Productivity of Selected African Leafy Vegetables under Varying Water Regimes

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Abstract: African leafy vegetables (ALVs) are nutrient dense and can contribute to crop and dietary diversity, especially in water-stressed environments. However, research on their productivity under limited water availability remains scant. The objective of the study was to evaluate growth, physiology and yield responses of three ALVs (*Vigna unguiculata*, *Corchorus. Olitorius* and *Amaranthus cruentus*) and a reference vegetable (*Beta vulgaris* var. *cicla*) to varying water regimes [30%, 60% and 100% of crop water requirement (ET_c)]. Field trials using a randomised complete block design, replicated three times, were conducted over two summer seasons, 2015/16 and 2016/17. Leaf number, plant height, chlorophyll content index (CCI), chlorophyll fluorescence (CF), and yield were measured in situ. For *A. cruentus* and *C. olitorius*, water stress (30% ET_c) was shown to produce a lower yield, although leaf number, plant height and chlorophyll content index were unaffected, while for *B. vulgaris*, leaf number and yield were reduced by water stress. For *V. unguiculata*, CF, CCI, plant height, leaf number, and yield were not affected by water stress, indicating its suitability for production in water scarce environments. Using 60% ET_c was suitable for the production of *A. cruentus*, *C. olitorius* and *B. vulgaris* var. *cicla*, whereas 30% ET_c is recommended for *V. unguiculata*. The yield results of *V. unguiculata* indicate that it performs better, while the yield of *A. cruentus* and *C. olitorius* is comparable to that of *B. vulgaris* under similar conditions, indicating potential for marginal production.

Keywords: irrigation; production; vegetables; yield

1. Introduction

South Africa is a water stressed country that faces challenges of population growth including food and nutrition insecurity [1]. Most smallholder communities live in marginal areas where crops struggle to survive and face challenges of water scarcity and malnutrition [1]. Furthermore, commercial or irrigated crop production takes place under water scarcity, with water availability likely to drop below the benchmark of 1000 m^3 person^{-1} year^{-1} [2]. African leafy vegetables (ALVs) offer alternatives both to smallholder and commercial farmers because they are nutrient dense and tolerant to several abiotic and biotic stresses [3,4]. They contain nutrients such as calcium, iron, vitamin A, vitamin C,

fibre and proteins [5]. Furthermore, they are good sources of antioxidants such as flavonoids, tannins and other polyphenolic constituents [6].

South Africa has more than 100 different species of ALVs that have been identified; however, few of these species are utilised [7]. *Corchorus olitorius* (jute mallow), *Amaranthus cruentus* (pigweed) and *Vigna unguiculata* (cowpea) are among the major ALVs that are utilized. *Amaranthus* spp. are reported to be tolerant to adverse environmental effects [8,9]. They grow naturally in arid and semi-arid ecological regions, which means that they could be tolerant to low water and high temperature conditions [10]. Although cowpea is relatively drought tolerant, it has been shown that water stress reduces essential physiological and biochemical processes that affect its growth and productivity [11–13]. *Corchorus olitorius* is susceptible to moisture stress owing to its shallow rooting depth, which can be mitigated through irrigation [14]. African leaf vegetables have been reported to have advantages over exotic vegetable species, because of their adaptability to marginal agricultural production areas and their ability to provide dietary diversity in poor rural communities [15,16]. Inclusion of ALVs in cropping systems can contribute to climate change adaptation, the environment, and employment creation in poor rural communities [17], as well as dietary diversification in poor rural communities [18]. However, their adoption is currently low because of limited research on their yield response to water.

ALVs have been documented to address challenges such as water scarcity and malnutrition; however, there is lack of information on their yield response to water [15,19]. Studies conducted to determine the water requirements of selected ALVs showed that although an adequate amount of water is needed to produce marketable yield [20,21], there is a possibility of producing ALVs [22] under limited water conditions. Recent studies on nutritional water productivity of *Amaranthus*, *Cleome gynandra* and *B. vulgaris* reported yield reduction in water stress conditions [16]. ALVs were also reported to produce yield comparable to that of *Beta vulgaris* var. *cicla* under similar conditions [16]. With this diversity of different species of ALVs and a wide genetic diversity in growth habit, leaf shape, leaf colour, leaf size, plant size [7], there is a need for further research on selected ALVs that have potential to be extensively utilised [23]. These include *A. cruentus*, *C. olitorius* and *V. unguiculata* in comparison to *B. vulgaris* under the same locality. In this study, we selected Swiss chard because it is a is highly nutritious and commercialized leafy vegetable widely consumed in sub-Saharan Africa [5]. The study also ought to compare *B. vulgaris* results with the AVLs grown under similar experimental settings. A greater number of species for people to select from, as well as a wider diversity of desirable traits, can lead to successful commercialisation because farmers have a wide range of species to choose from that are better adapted for their region within South Africa. The objective of the study was to evaluate the productivity and yield of *A. cruentus*, *C. olitorius*, *V. unguiculata* and a reference vegetable crop, *B. vulgaris,* under varying water regimes.

2. Materials and Methods

2.1. Plant Material

Seeds of *A. cruentus* and *C. olitorius* were obtained from the seed bank of the Agricultural Research Council (ARC)—Roodeplaat, Vegetable and Ornamental Plant Institute (VOPI). *V. unguiculata* (Bechuana white, a runner type) and Swiss chard (*B. vulgaris*) cultivar 'Ford Hook Giant' were obtained from Hygrotech Seed Pty. Ltd., South Africa. No treatment was done to the seeds.

2.2. Site Description

Trials were planted at Roodeplaat, Pretoria (25°60′S; 28°35′E) during the summer seasons of 2015/2016 and 2016/2017. The soil in the rain shelter was classified as loamy sand (USDA taxonomic system). Soil physical characteristics were used to generate parameters for the amount of water available at field capacity (FC), permanent wilting point (PWP), and saturation (SAT), as well as the saturated hydraulic conductivity using the Soil Water Characteristics Hydraulic Properties Calculator® (Version 6.02.74, USDA Agricultural Research Services). The daily maximum and minimum

temperature averages were 28.5 °C and 15 °C in summer (November—April) (Agricultural Research Council—Institute of Soil Climate and Weather). Rainfall was excluded since the rain shelter is designed to close when rainfall starts. The field capacity of the soil was 146 mm^{-1} and the permanent wilting point was 75 mm m^{-1}.

2.3. Experimental Design

The experimental design was a factorial experiment arranged in a randomised completely block design; individual plot size in the rain shelter was 6 m^2, with plant spacing of 0.3 m × 0.3 m. There were two factors: irrigation level and four crops, replicated three times. Vegetables species used as planting material were: *Amaranthus cruentus*, *Corchorus olitorius*, *Vigna unguiculata* (cowpea) and *Beta vulgaris* (Swiss chard). The irrigation levels were: 30% (deficit irrigation), 60% (moderate stress) and 100% (well-watered) of crop water requirement (ETc). Swiss chard was chosen because it is a commercialised leafy vegetable that is highly nutritious which contains high levels of Fe, Zn and β-carotene [5].

2.4. Irrigation

Drip irrigation was used to apply water in the rain shelter. The system consisted of a pump, filters, solenoid valves, a water meter, control box, online drippers, a 200 L water tank, a main line, sub-main lines and laterals. The system was designed to allow for a maximum operating pressure of 200 kPa with average discharge of 2 L/h per emitter. Drip lines were spaced according to the plant spacing (0.3 m × 0.3 m). A black 200 μm thick polyethylene sheet was trenched at a depth of 1 m to separate the plots to prevent water seepage and lateral movement of water between plots.

Irrigation scheduling was based on reference evapotranspiration (ET) and a crop factor [24]. Reference evapotranspiration (ET$_o$) values were obtained from an automatic weather station (AWS); the AWS calculates ET$_o$ daily according to Penman–Monteith's method [24]. The crop coefficient (K$_c$) values used were for spinach as described by Allen et al. [24], whereby Kc$_{initial}$ = 0.7, Kc$_{med}$ = 1 and K$_{clate}$ = 0.95. Using these values of K$_c$ and ET$_o$ from the AWS, the crop water requirement (ET$_c$) was then calculated as follows, as described by Allen et al. [24]:

$$ET_c = ET_o \times K_c \tag{1}$$

where, ET$_c$ = crop water requirement

ET$_o$ = reference evapotranspiration, and
K$_c$ = crop factor.

During the first two weeks, all treatments received the same amount of water to establish the plants and thereafter the irrigation treatments were imposed. Irrigation was applied three times every week and during the mornings to ensure water availability during peak periods of demand in the day. The total amount of irrigation water applied, taking into consideration the initial watering, ranged from 622 (100% ET$_c$-well watered) to 373 (60% ET$_c$-medium watered) and 186 mm (30% ET$_c$-stress) for 2015/16. During the 2016/17 season, watering ranged from 556 (100% ET$_c$) to 333 (60% ET$_c$) and 166 mm (30% ET$_c$). The soil water status during the growing period was monitored using Theta probes.

2.5. Agronomic Practices

Soil samples were taken from the field prior to land preparation at a depth of between 0.3 and 0.6 m and submitted for soil fertility analysis at the Agricultural Research Council, Institute of Soil, Climate and Water (ARC-ISCW). Land preparation included digging and harrowing to achieve a fine seedbed. Nitrogen (limestone ammonium nitrate (LAN) 28% N) was applied according to the results of soil fertility analysis for both the 2015/2016 and 2016/2017 seasons (Table 1).

Table 1. Soil physico-chemical analysis results of the soil used in the study.

K	Ca	Mg	Na	P	pH	N-NO3	N-NH4
				mg/kg			
105	1412	221	67	67.7	7.4	5.44	3.42

The application rates were: 125 kg ha^{-1} N for *A. cruentus* and *C. olitorius,* 150 kg ha^{-1} N for *B. vulgaris* and 135 kg ha^{-1} N for *V. unguiculata* for both seasons. Nitrogen was applied by banding in three split applications. The first application was at transplanting/sowing (50%), the second at 4 weeks after transplanting/sowing (25%), and the last at (25%) 8 weeks after transplanting/sowing. Double super phosphate was applied at 20 kg ha^{-1} (10.5% P) at planting for season 1 for all the crops. During the second season, 63 P kg ha^{-1} was used for *B. vulgaris*, 55 kg ha^{-1} P was used for *A. cruentus* and *C. olitorius*, and 75 kg ha^{-1} P was used for *V. unguiculata* at planting. Potassium was deemed sufficient based on the results of soil fertility analyses for both seasons. Seedlings of *A. cruentus*, *B. vulgaris* and *C. olitorius* were grown in 250 cavity polystyrene trays filled with a commercial growing medium, Hygromix$^{®}$ (Hygrotech Seed Pty. Ltd., South Africa) and covered with vermiculate to minimize water losses from the above surface. Seedlings were transplanted at four weeks after sowing. *V. unguiculata* was sown directly using seed at a rate of one (1) seed per station because the germination percentage was high based on results of previous standard germination tests carried out at the experimental site. Routine weeding and scouting for pests and diseases were done to ensure best management practices for the trials. Seedlings were planted at an inter-row and intra row spacing of 0.3 m × 0.3 m (111,111 plants ha^{-1}).

2.6. Data Collection

Data collection was done on the inner rows for both seasons to prevent border effects. A total of twelve (12) plants per replication were tagged for data collection for growth and physiology parameters. All measurements were done on leaves that had at least 50% green leaf area. Plant height, leaf number, chlorophyll content index (CCI) and chlorophyll fluorescence (CF) were measured starting from four weeks after transplanting (WAT). Plant height was measured using a measuring tape from the ground level to the tip or apex of the tallest stem. Chlorophyll content index was determined on the adaxial surface using the CCM-200 *Plus* chlorophyll content meter (Opti-Sciences, Inc., USA). All measurements were done before irrigation and at midday.

Harvesting commenced at six (6) weeks after transplanting (WAT) or sowing and every two weeks thereafter. The sample size for yield was 1 m^2 for each replicate for both seasons. During each harvest, *C. olitorius* and *A. cruentus* yield were determined by cutting the mass of the above ground portion of the plant, leaving 0.2 m of plant height above ground level. For *V. unguiculata*, harvesting was done by picking three to four fresh marketable leaves including their tender stems towards the growing tip of each runner, leaving the first and second growing leaves from the tip. Marketable leaves in *V. unguiculata* were defined as fresh or green tender leaves. The harvested portion was then partitioned into leaves and stems. For *B. vulgaris* during each harvest, yields were determined by picking fresh marketable leaves. Marketable leaves were defined as fresh green and tender leaves that were large enough to be marketable, starting from the fifth true leaf. At first harvest, the small lower leaves were removed to promote growth. To obtain accurate results, plants were weighed within an hour to avoid loss of water. Dry matter content was obtained by oven drying at 70°C for 48 h. Yield per hectare was obtained by conversion from measurements taken at 1 m^2 per replicate.

Soil water content (SWC) was monitored using ML-2X Theta Probes connected to a DL-6 data logger (Delta-T Devices, UK) in the rain shelters at varying depths. The frequency of data collection for SWC using the Theta probes was every day. Crop water productivity was determined as follows:

$$CWP = Y/ET_c \tag{2}$$

where: CWP = Crop water productivity in kg m^{-3},

Y = yields above ground in (t ha^{-1}) and
ET$_c$ = crop evapotranspiration in m^3.

2.7. Statistical Analysis

Data were subjected to one-way analysis of variance (ANOVA) using GenStat statistical software (Version 19, VSN International, Hertfordshire, UK). Where there were significant differences ($p \leq 0.05$), the means were further separated using Duncan's multiple range test (DMRT).

3. Results

3.1. Meteorological Conditions and Soil Water Content

Figure 1 shows the soil water content measurements from the three water regimes. The measurements confirmed that there were indeed differences between the three water regimes.
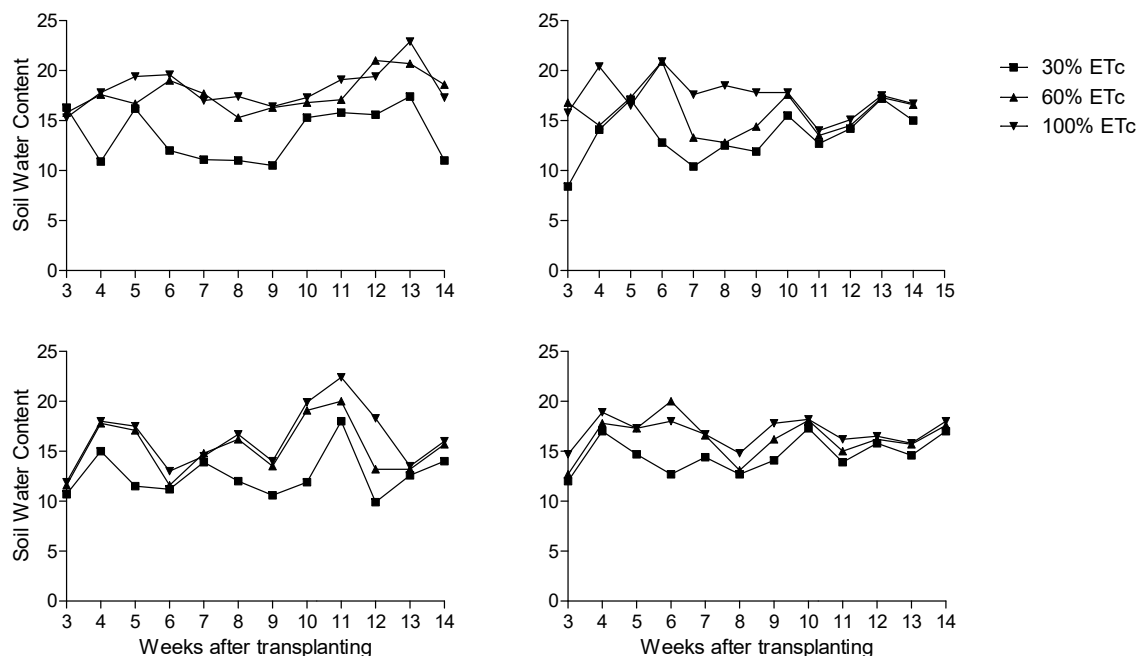
Figure 1. Volumetric soil water content observed from 3 weeks after transplanting (WAT), showing differences between the 30%, 60% and 100% ETc water regimes or cowpea, Amaranthus, Corchorus, and Swiss chard.

In the 2015-16 experiment, the amount of irrigation water applied was slightly higher than in the 2016–17 experiment, although the difference was negligible (Table 2). The ET$_o$ was slightly higher for 2015–16 compared to 2016–17. The 2015–16 season had higher temperature, with an average of 32.47°C, while during the 2016–17 season, the average temperature was 29.95°C. Minimum temperature, radiation and wind speed were similar for both seasons. The weather data were consistent for both seasons.

Table 2. Summary of monthly averages for climatic variables during the growing season of African leafy vegetables (ALVs).

Season 2016–17 Month	[a] T_x (°C)	[b] T_n (°C)	Total Radiation (MJ m^{-2} day^{-1})	Wind Speed (m s^{-1})	[c] ET_o
October	30.90	13.32	25.18	1.15	163.12
November	29.40	15.49	24.70	0.83	148.48
December	30.14	17.39	24.31	0.87	155.51
January	29.36	17.24	23.02	0.89	146.04
Season 2015–16					
October	32.58	14.16	25.17	0.69	161.52
November	31.77	13.95	27.88	1.15	176.03
December	33.88	18.09	26.54	0.94	176.96
January	31.67	17.63	25.68	0.87	165.89

[a] Maximum temperature; [b] minimum temperature; [c] Food and Agriculture Organization (FAO) reference evapotranspiration; Monthly averages and totals were calculated from hourly data. Note: meteorological variables do not include rainfall, because it was excluded in the rain shelter.

3.2. Growth Parameters

Plant height of *A. cruentus* was not significantly ($p > 0.05$) affected by different water regimes for both seasons (Table 3). Despite a lack of statistical significance, the trend was an increase in plant height with the increase in water application for the first season, while during the second season, the trend was an increase from 30% ET_c to 60% ET_c, and then a decline at 100% ET_c (Table 3).

Table 3. Effect of irrigation on growth of selected African leafy vegetables for two seasons.

Plants	Parameters	Irrigation Levels					
		2015/16 Summer (Season 1)			2016/2017 Summer (Season 2)		
		30% ET_c	60% ET_c	100% ET_c	30% ET_c	60% ET_c	100% ET_c
A. cruentus	Plant height (cm)	52.11 ± 3.91 [a]	63.83 ± 4.27 [a]	68.31 ± 6.00 [a]	29.51 ± 1.15 [a]	37.54 ± 1.11 [a]	34.61 ± 3.19 [a]
	Leaf number	80.01 ± 5.87 [a]	103.03 ± 8.61 [a]	111.13 ± 8.10 [a]	69.31 ± 5.14 [a]	64.34 ± 6.10 [a]	74.27 ± 6.44 [a]
C. olitorius	Plant height (cm)	41.10 ± 3.11 [a]	34.30 ± 2.47 [a]	41.63 ± 4.09 [a]	41.82 ± 3.61 [a]	39.58 ± 2.38 [a]	51.40 ± 3.15 [a]
	Leaf number	128.00 ± 6.43 [a]	139.00 ± 9.28 [a]	149.11 ± 9.97 [a]	46.28 ± 3.33 [a]	44.31 ± 3.76 [a]	67.00 ± 4.31 [a]
V. unguiculata	Plant height (cm)	65.44 ± 4.36 [a]	74.31 ± 4.44 [a]	77.02 ± 5.12 [a]	31.30 ± 2.37 [a]	30.53 ± 2.77 [a]	23.72 ± 1.88 [a]
	Leaf number	89.03 ± 3.19 [a]	95.08 ± 7.21 [a]	86.04 ± 7.71 [a]	49.34 ± 3.55 [a]	48.44 ± 3.14 [a]	36.06 ± 0.73 [a]
B. vulgaris	Plant height (cm)	22.91 ± 2.38 [a]	21.14 ± 1.73 [a]	20.7 ± 1.45 [a]	27.51 ± 1.57 [a]	24.31 ± 2.00 [a]	21.52 ± 2.00 [a]
	Leaf number	10.05 ± 0.99 [a]	11.06 ± 0.99 [a]	11.41 ± 0.59 [a]	7.14 ± 0.59 [a]	13.33 ± 0.83 [b]	9.09 ± 0.76 [a]

Mean ± SE values followed by the same letters within a row are not significantly different according to Duncan's multiple range test at $p \leq 0.05$ ($n = 12$).

Although not significant for both seasons, at 100% ET_c, plants had a higher leaf number than at lower water applications during the second season in *A. cruentus*. For the first season, leaf number increased with an increase in water application, as observed in plant height. Although not statistically significant, for both seasons, the trend suggested that limiting water application led to reduced leaf number and plant height. From the study, *A. cruentus* growth was favoured at 30% ET_c to 60% ET_c, although better growth could be expected when the crop was irrigated at 100% ET_c.

In *C. olitorius*, plant height and leaf number were higher in 100% ETc compared to limited water application of 30% ET_c to 60% ET_c for both seasons; however, the differences observed were not significant ($p > 0.05$) for all seasons (Table 3).

There was no significant ($p > 0.05$) difference in leaf number and plant height of *V. unguiculata* for both seasons (Table 3). Although not significant ($p > 0.05$), plant height and leaf number increased from 30% ET_c to 60% ET_c and then declined at 100% ET_c during the first season.

Irrigation regimes did not significantly ($p > 0.05$) affect the plant height of *B. vulgaris* in both seasons (Table 3). Significant ($p < 0.05$) differences were observed for leaf number during the second

season, although no significant differences were recorded during the first season (Table 3). Leaf number increased significantly from 30% ET_c to 60% ET_c and then declined significantly ($p < 0.05$) at 100% ET_c.

3.3. Crop Physiology

Chlorophyll content index was not significantly ($p > 0.05$) affected by varying water regimes in all four crops in both seasons (Figure 2). In *C. olitorius* and *V. unguiculata*, CCI increased with an increase in water application for both seasons, although not statistically significant ($p > 0.05$). A similar trend was observed for *A. cruentus* and *B. vulgaris*, although in some instances, the trend was an increase in CCI from 30% ETc up to 60% ET_c, then a decline.
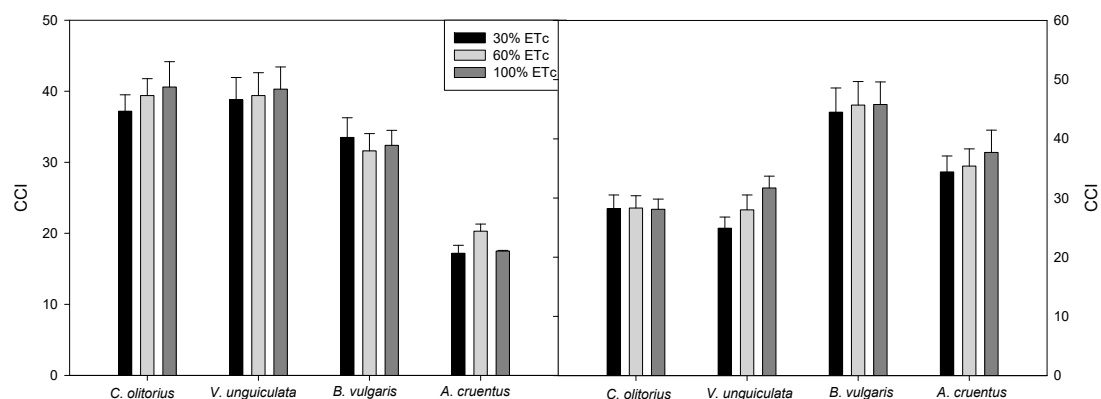

Figure 2. Effect of irrigation on chlorophyll content index (CCI) of selected African leafy vegetables for two seasons. ($n = 12$).

There were no significant ($p > 0.05$) differences in chlorophyll fluorescence (CF) in response to varying water regimes in *A. cruentus*, *C. olitorius*, *B. vulgaris* and *V. unguiculata* (data not shown). Despite lack of statistical significance, there was a tendency of CF in all crops to increase from 30% ET_c to 60% ET_c and up to 100% ET_c.

3.4. Yield Parameters

Yield in *A. cruentus* was significantly ($p < 0.05$) affected by water regimes in both seasons (Table 4). The fresh mass of stems, leaves and leaf dry matter increased significantly ($p < 0.05$) with an increase in water application from 30% ET_c to 60% ET_c, then remained the same at 100% ET_c for both seasons.

In *C. olitorius,* leaf dry matter content (first season) and fresh leaf mass (second season) were significantly ($p < 0.05$) affected by water regimes (Table 4). Leaf dry matter and fresh leaf mass increased significantly ($p < 0.05$) with an increase in water application from 30% ET_c to 60% ET_c, although the further application of water to 100% ET_c did not improve yield. The same trend was observed in other measured yield components for both seasons, although it was not significant ($p > 0.05$). Fasinmirin and Olufayo [25] reported that above ground biomass increased with the amount of water application when grown under irrigated conditions.

Yield components in *V. unguiculata* increased with an increase in irrigation water regimes from 30% ET_c to 100% ET_c in the first season, although these were not significant differences (Table 4). During the second season, yield components increased from 30% ET_c to 60% ET_c, and then remained unchanged at 100% ET_c; however, no significant differences were observed.

In *B. vulgaris,* the fresh mass and dry mass yields were significantly ($p < 0.05$) affected by different water regimes during both seasons (Table 4). Stem fresh mass leaves and leaf dry matter increased significantly ($p < 0.05$) with an increase in water application from 30% ET_c to 60% ET_c and up to 100% ET_c in both seasons. Statistical analysis showed that there was no difference at 60% ET_c to 100% ET_c, and therefore it will be economic for farmers to adapt 60% ET_c for *B. vulgaris*.

Table 4. Effect of irrigation on the yield of selected African leafy vegetables obtained from two growing seasons.

Crops	Plant Parts (t ha^{-1})	Irrigation Levels					
		2015/16 Summer (Season 1)			2016/2017 Summer (Season 2)		
		30% ET$_c$	60% ET$_c$	100% ET$_c$	30% ET$_c$	60% ET$_c$	100% ET$_c$
A. cruentus	FM stem + leaves	**4.11 ± 0.65** [a]	**10.84 ± 1.86** [b]	**7.85 ± 1.15** [ab]	**2.87 ± 0.51** [a]	**4.35 ± 0.49** [ab]	**5.00 ± 0.40** [b]
	FM leaves	3.17 ± 0.72 [a]	4.14 ± 0.53 [a]	3.71 ± 0.32 [a]	**1.66 ± 0.13** [a]	**1.97 ± 0.15** [ab]	**2.45 ± 0.22** [b]
	FM stem	2.92 ± 0.80 [a]	4.67 ± 0.13 [a]	3.60 ± 0.43 [a]	**1.32 ± 0.19** [a]	**1.86 ± 0.17** [ab]	**2.48 ± 0.29** [b]
	DM leaves	**0.54 ± 0.43** [a]	**0.87 ± 0.07** [b]	**0.71 ± 0.09** [ab]	0.38 ± 0.04 [a]	0.50 ± 0.03 [a]	0.54 ± 0.02 [a]
	DM stem	0.45 ± 0.28 [a]	0.70 ± 0.14 [a]	0.52 ± 0.09 [a]	0.38 ± 0.03 [a]	0.39 ± 0.02 [a]	0.48 ± 0.03 [a]
C. olitorius	FM stem + leaves	4.43 ± 0.15 [a]	7.21 ± 0.78 [a]	6.79 ± 1.17 [a]	1.95 ± 0.07 [a]	3.68 ± 0.33 [a]	4.04 ± 0.31 [a]
	FM leaves	2.05 ± 0.26 [a]	2.74 ± 0.49 [a]	2.62 ± 0.34 [a]	**0.83 ± 0.04** [a]	**1.46 ± 0.11** [ab]	**1.70 ± 0.01** [b]
	FM stem	2.40 ± 0.34 [a]	3.72 ± 0.61 [a]	3.40 ± 0.17 [a]	1.21 ± 0.02 [a]	1.32 ± 0.09 [a]	1.25 ± 0.01 [a]
	DM leaves	**0.50 ± 0.04** [a]	**0.63 ± 0.49** [ab]	**0.66 ± 0.04** [b]	0.33 ± 0.03 [a]	0.40 ± 0.00 [a]	0.43 ± 0.03 [a]
	DM stem	0.45 ± 0.04 [a]	0.43 ± 0.03 [a]	0.48 ± 0.03 [a]	0.33 ± 0.03 [a]	0.37 ± 0.03 [a]	0.36 ± 0.03 [a]
V. unguiculata	FM stem + leaves	5.04 ± 0.54 [a]	5.72 ± 0.54 [a]	6.90 ± 0.65 [a]	4.93 ± 0.52 [a]	7.34 ± 0.78 [a]	5.76 ± 0.55 [a]
	FM leaves	3.03 ± 0.34 [a]	3.34 ± 0.31 [a]	3.81 ± 0.34 [a]	2.28 ± 0.01 [a]	3.60 ± 0.34 [a]	2.91 ± 0.18 [a]
	FM stem	2.05 ± 0.29 [a]	2.39 ± 0.14 [a]	3.05 ± 0.21 [a]	2.56 ± 0.02 [a]	3.42 ± 0.29 [a]	2.93 ± 0.31 [a]
	DM leaves	0.62 ± 0.05 [a]	0.68 ± 0.06 [a]	0.68 ± 0.05 [a]	0.59 ± 0.03 [a]	0.54 ± 0.05 [a]	0.51 ± 0.03 [a]
	DM stem	0.36 ± 0.02 [a]	0.39 ± 0.01 [a]	0.43 ± 0.03 [a]	0.57 ± 0.02 [a]	0.44 ± 0.03 [a]	0.44 ± 0.01 [a]
B. vulgaris	FM leaves	**4.53 ± 0.32** [a]	**6.91 ± 0.59** [ab]	**10.26 ± 1.09** [b]	**4.08 ± 0.43** [a]	**6.44 ± 0.02** [b]	**8.67 ± 0.77** [b]
	DM leaves	0.83 ± 0.18 [a]	0.74 ± 0.06 [a]	1.04 ± 0.03 [a]	**0.61 ± 0.02** [a]	**0.72 ± 0.05** [ab]	**0.86 ± 0.06** [b]
	Leaf number	40.00 ± 3.22 [a]	51.00 ± 4.18 [a]	57.00 ± 1.11 [a]	28.00 ± 1.89 [a]	38.00 ± 2.91 [a]	37.00 ± 2.97 [a]

Mean ± SE values followed by the same letters within a row are not significantly different according to Duncan's multiple range tests at $p \leq 0.05$ ($n = 12$). Values in bold indicate treatments that showed significant differences between treatments. FM = fresh mass, DM = dry mass.

3.5. Water Productivity

Amaranthus cruentus grown in the 30% ET$_c$ irrigation treatment produced the lowest average biomass yield on a fresh and dry weight basis (Table 5). The fresh biomass yield for both seasons averaged 6.42 (100% ET$_c$) and 7.59 t ha^{-1} (60% ET$_c$) (Table 5). The average crop water productivity for *A. cruentus* increased from 30% ET$_c$ (1.98 kg m^{-3}) to 60% ET$_c$ (2.15 kg m^{-3}), then dropped at 100% ET$_c$ (1.09 kg m^{-3}). Although water productivity for dry mass decreased as the applied irrigation water increased, the maximum marketable fresh mass yield was obtained in the 60% ET$_c$ treatment (Table 5). Therefore, the results indicate that 60% ET$_c$ irrigation treatment was more water productive than all other treatments in terms of fresh biomass yield.

Corchorus olitorius yield obtained from the irrigation treatments were in the range of 3.18, 5.44 and 5.42 t ha^{-1} on a fresh weight basis for 30%, 60% and 100% ET$_c$, respectively (Table 5). A tendency for the yield to decrease was observed as irrigation was reduced from 100% ET$_c$ to 30% ET$_c$. The highest water productivity was obtained in the driest irrigation treatment (30% ET$_c$).

The highest yields of *V. unguiculata* leaves were obtained in the 60% and 100% ET$_c$ irrigation treatments on a fresh weight basis (Table 5). The highest yields were attained at 60% ET$_c$, while maximum water productivity was obtained where deficit irrigation (30% ET$_c$) was applied. *V. unguiculata* seems to grow at deficit irrigation (30% ET$_c$) without losing marketable quality of the leaves.

The average total yield of *B. vulgaris* obtained in both seasons ranged between 4.30, 6.67 and 9.46 t ha^{-1} on fresh weight (FW) basis for 30, 60 and 100% ET$_c$, respectively (Table 5). The fresh mass yield obtained from the 30% ET$_c$ treatment was not of marketable quality. The highest crop water productivity was obtained in the 30% ET$_c$, where deficit irrigation was applied. Water productivity decreased as applied irrigation water increased, but maximum marketable fresh mass yield was obtained in the 100% ET$_c$ treatment, which was statistical similar to 60% ET$_c$.

Table 5. Average total above ground fresh mass and dry yield, irrigation water use and crop water productivity of selected African leafy vegetables for two seasons (2015/2016 and 2016/2017) ($n = 12$).

African Leaf Vegetables	Well-Watered (100 ET$_c$)			Moderately Watered (60 ET$_c$)			Deficit Irrigation (30 ET$_c$)		
	Average total above ground fresh yield (t ha^{-1})	Average irrigation water Use (mm)	Crop water productivity (kg m^{-3})	Average total above ground fresh yield (t ha^{-1})	Average irrigation water use (mm)	Crop water productivity (kg m^{-3})	Average total above ground Fresh yield (t ha^{-1})	Average irrigation water use (mm)	Crop water productivity (kg m^{-3})
A. cruentus	6.42 ± 0.53	589	1.09 ± 0.01 [a]	7.59 ± 0.69	353	2.15 ± 0.18 [a]	3.49 ± 0.19	176	1.98 ± 0.08 [a]
C. olitorius	5.42 ± 0.37	589	0.91 ± 0.00 [a]	5.44 ± 0.37	353	1.50 ± 0.01 [a]	3.18 ± 0.11	176	1.80 ± 0.12 [a]
V. unguiculata	6.33 ± 0.45	589	**1.07 ± 0.01 [a]**	6.53 ± 0.55	353	**1.84 ± 0.01 [b]**	4.98 ± 0.39	176	**2.83 ± 0.13 [b]**
B. vulgaris	9.46 ± 0.73	589	**1.60 ± 0.02 [b]**	6.67 ± 0.60	353	**1.89 ± 0.02 [b]**	4.30 ± 0.12	176	**2.40 ± 0.07 [a]**

African Leaf Vegetables	Well-Watered (100 ET$_c$)			Medium-Watered (60 ET$_c$)			Deficit Irrigation (30 ET$_c$)		
	Average total above ground dry matter yield (t ha^{-1})	Average irrigation water use (mm)	Crop water productivity (kg m^{-3})	Average total above ground dry matter yield (t ha^{-1})	Average irrigation water use (mm)	Crop water productivity (kg m^{-3})	Average total above ground dry matter yield (t ha^{-1})	Average irrigation water use (mm)	Crop water productivity (kg m^{-3})
A. cruentus	0.56 ± 0.03	589	0.10 ± 0.00 [a]	0.61 ± 0.01	353	0.17 ± 0.01 [a]	0.43 ± 0.03	176	0.24 ± 0.01 [a]
C. olitorius	0.48 ± 0.01	589	0.08 ± 0.00 [a]	0.45 ± 0.04	353	0.12 ± 0.02 [a]	0.40 ± 0.02	176	0.22 ± 0.01 [a]
V. unguiculata	0.51 ± 0.04	589	0.09 ± 0.01 [a]	0.51 ± 0.02	353	0.14 ± 0.00 [a]	0.53 ± 0.02	176	0.30 ± 0.00 [a]
B. vulgaris	0.95 ± 0.07	589	0.16 ± 0.02 [a]	0.73 ± 0.04	353	0.20 ± 0.01 [a]	0.70 ± 0.00	176	0.40 ± 0.02 [a]

Mean ± SE values followed by the same letters within a row comparing different treatments are not significantly different according to Duncan's multiple range tests at $p \leq 0.05$ ($n = 12$). Values in bold indicate treatments that showed significant differences between treatments.

4. Discussion

Although the present study did not show any significant differences in most of the investigated growth parameters, other researchers have reported decreasing plant height with low soil moisture under controlled environments [26,27]. Water stress was shown to reduce plant height, leaf number and area in ALVs such as wild mustard [26] and wild melon [27]. The impairment of mitosis and the elongation and expansion of cells due to moisture stress result in reduced leaf number and reduced crop growth [28]. The reported differences in the results obtained in the present study and previous studies may be due to variation in plant species used, since stress tolerance varies with species, level of stress applied and/or stage of plant growth. The present study, however, showed that *C. olitorius* is able to grow under soil moisture stress condition and hence its distribution in arid regions is thought to be attributed to its tolerance to soil moisture stress.

Researchers have reported various responses of CCI in plants. Chlorophyll content was shown to decrease in sunflower plants subjected to water stress [29]. Vurayai et al. [30] working on pot trials, reported that water stress did not have a significant effect on the chlorophyll content index (CCI) of bambara groundnut landraces and concluded that CCI was not reduced by water stress at all stages of growth. The lack of significant differences in *V. unguiculata* among different irrigation levels may be due to the ability of the crop to maximise resources even at a limited water application of 30% ET$_c$. Therefore, varying irrigation application in *V. unguiculata* did not compromise leaf colour or greenness of the leaf. According to Ashley [31], drought tolerance is the ability of a plant to live, grow and yield satisfactorily with a limited soil moisture supply or under periodic water deficiencies.

The lack of differences in CF in all four crops may suggest that CF was not as sensitive to water stress and is perhaps an indication of the adaptation of these vegetables to harsh environmental conditions.

With regard to *A. cruentus* biomass yield, the results concur with previous reports where irrigation improved biomass yield in amaranth [21]. Saleh et al. [32] also reported that green bean growth parameters and pod yield increased with increasing water application from 60% to 80% of ET$_c$, while a further increase up to 100% ET$_c$ did not improve yield. Water deficit often causes plant water stress, which has a negative effect on the growth and quality of plants and would cause substantial reductions in yield [33]. Similar observations were also made by Beletse et al. [20], where moderately watered plants had better yield than well-watered plants. Higher yield was obtained in the 60% ET$_c$ treatment than in the 100% ET$_c$ irrigation treatment. The reduced yield obtained in the 100% ET$_c$ treatment could be attributed to the high frequency of irrigation applied to replenish the soil water deficit, which may have caused nutrient leaching from the root zone [20]. Lower yields in limited water application for *A. cruentus* concur with previous researchers who reported that drought tolerance

in amaranth depends on the species [34–36]. Yarnia et al. [37] also reported that applying low levels of irrigation lead to a reduction in yield. According to Beletse et al. [20], however, yields obtained under water-stressed conditions may lack the quality needed to market the produce. Although the results on growth parameters (leaf number and plant height) were not significant, the trend was consistent with yield results.

Corchorus olitorius is susceptible to moisture stress owing to its shallow rooting depth [13]. Taylor and Wepper [38] reported that the yield of *C. olitorius* was enhanced when irrigation was used in conjunction with rainfall to reduce soil moisture stress. When evaporation rates are high, frequent irrigations are required to maintain the available water for plants at levels necessary to maximize growth and yield [39,40].

Studies conducted elsewhere showed that cowpea [41,42] is tolerant to adverse climatic conditions. The results of the present study indicate the potential of *V. unguiculata* production under deficit irrigation. *Vigna unguiculata* grew well under deficit irrigation of 30% ET_c without losing the quality of the leaves. Drought stress did not have an influence on the biomass of the crop. The results, however, are contrary to those of Hayatu and Mukhtar [43], who reported that drought stress significantly reduced plant aboveground biomass in cowpea genotypes. The differences in the reported results can be explained by Nkaa et al. [44], who deduced that different cowpea varieties perform differently under various stress conditions. In both seasons, applications of 100% ET_c produced double the amount of biomass compared to 30% ET_c in *V. unguiculata* [44]. The highest fresh leaf mass was obtained from the 100% ET_c treatment in *B. vulgaris*, which indicates that the crop favoured high levels of soil water availability for optimum growth and development. Similarly, Van Averbeke and Netshithuthuni [45] reported that *Brassica* species such as Chinese cabbage are sensitive to water stress. Sammis and Wu [46] found that cabbage marketable yield increased linearly with increased water application and Sanchez et al. [47] concluded that cabbage production was optimized when crops were irrigated for evapotranspiration (ET) replacement, while both deficit and excess irrigation reduced yield. The results from these studies suggest points to the resilience of indigenous vegetables (mostly growing in the wild) to moisture stress compared to those cultivated commercially.

Amaranth plants exhibit lower water loss rates and greater water use efficiency than many other C4 plants, and more so in dry conditions [48,49]. Amaranth has often been described as a drought-tolerant crop [49,50], capable of maintaining normal physiological processes under stress. The findings on yield response to limited water availability in *A. cruentus* are consistent with the results of water productivity on fresh mass basis. The results are also consistent with the findings of Beletse et al. [20], who observed higher water productivity in water limited treatments in comparison to well-watered treatments. Improving water productivity can contribute to global food production and poverty alleviation. On the contrary, Fasinmirin and Olufayo [25] reported higher biomass yield and WUE of *C. olitorius* can be achieved when the crop is grown at full irrigation. Deficit irrigation compromised leaf quality in *C. olitorius*, as the crop favours good application of water for its growth and development [20]. Water deficit reduces crop productivity, causing economic losses [1]. Drought stress has been reported to decrease water use efficiency (WUE), leaf production and root proliferation, and consequently, crop productivity [51]. According to Beletse et al. [20], if the crop is grown for seed or bean production, it must be well irrigated to get optimum yield. Water use efficiency is an important trait for improving drought tolerance in cowpea, as it saves a considerable amount of irrigation water. An improvement in water use efficiency would significantly enhance total biomass production as well as yield at a given level of soil water availability. Water use efficiency has been reported to increase with decreasing water supply [52,53].

The ALVs differed in their response to drought stress because plant response to drought depends on plant species and stress severity. The results from the 2-year data show that ALVs performed comparably to or better than *B. vulgaris* as far as water productivity was concerned. At deficit irrigation (30% ET_c), *V. unguiculata* produced the highest amount of biomass per cubic metre of water, followed by *B. vulgaris*, *A. cruentus* and *C. olitorius*. At 60% ET_c, *A. cruentus* produced the highest amount of

biomass per cubic metre of water, followed by *B vulgaris*, *V. unguiculata* and *C. olitorius.* In the *B. vulgaris* irrigation experiment, the highest leaf fresh weight was obtained from the 100% ET_c treatment and this indicates that *B. vulgaris* favours the regular application of water for optimum growth and development, confirming the findings reported by Van Averbeke and Netshithuthuni [45]. Nyathi et al. [21] reported that the results of water productivity of ALVs are comparable to those of *B. vulgaris*.

If farmers are to select a preferred crop among the three ALVs crops studied, they should consider yield, cost of inputs and irrigation set up, among other factors. At a limited water level of 30% ET_c, *V. unguiculata* performed similarly in terms of growth and yield compared to other water treatments. This suggests that the production of this crop is still possible under limited water supply. This confirms the study by Beletse et al. [20], in which *V. unguiculata* was ranked as one of the most drought-tolerant crops compared to *B. vulgaris*. *Vigna unguiculata* production was optimised in terms of a reduced amount of water use under limited water supply. Furthermore, limited water supply can be efficient in terms of the use of less fertiliser, which cannot be leached, and low maintenance of irrigation systems. At higher water application, the systems will have to run for a long time compared to limited water application. If farmers decide to grow *V. unguiculata*, the benefits include reduced soil erosion, and improved soil status due to nitrogen fixation.

For *A. cruentus* and *C. olitorius,* the application of 30% ET_c resulted in a reduced yield, and therefore production was optimal at 60% ET_c. In *B. vulgaris*, yield was higher in water regimes of 100% ET_c, which was statistically similar to 60% ET_c. This concurs with the report that water deficit affects the growth, development, yield and quality of plants in greenhouse and field conditions [54]. The development of a wider choice of crops adapted to dry areas is crucial because of global warming threats, a decrease in water supply and the demand to feed an increasing population. Research results on water productivity can help in the decision-making options of vegetable growers in terms of calculating gross returns. This gives important insights into economic water productivity per cubic metre of water applied. Where irrigation water is in limited supply, or where irrigation is expensive, irrigation management methods are needed which result in less water use while maintaining adequate yields of the economic product.

5. Conclusions

While water stress reduced yield for *A. cruentus*, *C. olitorius* and *B. vulgaris*, our results concur with reports that ALVs can perform better or comparable to alien/exotic vegetables such as *B. vulgaris* under similar conditions. In particular, *V. unguiculata* was stable, for all measured parameters, across the varying water regimes and performed better than other ALVs, including *B. vulgaris*. Yield followed a similar trend in *A. cruentus*, *C. olitorius* and *B. vulgaris*; an increase with an increase in water application from 30% ET_c to 60% ET_c, and then remained the same at 100% ET_c. Interestingly, irrigating at 100% ET_c led to lower yields than at 60% ET_c, suggesting that the latter was a more optimal irrigation level. However, there is a possibility that the optimum level of water application could still be lower than in the current study, making them even better adapted to marginal areas. In this regard, crop models may be applied to further optimise irrigation for ALVs. The highest WP was obtained at 30% ET_c; however, this compromised leaf quality for *B. vulgaris*, *C. olitorius* and *A. cruentus*. The highest WP was obtained in *V. unguiculata* and *A. cruentus*, respectively, compared to *B. vulgaris*. Overall, the results of this study indicate that the ALVs had a higher degree of drought tolerance than the reference crop, *B. vulgaris*. The ranking for drought tolerance, starting with the most tolerant, could be: *V. unguiculata*, *C. olitorius*, *A. cruentus* and *B. vulgaris*.

Considering that drought seldom occurs in isolation, and mostly interacts with a multitude of other abiotic and biotic stresses, such as temperature and incidence of disease, it is important that these factors are studied simultaneously. Further work needs to be done on using fertiliser application methods, such as fertigation along with irrigation, which could possibly reduce fertiliser application rates, thereby reducing fertiliser costs and increasing the sustainability of the enterprise. In addition, multi-location trials and studies of different varieties in South Africa are required.

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