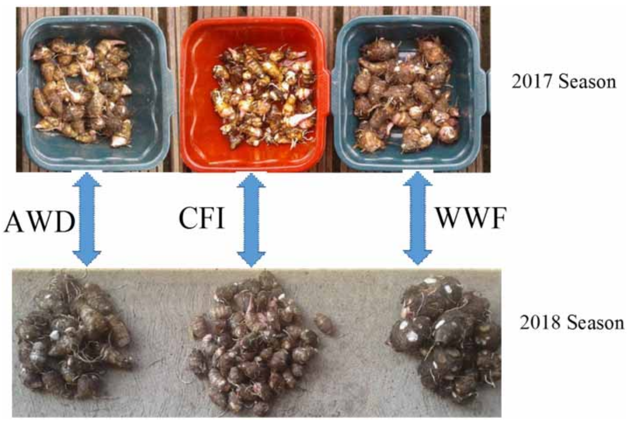

Figure 5 | Harvested corm from both seasons.

use CFI treatments to enhance the leafy part and WWF for higher madumbe corm yield. Weed infestation is reduced by flooding and this may be responsible for the highest mean value recorded for biomass with 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 results for biomass weight, which was highest at 250% ET compared with 50% or 100%. But standing or ponding effluent may result in a low oxygen content and may cause decaying of madumbe, thereby reducing the corm yield as found under CFI treatments (FAO 2018).

Table 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 madumbe. The significant differences observed indicated that the performance of the madumbe 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 the 2017 season. However, in the 2018 season, the means of corm numbers per plant among the three irrigation management techniques were

Table 4 | Corm number, corm yield and water productivity of madumbe grown with anaerobic filter (AF) effluent at three levels of irrigation water management techniques (AWD, CFI and WWF)

Season	Treatment	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	***	***	***

Notes: Means with different letters within the same column differ significantly at the 5% level, P = probability, *** = significant at 0.001 probability level. Superscripts a, b and c denote means which are significantly different.

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 the 2017 and 2018 seasons, respectively. The two values obtained in this study 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 important factor affecting madumbe yield and this showed in the yield obtained from 2018 compared with the 2017 planting season. 2018 planting was done during the summer while the 2017 season was planted in winter. Sibiya (2015) reported 4.71 t/ha for the same eddoes type of madumbe 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 madumbe to the trial field during the 2017 season and may also be a result of seasonal (winter vs. summer) variation. The establishment stage for madumbe is 8 weeks but the madumbe in the 2017 season went beyond to a part of vegetative growth (critical stage). This may have contributed to the yield reduction between seasons. Madumbe was planted in winter 2017 (received more rainfall) and summer 2017 (characterized by lesser rainfall but more nutrient-rich AF effluent). This could be supported by DAFF (2011) that said madumbe prefers warm conditions (summer). WP was highest (0.42 kg/m^3) for AWD treatments in both seasons. It was, however, attached to a yield penalty (reduction). The highest WP for AWD was a result of the smaller 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 the 2018 season. The lowest means of WP obtained in treatment CFI were a result of the maximum amount of water used (continuous ponding).

CONCLUSION

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

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