Water SA 46(3) 410–418 / Jul 2020
https://doi.org/10.17159/wsa/2020.v46.i3.8651

Research paper

Nutritional yield and nutritional water productivity of cowpea (*Vigna unguiculata* L. Walp) under varying irrigation water regimes

Edwin Kimutai Kanda[1,3], Aidan Senzanje[1], Tafadzwanashe Mabhaudhi[2] and Shadrack Chisenga Mubanga[1]

[1] *School of Engineering, University of KwaZulu-Natal, P. Bag X01, Scottsville, Pietermaritzburg, South Africa*
[2] *Centre for Transformative Agricultural and Food Systems, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, P. Bag X01, Scottsville, 3209, Pietermaritzburg, South Africa*
[3] *Department of Civil and Structural Engineering, Masinde Muliro University of Science and Technology, PO Box 190, Kakamega, 50100, Kenya*

There is a need to mainstream traditional crops in sub-Saharan Africa, in order to tackle food and nutritional insecurity through incorporating nutritional quality into crop water productivity, in the wider context of the water–food–nutrition–health nexus. The objective of the study was to determine the effect of irrigation water regimes on the nutritional yield (NY) and nutritional water productivity (NWP) of cowpea under Moistube irrigation (MTI) and subsurface drip irrigation (SDI). We hypothesized that NY and NWP of cowpea were not different under MTI and SDI and that deficit irrigation improved NWP. The experiment was laid as a split-plot design arranged in randomized complete blocks, replicated 3 times, with 3 irrigation water regimes: 100% of crop evapotranspiration (ET_c), 70% of ET_c, and 40% of ET_c. Irrigation type and water regime did not significantly ($p > 0.05$) affect the nutritional quality of cowpea. Similarly, NWP of crude fat (28.20–39.20 $g \cdot m^{-3}$), ash (47.20–50.70 $g \cdot m^{-3}$) and crude fibre (30.70–48.10 $g \cdot m^{-3}$) did not vary significantly. However, protein and carbohydrate NWP showed significant ($p < 0.05$) differences across irrigation water regimes and irrigation type. The highest protein NWP (276.20 $g \cdot m^{-3}$) was attained under MTI at 100% ET_c, which was significantly ($p < 0.05$) higher than SDI (237.1 $g \cdot m^{-3}$) and MTI (189.8 $g \cdot m^{-3}$) at 40% ET_c. Cowpea is suited for production in water-scarce environments; however, there are trade-offs with carbohydrate NWP. This should not be of concern as often diets are already energy-dense but lacking in other micronutrients.

CORRESPONDENCE
Edwin Kimutai Kanda

EMAIL
Kandaedwin@gmail.com

DATES
Received: 30 December 2019
Accepted: 30 June 2020

KEYWORDS
deficit irrigation
nutritional quality
proximate composition
subsurface irrigation
traditional legume

INTRODUCTION

Food and nutritional insecurity are a global concern, which is the main cause of deaths in children, especially in developing countries; it is mostly attributed to consumption of foods rich in carbohydrates but lacking in protein and other micronutrients (Jayathilake et al., 2018). Food and nutrition insecurity in the world's arid and semi-arid tropics is aggravated by previous efforts to address this, which were biased towards cereals and tubers; this inadvertently led to protein and other micronutrient deficiencies among the populace (Chibarabada et al., 2017a). In South Africa, food and nutritional insecurity are also a major problem; statistics indicate that one in every two households faces some form of hidden hunger (deficiency in micronutrients), with only a fifth of the population being food-secure (Schonfeldt and Pretorius, 2011). Food and nutrition insecurity tend to disproportionately affect rural resource-poor households in South Africa (Nyathi et al., 2018). Therefore, there is a need for the incorporation of low-cost nutrient-dense foods into the diets of rural resource-poor households.

Legumes are important sources of nutrients in human diets, with cowpea (*Vigna unguiculata* L. Walp) having agronomic, environmental and economic advantages, which are relevant in improving the livelihoods of small-scale farmers in the global South (Gonçalves et al., 2016). For example, the protein content in cowpea, on average, is three times greater than that of tubers and cereals (Timko et al. 2007). Cowpea is more tolerant to water stress and demonstrates yield stability relative to other legumes such as groundnut (*Arachis hypogea*) (Halilou et al., 2015). Besides drought tolerance, cowpea also grows favourably under heat stress and low fertility conditions (Carvalho et al., 2017; Timko et al., 2007; Timko and Singh, 2008). Cowpea is a dual-purpose crop, in several ways. Firstly, it can be considered as both a small grain crop and a leafy vegetable. Secondly, cowpea can be grown for both human consumption and livestock feed. This adds to its suitability in resource-poor environments where cropping systems must be able to meet diverse household needs. Among the traditional leafy vegetables, edible parts of cowpea had the highest protein and iron contents that would supply the full recommended dietary allowance (RDA) for iron and half for protein when compared to amaranths (*Amaranthus* spp.), spider plant (*Cleome gynandra*), pumpkin leaves (*Cucurbita moschata*) and Jute mallow (*Corchorus olitorius*) (Abukutsa-Onyango et al., 2010). Despite its nutritional significance, cowpea production in South Africa is low compared to West and Central African countries (DAFF, 2014). This may be attributed to, among other factors, lack of information describing best management practices for cowpea production (Asiwe, 2009).

Most of the research regarding food security has been on food and water either in isolation or jointly under crop water productivity (WP), i.e., producing more food using less water. However, issues surrounding WP and nutritional security should not be addressed in isolation but by adopting a holistic approach through the inclusion of nutritional value into WP (Mabhaudhi et al., 2016). Adopting WP index in agriculture is limiting since it aims at maximizing the output (quantity); using less inputs (water quantity) without addressing the quality of the output. Linking WP to nutritional quality gives rise to the term nutritional water productivity (NWP), which was initially reported by Renault and Wallender (2000). Therefore, enhancement of nutrient water productivity of a crop is achieved by improving the crop water productivity and the nutritional content. Water productivity is improved by adopting efficient irrigation systems, such as micro-irrigation, and appropriate agricultural water management practices, such as deficit irrigation. Micro-irrigation helps in improving crop water productivity by minimizing the non-effective water losses such as evaporation, runoff and drainage (Ali and Talukder, 2008; Van Halsema and Vincent, 2012). Deficit irrigation is one of the main water-saving irrigation strategies where volume of water applied is below the crop water requirement with the aim of maximizing water productivity (Fereres and Soriano, 2007).

There are minimal studies on nutrient water productivity in legumes since most research has been on quantity (Faloye and Alatise, 2017; Mousa and Al-Qurashi, 2017; Ntombela, 2012) and quality (Henshaw, 2008; Okonya and Maass, 2014; Schönfeldt and Pretorius, 2011) in isolation, rather than a combination of the two in the wider context of the water–food–nutrition–health nexus (Mabhaudhi et al., 2016). A study by Chibarabada et al. (2017b) determined the nutrient water productivity of groundnut, cowpea, dry bean and bambara groundnut with respect to varying water regimes across different environments. The main constituents considered were fat, protein and micro-nutrients such as calcium and iron. In their study, cowpea data were only available for one site and thus it was not conclusive since it did not include varying water regimes like the other three legumes. Nyathi et al. (2018) conducted a study on nutrient water productivity of African leafy vegetables which included amaranth (*Amaranthus cruentus*), spider flower (*Cleome gynandra*) and Swiss chard (*Beta vulgaris*), an alien leafy vegetable widely consumed in Sub-Saharan Africa (SSA).

Moistube irrigation (MTI) is a relatively new type of subsurface irrigation technology, which originated in China. It is similar to subsurface drip irrigation (SDI), whereby, instead of emitters, water flows out of the Moistube membrane as a function of applied pressure and the soil water potential (Yang et al., 2008). Moistube irrigation improved the total yield, Vitamin C, soluble sugars and soluble acid ratio of tomato, despite using 38% less water, compared to drip irrigation (Lyu et al., 2016). Yao et al. (2014) established that Moistube irrigated navel orange fruit had the highest photosynthetic rate, leaf respiration and yield compared to conventional irrigation and rainfed conditions. Recently, Kanda et al. (2020) established that there was no difference between yield of cowpea under Moistube irrigation and subsurface drip irrigation in South Africa. The yield and water productivity under Moistube irrigation have been reported to be similar or higher than conventional irrigation in spinach, wheat and eggplant, as reviewed in Kanda et al. (2019). This therefore indicates that Moistube irrigation has the potential for improving not only the crop growth and yield quantity, but also the yield quality.

To the best of our knowledge, no detailed study has been done to determine nutrient water productivity of cowpea since it is one of the traditional crops. Further, being a new technology, there is no information on the nutritional quality and NWP of cowpea under Moistube irrigation. Therefore, this study aimed at determining the nutritional yield and NWP of cowpea under varying water regimes and under Moistube and subsurface drip irrigation. Our hypotheses were: (i) the nutritional yield of cowpea is not different between the two types of irrigation and water regimes and (ii) NWP can be improved by deficit irrigation strategy.

MATERIALS AND METHODS

Description of study sites and experimental designs

Two sets of experiments were conducted during 2018 in tunnels located at the University of KwaZulu-Natal's Ukulinga Research Farm in Pietermaritzburg (29.67° S, 30.41° E) and Controlled Environment Research Unit (CERU) (29.58° S, 30.42° E), KwaZulu-Natal, South Africa.

The first tunnel experiment was conducted in a 12 m by 5 m tunnel. The soil texture was clay (24.3% sand, 23.6% silt and 52.1% clay) with a bulk density of 1.23 g·cm^{-3} and hydraulic characteristics indicated in Table 1. The tunnel at Ukulinga had open ends to allow free horizontal movement of air. During the growing period, the temperature in the tunnel varied from 4°C to 15°C. A split-plot design was used, arranged in randomised complete blocks, with 3 replications. The main plots were assigned to 2 irrigation types (subsurface drip irrigation and Moistube irrigation) and the sub-plots were 3 irrigation water regimes (100% of ET_c, 70% of ET_c and 40% of ET_c). The drip emitters and Moistube tapes were installed at a depth of 15 cm, which was guided by the crop rooting depth. Cowpea (brown mix variety) was planted on 25 May 2018 during winter season. The spacing was 50 cm between rows and 30 cm within rows (66 667 plants·ha^{-1}). Soil fertility results (Table 2) indicated soils at Ukulinga were not nutrient-deficient; hence fertilizers were not added. The deficit irrigation treatments were introduced 30 days after planting (DAP), when the crops were fully established.

The second tunnel experiment was conducted in 11 m long raised beds measuring 0.75 m wide and 0.75 m high at CERU. The soil texture was loam (42.3% sand, 33.3% silt, 24.4%), with bulk density of 1.36 g·cm^{-3} and hydraulic characteristics in Table 1.

Table 1. Soil hydraulic properties

Experiment location	Texture class	θ_{FC} (cm^3·cm^{-3})	θ_{PWP} (cm· cm^{-3})	θ_{sat} (cm^3·cm^{-3})	K_s (mm·d^{-1})	TAW (mm)
CERU	Loam	0.315	0.160	0.458	186	155
Ukulinga	Clay	0.436	0.293	0.534	32.4	143

θ_{FC} = water content at field capacity, θ_{PWP} = water content at wilting point, θ_{sat} = water content at saturation, K_s = saturated hydraulic conductivity, TAW = total available water, CERU = Controlled Experiment Research Unit

Table 2. Soil nutrient status

Experiment location	N (mg·L^{-1})	P (mg·L^{-1})	K (mg·L^{-1})	Ca (mg·L^{-1})	Mg (mg·L^{-1})	pH	Zn (mg·L^{-1})	Mn (mg·L^{-1})	Cu (mg·L^{-1})
CERU	1 900	4	209	1 125	l29	5.06	2.1	54	4.8
Ukulinga	3 200	129	256	1 959	388	5.62	31	48	5.8

CERU = Controlled Experiment Research Unit

The experimental design, cowpea variety and plant density were similar to the tunnel experiment at Ukulinga. However, soil fertility tests (Table 2) indicated that the soil required phosphorus, which was applied as Single Superphosphate (10.5% P) at 60 kg·ha^{-1}. Cowpea was planted on 14 February 2018 and deficit irrigation treatments were introduced 21 DAP; other agronomic management practices were done accordingly based on recommended best practices (DAFF, 2014). The description of the experimental design used in this study is found in Kanda et al. (2020).

Data collection

Weather data were obtained inside the tunnel using HOBO data logger sensors (Onset Computer Corporation, USA). The variables measured were temperature, relative humidity and solar radiation. Wind speed was measured using a Kestrel 3000 anemometer (Nielsen-Kellerman, Inc. USA).

The soil water content during the crop season at the CERU experiment was measured weekly using Water Mark sensors (Irrometer Inc. USA) and MPS-2 sensors (Decagon, Inc. USA) installed at 10 cm, 20 cm and 40 cm depths. Gravimetric water measurements were carried out occasionally and together with volumetric measurements obtained from EC-5 sensors (Decagon, Inc. USA) used to calibrate the MPS-2 measurements. In the tunnel experiment at Ukulinga, soil water content was measured weekly using PR2/6 profile probe attached to HH2 meter (Delta-T, UK).

Determination of cowpea grain yield components was done by sampling 10 plants per plot, excluding border plants. All the pods were harvested from each plant, air dried, counted and then shelled for yield analysis. However, due to low winter temperatures, the cowpea grown in the Ukulinga tunnel failed to flower and thus no yield was realized. Therefore, the results in this study were for the CERU experiment.

Irrigation management and actual evapotranspiration

The different irrigation water regimes were applied by varying the irrigation interval in such a way that the total amount of irrigation was 100%, 70%, and 40% of ET_c. In subsurface drip irrigation, the amount of water applied per irrigation event was the same, but the irrigation interval was different for the deficit irrigation. Drip emitters of nominal flow rate of 1.6 L·h^{-1} were used in this study. This flow rate was used to calculate the amount of water to be applied every irrigation event. In Moistube irrigation treatment, a pressure of 20 kPa was used which gave a Moistube discharge of 0.24 L·h^{-1}·m^{-1}. The water application was applied intermittently, ranging from as low as 3 days, 5 days, and 8 days continuously per 10 days for 100% ETc, 70% ETc and 40% ETc, respectively. The description of the irrigation management is found in Kanda et al. (2020).

Actual evapotranspiration for cowpea over the growing period was computed using the water budget method (Eq. 1):

$$ET_a = P + I + C - D - R \pm \Delta S \tag{1}$$

where ET_a = actual evapotranspiration, P = rainfall, I = irrigation, C = capillary rise, R = surface runoff, D = drainage, and ΔS = change in soil water storage.

The experiments were carried out in tunnels and, therefore, rainfall was zero. Also, there was no capillary rise, as well as drainage, since the soil water content hardly ever exceeded field capacity. Subsurface irrigation eliminates the runoff component. Therefore, the water balance equation was simplified to:

$$ET_a = I \pm \Delta S \tag{2}$$

where ET_a = actual evapotranspiration (mm) and ΔS = change in soil water storage (mm).

ET_a (m^3·ha^{-1}) was obtained using Eq. 3 (Allen et al., 1998):

$$1\,\text{mm} \cdot \text{day}^{-1} = 10\ \text{m}^3 \cdot \text{ha}^{-1} \cdot \text{day}^{-1} \tag{3}$$

The change in soil water content (ΔS) was determined using the Water Mark sensors, EC-2 sensors and PR2/6 probes.

Nutrient analysis

All nutrient analyses were conducted in the Proximate Analysis laboratory of the School of Agricultural, Earth and Environmental Sciences (SAEES) at the University of KwaZulu-Natal. Moisture content, crude fibre, lipids, ash and protein were determined according to the Association of Official Analytical Chemists (AOAC) protocol (AOAC, 2012). The carbohydrate content was determined by difference as described in Emmanuel et al. (2012) using Eq. 4:

$$\text{Carbohydrate content (\%)} = 100 - (\text{moisture} + \text{ash} + \text{protein} + \text{lipid} + \text{fibre}) \tag{4}$$

Nutritional yield and nutritional water productivity

Nutritional yield is a function of nutritional composition and edible biomass; it was calculated using Eq. 5 (Nyathi et al., 2019):

$$\text{NY} = (\text{NC} \times Y) \div 100 \tag{5}$$

where NY = nutritional yield (kg·ha^{-1}), Y = yield (kg·ha^{-1}) and NC = nutrient concentration per kg of product (nutrient unit·kg^{-1})

Nutritional water productivity was then computed using Eq. 6 (Renault and Wallender, 2000):

$$\text{NWP} = \frac{Y_a}{ET_a} \times \text{NC} \tag{6}$$

NWP = nutritional water productivity (nutritional unit per m^3 of water)
Y_a = actual harvested yield (kg·ha^{-1})
ET_a = actual evapotranspiration (m^3·ha^{-1})
NC = nutrient concentration per kg of product (nutrient unit·kg^{-1})

The yield in Eqs 5 and 6 refers to the edible part of the crop (Nyathi et al., 2019). This means that for leafy vegetables, the yield is aboveground biomass. However, in this study, cowpea was assumed as a grain legume, notwithstanding the fact that it is also consumed as leafy vegetable. Therefore, this study defined yield of cowpea as grain yield.

The percentage contribution to the daily recommended nutrient intake (DRNI) and the potential contribution to human nutrition were computed using Eqs 7 and 8, respectively (Nyathi et al., 2019)

$$\text{Contribution to DRNI (\%)} = (\text{NC} \div \text{nutrient requirement in g} \cdot \text{day}^{-1}) \times 100 \tag{7}$$

$$\text{Water required (L} \cdot \text{person}^{-1} \cdot \text{day}^{-1} = \text{average nutrients required} \div \text{NWP} \times 1\,000 \tag{8}$$

Equation 8 was computed using a family of 4 people: one male adult (31–50 years), one female adult (31–50 years), one 1–3-year-old child, and one 4–8-year-old child).

Statistical analysis

The reported data were analysed using ANOVA in GenStat version 18 (VSN International, Hemel Hempstead, UK). Tests for homogeneity of variance and normality of the data were done using Bartlett's test and Shapiro-Wilk test, respectively. Separation of means of significant variables were done using Duncan's least significant differences (LSD) at 5% significance level.

RESULTS

Irrigation amount

The total amount of water applied during the growing season (Fig. 1) varied from 162 mm to 369 mm. The irrigation amount was not significantly different ($p > 0.05$) among irrigation types.

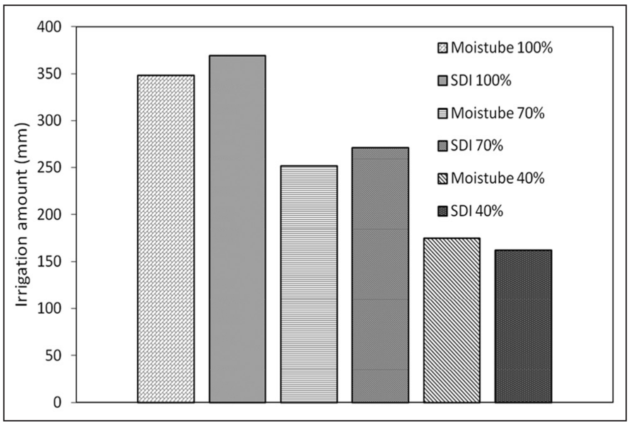

Figure 1. Amount of irrigation applied

Yield, biomass and harvest index

The grain yield, biomass and harvest index of cowpea varied significantly ($p < 0.05$) across water regimes (Table 3). Grain yield, on average, decreased by 19% and 55% under 70% ET_c and 40% ET_c, respectively. Cowpea plants subjected to irrigation at 70% ET_c and 40% ET_c attained 12% and 35% less biomass yield than plants which received irrigation at 100% ET_c. Harvest index decreased by 9% and 32% under 70% ET_c and 40% ET_c, respectively. The results in Table 3, including those of yield components such as pod number, seed number, seed mass and pod mass, are found in Kanda et al. (2020).

Nutritional yield and potential contribution to human nutrition

There were no significant ($p > 0.05$) differences in the nutritional quality of cowpea grains across the water regimes and irrigation types (Table 4). This demonstrates the attribute of cowpea as a drought-tolerant crop. The average crude fat content was 3.42%, whereas crude fibre content was 3.92%. Ash content ranged between 4.5% and 4.8%. The average crude protein and carbohydrate contents were 24.33% and 50.84%, respectively.

The correlation among nutritional components of cowpea is shown in Table 5. Protein content exhibited significant negative correlation with water regimes ($r = -0.437$, $p < 0.05$). This suggests that protein content decreased with increase in water deficit, except under subsurface drip irrigation at 70% ET_c marginally lower than at 40% ET_c (Table 4). The highest protein content was achieved under Moistube irrigation at 100% ET_c, whereas the lowest value was under Moistube irrigation at 40% ET_c. Carbohydrate showed significant ($p < 0.05$) negative relationship with crude fat ($r = -0.953$), ash ($r = -0.615$) and protein ($r = -0.537$). Crude fibre showed significant negative ($r = -0.520$) and positive ($r = 0.664$) correlation with protein and moisture, respectively. Crude fat has a significant positive relationship with ash ($r = 0.668$) and protein ($r = 0.484$).

The nutritional yield (NY) of cowpea varied across water regimes and irrigation type (Table 6). Protein and carbohydrate nutrient yields varied significantly ($p < 0.05$) across water regimes but non-significantly ($p > 0.05$) due to irrigation type. Optimum irrigation under Moistube irrigation recorded the highest protein yield.

Table 3. Grain yield, biomass and harvest index of cowpea

Irrigation type	Water regime	Grain yield ($kg{\cdot}ha^{-1}$) (SD)	Final biomass ($kg{\cdot}ha^{-1}$) (SD)	Harvest index (%) (SD)
Moistube	100% ET_c	3 189 (634) ^{a}	9 272 (1 247) ^{a}	34.8 (5.3) ^{a}
SDI	100% ET_c	3 025 (695) ^{a}	9 678 (1 098) ^{a}	31.5 (6.2) ^{b}
Moistube	70% ET_c	2 401 (612) ^{b}	8 012 (1 048) ^{c}	30.1 (5.5) ^{b}
SDI	70% ET_c	2 605 (701) ^{b}	8 590 (1 339) ^{b}	30.5 (6.0) ^{b}
Moistube	40% ET_c	1 280 (598) ^{c}	5 701 (926) ^{e}	22.4 (9.2) ^{c}
SDI	40% ET_c	1 505 (462) ^{c}	6 694 (1 263) ^{d}	22.6 (4.8) ^{c}
LSD (irrigation x ET_c)		152.9	607.2	2.9

Mean values in the same column followed by the same superscript letter do not differ significantly at 5% significance level by LSD.
SD = standard deviation, ET_c = crop evapotranspiration, SDI = subsurface drip irrigation

Table 4. Nutritional quality of cowpea seeds per 100 g (%)

Irrigation	Water regime	Crude fat (SD)	Ash (SD)	Protein (SD)	Crude fibre (SD)	Moisture (SD)	Carbohydrate (SD)
SDI	100% ET_c	3.70 (0.36)	4.65 (0.12)	25.01 (1.04)	3.41 (0.75)	12.20 (0.17)	51.04 (1.08)
Moistube	100% ET_c	3.57 (1.04)	4.75 (0.24)	25.57 (0.76)	3.30 (0.69)	12.40 (0.20)	50.41 (2.99)
SDI	70% ET_c	3.07 (0.94)	4.45 (0.35)	24.13 (0.88)	4.06 (1.57)	12.83 (0.21)	51.45 (1.76)
Moistube	70% ET_c	3.11 (0.85)	4.59 (0.63)	23.67 (1.43)	4.02 (1.70)	12.27 (0.15)	52.35 (2.46)
SDI	40% ET_c	4.40 (1.03)	4.78 (0.92)	24.20 (1.74)	4.91 (0.12)	12.77 (0.32)	48.95 (2.49)
Moistube	40% ET_c	2.66 (0.76)	4.64 (0.58)	23.44 (2.51)	3.79 (1.07)	12.53 (0.60)	52.95 (3.31)
LSD (irrigation x ET_c)		3.45	0.75	2.52	2.00	0.56	4.19

ET_c = crop evapotranspiration, SD = standard deviation, SDI = subsurface drip irrigation

Table 5. Correlation among nutritive values and water regimes

	Water regime	Crude fat	Ash	Protein	Crude fibre	Moisture	Carbohydrate
Water regime	1						
Crude fat	−0.026	1					
Ash	0.013	0.668*	1				
Protein	−0.437*	0.484*	0.408	1			
Crude fibre	0.384	0.429	0.109	−0.520*	1		
Moisture	0.407	0.116	−0.166	−0.287	0.664*	1	
Carbohydrate	0.040	−0.953*	−0.615*	−0.547*	−0.423	−0.324	1

**significant at* p *= 0.05*

Table 6. Nutritional yield of cowpea

Irrigation	Water regime	Nutritional yield ($kg \cdot ha^{-1}$)			
		Crude fat (SD)	Protein (SD)	Crude fibre (SD)	Carbohydrate (SD)
Moistube	100% ET_c	115 (32)[a]	815 (159)[a]	105 (25)[a]	1 608 (337)[a]
SDI	100% ET_c	111 (25)[a]	759 (184)[a]	104 (34)[a]	1 541 (344)[a]
Moistube	70% ET_c	68 (28)[b]	571 (162)[b]	94 (35)[a]	1 262 (347)[b]
SDI	70% ET_c	80 (26)[b]	628 (175)[b]	106 (44) [a]	1 341 (353)[b]
Moistube	40% ET_c	34 (14)[c]	304 (159)[c]	47 (18)[c]	675 (306)[c]
SDI	40% ET_c	66 (20)[b]	364 (110)[c]	74 (22)[b]	738 (231)[c]
LSD (irrigation x ET_c)		23.9	81.4	15.9	164.3

Mean values in same column followed by same superscript letter do not differ significantly at 5% significance level by LSD.
ET_c = crop evapotranspiration, SD = standard deviation, SDI = Subsurface drip irrigation, nutritional yield = grain yield x nutrient content

Table 7. Contribution to recommended daily nutrient intake

	ET_c (%)	Contribution to daily recommended nutrient intake (%)															
		Carbohydrate				Total fibre				Total fat*				Protein			
		1–3 yr	4–8 yr	Adult male	Adult female	1–3 yr	4–8 yr	Adult male	Adult female	1–3 yr	4–8 yr	Adult male	Adult female	1–3 yr	4–8 yr	Adult male	Adult female
Moistube	100	39	39	39	39	17	13	9	13	10	12	13	13	197	135	46	56
SDI	100	39	39	39	39	18	14	9	14	11	12	13	13	192	132	45	54
Moistube	70	40	40	40	40	21	16	11	16	9	10	11	11	182	125	42	51
SDI	70	40	40	40	40	21	16	11	16	9	10	11	11	186	127	43	52
Moistube	40	41	41	41	41	20	15	10	15	8	9	9	9	180	123	42	51
SDI	40	38	38	38	38	26	20	13	20	13	15	16	16	186	127	43	53

*SDI = subsurface drip irrigation, ET_c = crop evapotranspiration, *total fat was computed using average of acceptable macronutrient distribution range (AMDR) instead of recommended dietary allowance*

At the largest water deficit, Moistube irrigation had the lowest protein yield. Protein NY decreased with increasing water deficit from 815 $kg \cdot ha^{-1}$ to 304 $kg \cdot ha^{-1}$, while carbohydrate NY decreased from 1 608 $kg \cdot ha^{-1}$ to 675 $kg \cdot ha^{-1}$. Crude fat NY varied significantly across water regimes. Irrigation type did not significantly affect the nutritional yield of crude fat, except under 40% ET_c where Moistube irrigation was 49% lower than subsurface drip irrigation at 40% ET_c. Crude fat NY decreased from 115 $kg \cdot ha^{-1}$ to 34 $kg \cdot ha^{-1}$. There were no significant differences in crude fibre NY across water regimes and irrigation type, except under severe water deficit (40% ET_c) where this was 29% and 55% lower under Moistube and subsurface drip irrigation, respectively, than the optimum (100% ET_c) water regimes.

The contribution of cowpea nutritional quality to daily dietary requirements of members of a family consisting of 2 adults and 2 children is shown in Table 7. Carbohydrates contribute an average of 40% of the daily recommended nutrient intake (DRNI) for all the age groups. The contribution of total fibre to DRNI increased with increasing water deficit. Total fibre under optimum irrigation contributes 9% of the DRNI of an adult male and 18% of a child aged 1–3 years, while accounting for 14% of the DRNI of an adult female and child aged 4–8 years. Total fibre at severe water deficit under subsurface drip irrigation contributed the highest DRNI of 26%, 20%, 13% and 20% of a 1–3-year-old child, 4–8-year-old child, adult male, and adult female, respectively. Fat content for all water regimes and irrigation types contributed between 8% and 13%, and 9% and 15% of the DRNI of children of 1–3 years and 4–8 years old, respectively. Adult members of the family can derive 9% to 16% of their DRNI of fat from consumption of cowpea grains. Severe water deficit under Moistube irrigation contributed the lowest percentage of DRNI of fat for all the age groups. Protein in cowpea provides more than 100% of the DRNI of children under 8 years, and from 42% to 46% for an adult male and 51% to 56% for an adult female.

Water productivity and nutritional water productivity of cowpea

Nutritional water productivity (NWP) for carbohydrates and protein varied significantly ($p < 0.05$) across irrigation water regimes and irrigation type (Table 8). However, NWP for crude fat, ash and crude fibre did not have significant differences across water regimes and irrigation type. Fat NWP was highest under subsurface drip irrigation at 40% ET_c and lowest at 40% ET_c under Moistube irrigation. This is due to the combination of low fat content and low WP at 40% ET_c. Although water productivity under subsurface drip irrigation at 40% ET_c was lower than at 100% ET_c and 70% ET_c in both irrigation types, it is compensated by the higher fat content at 40% ET_c. Fat NWP averaged 33.0 $g \cdot m^{-3}$ and 39.4 $g \cdot m^{-3}$ under Moistube and subsurface drip irrigation, respectively.

Crude fibre NWP was highest under subsurface drip irrigation at 40% ET_c and lowest under Moistube irrigation at 40 % ET_c, with the latter being contributed by low water productivity. Moderate deficit irrigation (70% ET_c) had higher fibre NWP than optimum irrigation (100% ET_c). This could be attributed to higher water productivity at 70% ET_c than 100% ET_c. Fibre NWP was 16% higher in subsurface drip irrigation than in Moistube irrigation. This was partly due to an 11% increase in water productivity under subsurface drip irrigation than with Moistube irrigation.

Moderate deficit irrigation had the highest carbohydrate NWP, followed by optimum irrigation. The lowest carbohydrate NWP was attained under Moistube irrigation at 40% ET_c, which was 28% lower than the corresponding water regime at 70% ET_c. This was due to a 29% reduction in water productivity under 40% ET_c when compared to 70% ET_c. This shows that severe water deficit detrimental to crop NWP occurs at 40% ET_c under Moistube irrigation and not under subsurface drip irrigation. Therefore, cowpea is less productive in terms of carbohydrate quality under severe water deficit in Moistube irrigation.

Table 8. Nutritional water productivity of cowpea seeds

Irrigation	Water regime	WP ($kg \cdot m^{-3}$)	Nutritional water productivity ($g \cdot m^{-3}$)				
			Crude fat (SD)	Ash (SD)	Protein (SD)	Crude fibre (SD)	Carbohydrate (SD)
SDI	100% ET_c	1.06	39.2 (3.9) ^{a}	49.3 (1.3) ^{a}	265.2 (11.1) ^{a}	36.1 (8.0) ^{a}	541.0 (11.5) ^{b}
Moistube	100% ET_c	1.08	37.8 (11.3) ^{a}	50.4 (2.5) ^{a}	276.2 (8.2) ^{a}	35.7 (7.4) ^{a}	544.4 (32.3) ^{b}
SDI	70% ET_c	1.10	32.5 (9.7) ^{a}	47.2 (3.7) ^{a}	265.5 (9.7) ^{a}	44.7 (17.3) ^{a}	566.0 (19.3) ^{ab}
Moistube	70% ET_c	1.14	33.0 (9.6) ^{a}	48.6 (6.6) ^{a}	269.8 (16.3) ^{a}	45.8 (19.4) ^{a}	596.8 (28.0) ^{a}
SDI	40% ET_c	0.98	46.6 (6.9) ^{a}	50.7 (4.0) ^{a}	237.1 (11.2) ^{b}	48.1 (1.2) ^{a}	479.7 (17.4) ^{c}
Moistube	40% ET_c	0.81	28.2 (6.1) ^{a}	49.2 (6.2) ^{a}	189.8 (20.3) ^{c}	30.7 (8.6) ^{a}	428.9 (26.8) ^{d}
LSD (Irrigation x ET_c)			36.6	7.9	23.9	21.4	42.1

Mean values in same column followed by same superscript letter do not differ significantly at 5% significance level by LSD. Data in parenthesis are the standard deviations, WP = water productivity, SDI = subsurface drip irrigation, ET_c = crop evapotranspiration, SD = standard deviation

Table 9. Amount of water needed to meet human nutritional requirements for cowpea

Irrigation	Water regime	Amount of water ($L \cdot person^{-1} \cdot day^{-1}$)			
		Crude fat	Protein	Crude fibre	Carbohydrate
SDI	100% ET_c	772	126	741	240
Moistube	100% ET_c	800	121	749	239
SDI	70% ET_c	931	126	598	230
Moistube	70% ET_c	917	124	584	218
SDI	40% ET_c	649	141	556	271
Moistube	40% ET_c	1 073	177	871	303
Average		857	136	683	250

SDI = subsurface drip irrigation, ET_c = crop evapotranspiration

There were no significant differences in protein NWP among optimum and moderate deficit irrigation types. However, NWP at 40% ET_c subsurface drip irrigation was significantly lower than 70% ET_c and 100% ET_c for both irrigation types. Under severe water deficit, the protein NWP was significantly lower under Moistube irrigation than under subsurface drip irrigation. Severe water deficit reduced protein NWP by 14% and 31% in subsurface drip irrigation and Moistube irrigation, respectively. Therefore, in terms of productivity of proteins, 70% ET_c and 100% ET_c gave desirable results in Moistube irrigation (270–276 $g \cdot m^{-3}$) and subsurface drip irrigation (265 $g \cdot m^{-3}$).

The per capita water requirement to meet human nutrition indicated that protein required the least amount while fat required the highest amount (Table 9). Severe deficit under Moistube irrigation required the largest amount of water (1 073 $L \cdot person^{-1} \cdot day^{-1}$) to meet human nutritional requirements for fat while the lowest (649 $L \cdot person^{-1} \cdot day^{-1}$) is required by severe deficit under subsurface drip irrigation. Protein required an average of 124 $L \cdot person^{-1} \cdot day^{-1}$ under optimum and moderate deficit irrigation, which was 14% and 43% lower than at severe water deficit under subsurface drip and Moistube irrigation, respectively. The amount of water required per total fibre content to meet the human nutritional requirements ranged from 556 $L \cdot person^{-1} \cdot day^{-1}$ (subsurface drip irrigation) and 871 $L \cdot person^{-1} \cdot day^{-1}$ (Moistube irrigation), with both being under severe deficit irrigation. The amount of water required by carbohydrate content ranged from 218 $L \cdot person^{-1} \cdot day^{-1}$ to 303 $L \cdot person^{-1} \cdot day^{-1}$, with the highest being under Moistube irrigation at 40% ET_c.

DISCUSSION

Protein is one of the most important parameters used in the assessment of nutritional quality of legumes (Ntatsi et al., 2018). The average crude protein content reported in the present study (24%) was consistent with previously reported protein contents of between 20% and 27% (Antova et al., 2014; Henshaw, 2008; Iqbal et al., 2006; Mamiro et al., 2011). Genetic diversity accounts for variations in protein content (Muranaka et al., 2016). Nevertheless, the high protein content of cowpea serves as a source of dietary protein for urban and rural households in Africa, and has been promoted for increased consumption among poor households with the aim of reducing the high prevalence of protein and energy malnutrition (Jayathilake et al., 2018). Protein content exhibited negative correlation with irrigation water regimes, meaning that protein content decreased with increase in water deficit, which concurs with the findings of Ilunga (2014) where water deficit at 30% ET_c lowered the protein content of cowpea relative to that at 60% ET_c and 80% ET_c. Chibarabada et al. (2017b) reported low protein contents of groundnut, bambara groundnut and dry bean due to water deficit induced by rainfed farming. The reduction in protein content due to water deficit is attributed to low nitrogen uptake by legume plants (Chibarabada et al., 2017b; Farooq et al., 2017).

The average carbohydrate content reported in this study was 51%, which is close to that reported for Tanzanian improved cowpea varieties, of between 35% and 49% (Mamiro et al., 2011). The carbohydrates reported in the present study indicate that cowpea has comparable amounts to bambara groundnut, dry beans and pigeon pea (Adamu et al., 2016; Anhwange and Atoo, 2015). Carbohydrate content of cowpea is predominantly starch. The variation in the pasting properties of starch among cultivars has been suggested for use in selection of suitable cowpea varieties (Ashogbon and Akintayo, 2013; Muranaka et al., 2016). Water deficit increased the carbohydrate content, except under 40% ET_c under subsurface drip irrigation, which is similar to results by Al-Suhaibani (2009) where water deficit increased the carbohydrate content in faba beans. Increase in water-soluble carbohydrates leads to osmotic adjustment, which is a physiological response mechanism to drought in legumes (Küchenmeister et al., 2013).

The average crude fat content was 3.4%, which is consistent with the 4.8% and 4.7% reported in Pakistan and South Africa, respectively (Chibarabada et al., 2017b; Iqbal et al., 2006). Crude fibre content averaged 3.9%, similar to that previously reported, of 1.7% to 3% (Antova et al., 2014). Crude fibre values under optimum irrigation were 30% lower than the highest value attained by under subsurface drip irrigation at 40% ET_c. This implied that deficit irrigation increased the crude fibre content. The high crude fibre content is beneficial to human health as it helps in digestion (Kir et al., 2017; Tosh and Yada, 2010). Crude ash was not affected by water regime, which concurs with findings by Staniak and Harasim (2018) where low water availability did not affect the crude ash content of alfalfa. Crude ash is an indicator of mineral content and thus its non-significant variation due to water deficit is beneficial since it shows that cowpea can maintain its mineral content despite low water availability.

The nutritional quality of cowpea in this study demonstrated trade-offs among the key nutritional parameters under water deficit. There is probably a functional relationships among seed chemical constituents where a reduction in one of the constituents leads to an increase in others (Burstin et al., 2011). The reduction in crude protein was compensated by an increase in carbohydrate and crude fibre.

Nutrient yield (NY) is one of the important agronomic parameters, and indicates nutrient mass that can be harvested from a crop during the entire season; it also indicates the opportunity for commercialization and marketing of crops (Nyathi et al., 2016). To the best of our knowledge, this is the first study on NY of cowpea using grain as the edible portion instead of leaves. Cowpea is grown predominantly as a substitute for meat-based protein. Protein NY under optimum irrigation conditions averaged 787 kg·ha^{-1} and 600 kg·ha^{-1}, respectively. Water deficit decreased nutritional yield of protein. This was due to decreased grain yield (Table 3) and protein content (Table 4) of cowpea. Nutrient yield is strongly associated with the crop yield and thus a reduction of crop yield due to abiotic stresses ultimately reduces NY. Abiotic stresses which negatively affect nutritional quality and crop yield will have a negative effect on NY as illustrated by protein and crude fat NY under severe deficit of Moistube irrigation. Therefore, crops which are tolerant to water deficit should be promoted if it is established that their NY is stable across environmental conditions. It is interesting to note that when subsurface drip irrigation is practised at 70% ETc, it results in a 17% decrease in the nutrient yield for protein. Therefore, in areas of water scarcity, farmers can opt for moderate deficit irrigation without compromising nutrient productivity. Cowpea nutritional quality contributes >100% of the daily recommended nutrient intake (DRNI) of protein for children under 8 years and an average of 48% for adults across all water regimes. This implies that cowpea is good source of protein for resource-poor households.

The nutritional yield for carbohydrates decreased with increasing water deficit. However, its contribution to DRNI was stable at between 38% and 41% for all age groups, which indicates that people can rely on cowpea to supply their energy intake irrespective of water availability constraints. The results in this study showed that crude fibre contributes an average of 16% of the DRNI for all age groups across all the treatments, which is higher than the reference value (10%) for legumes reported by Wenhold et al. (2012).

Nutritional water productivity (NWP) is a new concept which aids analysis of the relationship among nutritional content, crop yield and water consumption (Mabhaudhi et al., 2016). This assists in assessing the importance of a crop holistically in the wider food–water–health–nutrition nexus. This study established an average fat NWP of 36 g·m^{-3} which is higher than the 18 g·m^{-3} and 1.8 g·m^{-3} reported by Chibarabada et al. (2017b) for cowpea grown under rainfed conditions at Fountain Hill and Umbumbulu Rural District in KwaZulu-Natal Province, South Africa. The low fat NWP values were attributed to low yields occasioned by low rainfall which had a direct effect on crop water productivity. The NWPs for fat reported in this study were similar to those for lentils (39 g·m^{-3}) computed in a benchmarking report for South Africa by Wenhold et al. (2012). There is limited literature on nutritional water productivity of macronutrients for legumes.

The average protein NWP in this study was 251 g·m^{-3}. This value was higher than protein NWP for all the legumes reported by Wenhold et al. (2012), which included soybean (117 g·m^{-3}), peanut (111 g·m^{-3}) and lentils (125 g·m^{-3}), among others. Chibarabada et al. (2017b) reported protein NWPs of between 111 g·m^{-3} and 84 g·m^{-3} for cowpea, which were inferior to those of bambara groundnut, groundnut and dry bean. The low NWPs reported were due to low yields (1 011 kg·ha^{-1} and 953 kg·ha^{-1}), compared to an average of 2 300 kg ·ha^{-1} (Table 3) reported in the present study. Severe water deficit reduced protein NWP by an average of 21%. This is attributed to a reduction in yield (Table 3) and protein content (Table 4). The average carbohydrate NWP was 526 g·m^{-3}, which was higher than that reported for legumes, and comparable to maize (Wenhold et al., 2012). Optimum and moderate deficit irrigation did not affect carbohydrate NWP. However, severe water deficit had a detrimental effect on carbohydrate NWP.

Growing cowpea for protein and carbohydrate is productive since it requires less water per person to meet the human nutritional requirements than if it were to be grown for fat and fibre. Fat and fibre required 5 and 6 times more water, respectively, than that required for protein (Table 9). In most cases cowpea is grown together with other crops, such as millet, sorghum and maize, in a mixed farming system (Asiwe, 2009; Timko et al., 2007). Since millet, sorghum and maize are starch-rich foods, cowpea can provide the protein to address a protein deficiency in these foods.

CONCLUSIONS AND RECOMMENDATIONS

The study revealed that all the nutritional elements considered did not vary significantly across water regimes and irrigation type. This confirmed our initial hypothesis that the nutritional quality of cowpea is not affected by irrigation type and water regime. This confirms the drought tolerance of cowpea and ability to retain nutritional composition under drought. This makes it an important crop for addressing food and nutritional security in water-scarce environments.

The NWP depicted varied responses to irrigation water regimes and irrigation type due to the effect on the crop's nutritional content or water productivity or both. Moistube irrigation had the highest protein productivity under optimum irrigation conditions. Severe water deficit significantly reduced the protein productivity in both irrigation types. Carbohydrate water productivity decreased with respect to an increase in water deficit and Moistube irrigation performed relatively poorer than subsurface drip irrigation. Therefore, the hypothesis that nutritional water productivity is improved by deficit irrigation was rejected.

Households in water-scarce regions can practice moderate deficit irrigation for growing cowpea without compromising on the nutritional benefits. Further studies are required to determine the effect of agronomic factors such as fertilizer deficiency on the nutritional quality and nutritional water productivity of cowpea under Moistube irrigation. The concept of nutritional yield is new and, therefore, further research is required to determine the nutritional yield of cowpea as a traditional leafy vegetable, considering both macro- and micro-nutrients.

ACKNOWLEDGEMENTS

The authors are grateful to the Association of African Universities (AAU), National Research Fund (NRF) of Kenya, Masinde Muliro

University of Science and Technology (MMUST) and University of KwaZulu-Natal (UKZN) for their financial contributions towards this research. The Water Research Commission Project K5/2717//4 on 'Developing guidelines for estimating green water use of indigenous crops in South Africa and estimating water use using available crop models for selected bio-climatic regions of South Africa' is also acknowledged.

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