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Optimizing water and nitrogen application for neglected horticultural species in tropical sub-humid climate areas: A case of African eggplant (*Solanum aethiopicum* L.)

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ABSTRACT

African eggplant, a traditional and important nutrient-dense crop to Tanzania's nutrition and food security. However, yields remain low as a result of sub-optimal irrigation and fertilizer practices. To reduce the yield gap, a randomized split-plot design set up with irrigation as a main and nitrogen (N) treatments as a sub-factor. The irrigation regimes were 100 % (I100), 80 % (I80) and 60 % (I60) of crop water requirements whilst nitrogen levels were 250 kg N/ha (F100), 187 kg N/ha (F75), 125 kg N/ha (F50) and 0 kgN/ha (F0). The study evaluated the effect of irrigation water and N on crop growth variables and yield, fruit quality, WUE and NUE. The study showed the importance of combining different irrigation performance indicators which responds to different levels of water and nitrogen to evaluate and assess suitable irrigation and fertilizer strategies for African eggplant. The crop growth variables (plant height and LAI) had a good correlation with fruit yield ($R^2 = 0.6$ and 0.8). The fruit quality was best performed by 100 % water in combination with 75 % N treatment. The best WUE and NUE was attained at 80 % and 100 % levels of water in combination with 75 % N. However, minimizing trade-offs between the various indicators, the optimal application for African eggplant would likely be around 80 % of the total irrigation requirement and 75 % of the N requirement in sandy clay loam soils under tropical sub-humid conditions.

1. Introduction

African eggplant (AEP) (*Solanum aethiopicum* L.) is one of the most consumed vegetables in Tanzania (Keding et al., 2007; Ochieng et al., 2018). AEP is grown extensively, in river valleys, generally after the rainy season under irrigation. Post rainy-season production ensures less fungal disease incidences and hence less sprays of fungicides. The crop is important for nutritional and food security purposes as well as income generation for smallholder farmers (Afari-Sefa et al., 2012; Ochieng et al., 2018).

AEP is low in calories, high in dietary fibre and has a higher nutritional value compared to most vegetables. The crop is rich in different minerals such as potassium, magnesium, calcium and iron (Hossein Aminifard et al., 2010) and carotenoids, a precursor for Vitamin A. Deficiency in Vitamin A can result in poor vision, compromised immunity functioning and sterility in human beings (Kamga et al., 2013). The nutrient-dense crop provides low-cost quality nutrition opportunities in rural areas, especially where diets consists of carbohydrate-rich staples (Ochieng et al., 2018). Furthermore, its shelf-life and transportability makes the crop highly favourable for Africans vegetable markets given the unfavourable market access infrastructures. Compared to other horticultural crops, the transportation of African eggplant results in minimal food waste as a result of transportation.

The crop is an important genetic resource for breeding improvements of eggplant due to its tolerance to biotic and abiotic stresses (Plazas et al., 2014; Sabatino et al., 2018, 2019). Likewise, it is used as grafting rootstock for improving plant vigour, yield and fruit quality of a hybrid eggplant due to its resistance to most soil-borne diseases such as root-knot nematodes (Plazas et al., 2014; Sabatino et al., 2018). Besides

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of these benefits, AEP has not received due attention in terms of climate adaptation and sustainable agricultural intensification in East Africa.

The average potential yield of AEP has been 57 t/ha and 42 t/ha under subtropical highland and humid tropics climate areas, respectively (Oluoch and Chadha, 2006; Kamga et al., 2015). Hence, Tanzania's current low productivity of 15–25 t/ha per season can be increased to more than 40–60 t/ha (Msogoya et al., 2014; Kamga et al., 2016). The large yield gap, can be partially explained by inadequate water and nitrogen management practices during the growing season (Chaves et al., 2007, 2010), though so far has received insufficient attention.

Water and nitrogen are important factors influencing crop biomass accumulation and therefore the yield gap (Hamzei and Soltani, 2012; Yang et al., 2012; Fondio et al., 2016; Du et al., 2017). However, current irrigation water management practices in Tanzania is largely based on traditional irrigation knowledge (de Bont et al., 2019), which may result into under or over application (Kabogo et al., 2017; Kimaro, 2019). Applying large quantities of water results into low water and fertilizer use efficiency, affecting farm income and the environment (Senyigit et al., 2013). Furthermore, the quality of eggplant has shown to decrease with the increase in irrigation amounts (Leogrande et al., 2014). The compensation of low fertilizer use efficiency and nitrogen leaching with increased nitrogen application, leads to excessive vegetative growth, plant water and potassium stress and pollution of water bodies. As a result of increased fertilizer use, production costs for AEP have been high reducing returns on investment (Olunloyo et al., 2019).

Balancing N and water remains a significant challenge since under-supply or oversupply of either may offset the benefits of the other reducing the overall production and nutrient gains. When water is in short supply, applying recommended N doses may increase water stress due to increased evaporative demands as a result of enhanced vegetative growth, ultimately reducing crop yield (Fondio et al., 2016). In situations where water is available, sub-optimal N supply limits the quantity and quality of produce and hence income and return on investment for smallholder farmers.

While, N and water management for eggplant crop production have been substantially investigated (Amiri et al., 2012; Leogrande et al., 2014; Díaz-Pérez and Eaton, 2015; Fondio et al., 2016; Ghaemi and Rafiee, 2016), little focus has been paid to improving water and nutrient practices for the African eggplant variety. Hence, actual yields have stagnated, to a level, far below the potential, with low input use efficiency as well as high production costs. To address these challenges, a study was conducted to improve water and nitrogen application under tropical sub-humid conditions. The overall objective was to increase African eggplant productivity through improved water and nitrogen management. The specific objectives were to evaluate the influence of water and nitrogen regimes on: 1) crop performance and yield, (2) fruit quality and, (3) efficiency of water use (WUE) and agronomic nitrogen use (NUE).

2. Materials and methods

2.1. Experimental site soil characteristics

The study was conducted at an experimental site located within Rudewa ward. The ward is one of the administrative areas forming Kilosa District in Morogoro Region, Tanzania (Fig. 1). Geographically, the site can be found at 6°32′ to 6°47′South and 36°8′ to 37°28′East with an average altitude of 437 m above mean sea level. The area is characterised by warm climate with annual average temperature of 25 °C. Temperatures are normally low in July (18 °C) and high in February

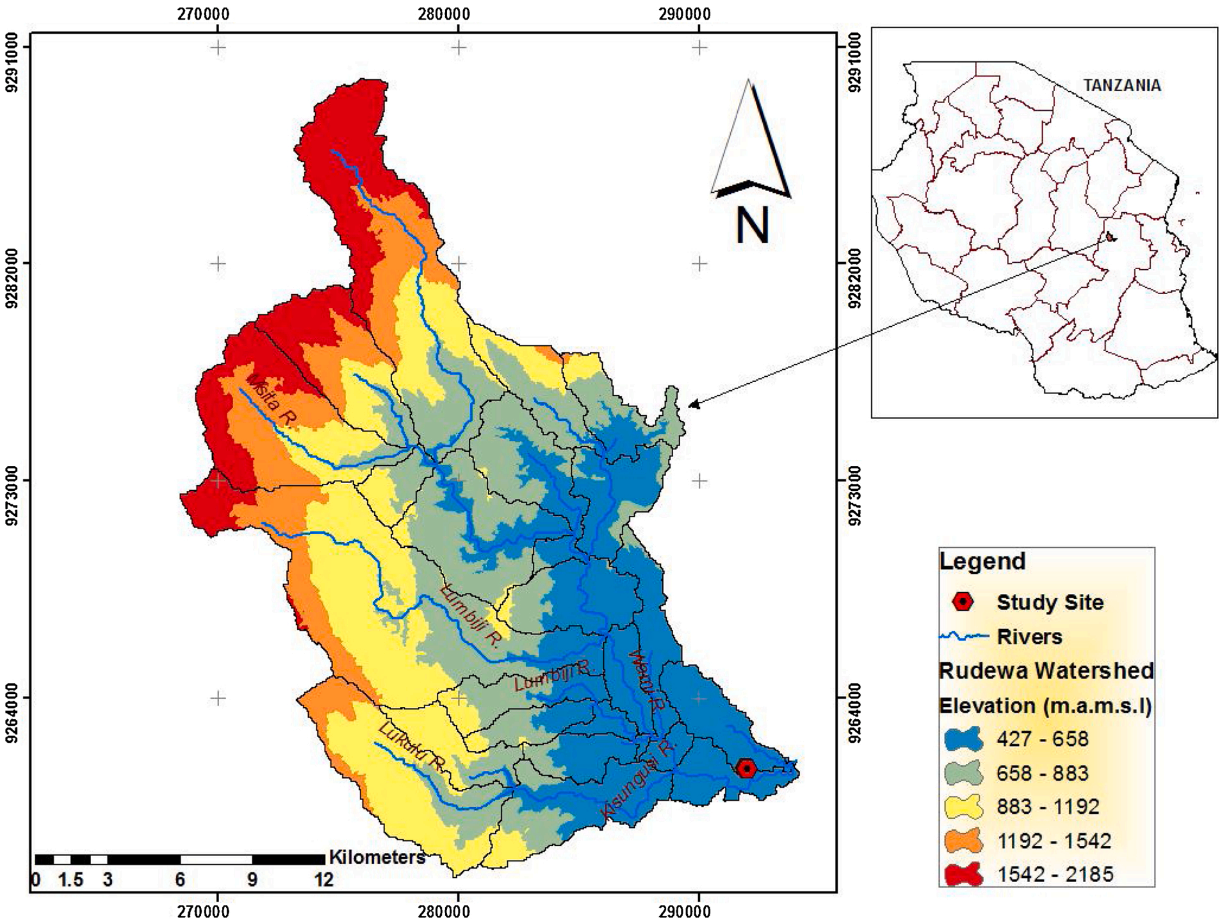

Fig. 1. The watershed of the study site, Rudewa village in Kilosa – Morogoro region, Tanzania.

reaching up to 32.1 °C. The study site has a bimodal rainfall regime with short rains starting from October to December and long rains from March to May, with an annual average rainfall ranging between 1000 mm and 1400 mm. The Wami River is the major water source for irrigated agriculture within the watershed.

Soil depth, physical and chemical properties vary throughout the study area. The upslope mountainous areas are rather characterized by shallow eroded soils whilst the valley bottoms have deeper soils (Kimaro, 2014) due to alluvial deposition from the Wami River. Due to flooding conditions of the Wami River, moderately fine and medium textured soils are formed in valley areas resulting in fertile soils. The lowland areas are converted to agriculture with irrigation of horticultural crops occurring in the dry season along the alluvial plains of the Wami River. Forests reserves such as the Mamiwa Forest Reserve is located in the hillslopes of Rudewa.

2.2. *Experimental design*

Drip irrigated African eggplant experiments were conducted for two dry seasons. The first season was conducted between June through October of 2017 while the second season were conducted during the same months of 2018. The field experiment was organized in a split plot design with main factor irrigation and sub-factor fertilizer treatment to facilitate irrigation practices. For each factor the treatments were randomized and replicated 3 times. Irrigation treatments were 100 % (I100), 80 % (I80) and 60 % (I60) of the estimated crop water requirements (see Section 2.4 below) and N fertilizer treatments were 100 % (F100), 75 % (F75), 50 % (F50) and 0% (F0) of the calculated crop N requirements (see below Section 2.4), respectively. Each sub-plot had a total area of 35 m^2 with plant and row spacing of 60 cm and 90 cm respectively. Transplanting was conducted on top of ridges where driplines had been laid.

2.3. *Soil physical and chemical properties*

Physical and chemical soil characteristics of the study site were determined to guide fertilizer application and irrigation water management recommendations to be tested for African eggplant (Table 1). Five soil sampling quadrants of 5 × 5 m were established to represent the field. From each quadrant five sampling point were marked from the apexes and the middle of each quadrant. Then the disturbed and undisturbed soil sampling were taken at two different soil depths (i.e. 0 cm–20 cm and 20 cm–40 cm) to capture initial soil conditions. Undisturbed samples were taken for bulk density analysis using 100 cm^3 cylinders. Composite disturbed samples were taken for texture and standard soil chemical properties analysis using a soil auger.

Soil pH (pH H_2O) at both depths 0–20 cm and 20–40 cm was slightly acidic, Soil organic carbon (C), was around 2% at all depths, soil total N ranged between very low to low and available P was medium to high at both depths. Measured cation exchange capacity and exchangeable calcium were found to be at a medium level, magnesium concentration ranged between medium and high, exchangeable Na concentration was low and exchangeable K low to very low. The soil texture was sandy clay loam (scl) with more than 60 % sand content and an average bulk density of 1.4 g/cm^3.

2.4. *Irrigation and nitrogen scheduling*

The gross seasonal irrigation requirement was estimated by calculating the crop evapotranspiration (ETc) throughout the season for each irrigation regime (100 %, 80 % and 60 %) of crop water requirement, an application efficiency of 94 % and conveyance efficiency of 90 %. The ETc (mm) was estimated using the crop coefficient (Kc) and crop reference evapotranspiration (ETo, mm) (Eq. (1)). ETo was computed using a 15 years' climatic data from Ilonga weather station using a CLIMWAT 2.0 and CROPWAT 8.0 software as recommended by FAO (Diku et al., 2015). The Kc values for African eggplant under tropical sub-humid conditions, were 0.6, 0.75, 1.15 and 0.8 for crop initial, development, vegetative and maturity stages, respectively (Bos et al., 2008). The seasonal total crop water requirement was estimated using Eq. (2).

The net irrigation water (IWR_{net}, mm) requirement was calculated using the estimated crop evapotranspiration (ET_c) and effective rainfall (R_e, mm), capillary rise (GW_c, mm), deep percolation (P, mm) (Eq. (3)). However, the contribution of capillary rise was not sufficient and hence neglected. The deep percolation was also neglected due to efficient water application and low application rates. Calculation of the gross irrigation requirement included the field application efficiency (E_a) and conveyance efficiency (E_c), respectively. For each irrigation event, gross water irrigated was measured using the flow meter installed at the primary drip line.

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

$$CWR = \sum_{i=1}^{n} (ET_{c\ i}) \tag{2}$$

$$IWR_{net} = \sum_{i=1}^{n} [ET_c + P - (R_e + GW_c)] \tag{3}$$

$$IWR_{gross} = \frac{IWR_{net}}{E_a \times E_c} \tag{4}$$

The nitrogen recommendation was based on the soil analysis and adopted from RSA (2012) and Fondio et al. (2016), resulting in a total N of 250 kg/ha. To improve crop roots development, Diammonium Phosphate $(NH_4)2HPO_4$ (DAP) (18-46-00) was applied uniformly among all treatments at a rate of 80 kg/ha of P_2O_5 7 days after transplanting. The respective seasonal N applied in the form of Urea (46-0-0) was 250 kg/ha, 187 kg/ha, 125 kg/ha and 0 kg/ha of N for 100 %, 75 %, 50 % and 0% N treatments, respectively. The N was applied at 7, 30, 60 and 90 days after transplanting distributed as 16 %, 34 %, 34 % and 16 % of N respectively.

Table 1

Study site soil properties for dry seasons of 2017 and 2018.

Season	Soil depth (cm)	Soil chemical properties									Particle size distribution				Bulk density (g/cm^3)
		pH	OC (%)	Total N (%)	Avail P (mg/kg)	CEC (cmol/kg)	Ca^{2+} (cmol/kg)	Mg^{2+} (cmol/kg)	Na^+ (cmol/kg)	K^+ (cmol/kg)	Clay (%)	Silt (%)	Sand (%)	Soil class	
Season 1	0–20	6.39	2.40	0.15	36.14	18.59	9.51	3.49	0.26	0.20	26.76	13.95	59.29	scl	1.34
	20–40	6.55	2.08	0.11	30.74	15.88	7.17	2.89	0.30	0.08	27.02	10.95	62.03	scl	1.54
Season 2	0–20	6.79	2.43	0.15	34.65	17.42	8.31	2.75	0.25	0.11	24.71	10.69	64.60	scl	1.35
	20–40	6.49	2.05	0.15	30.91	15.09	8.46	2.64	0.21	0.08	26.11	11.44	62.40	scl	1.45

Note: scl refers to sandy-clay loam.

2.5. The influence of water and N on crop growth variables and fruit yield

The influence of water and N on plant growth was evaluated at different crop development stages. The parameters examined included leaf area index (LAI) and plant height were measured during the early, vegetative, full vegetative and maturity stages. Measurements of leaf area index (LAI) were performed between 9:00 and 11:30 am to minimize the effect of direct solar radiation using Pocket LAI software installed in Samsung galaxy Grand Prime, android version 5.0.2 application (Yonah et al., 2018). The plant height was measured using a collapsible measuring stick at each crop development stage. Fruits number per plant were counted from six representative plants in each treatment during the whole period of harvesting.

To estimate seasonal fruit yields in terms of fruit weight per hectare (Y, t/ha), total wet weight of fruit (W_p, kg) harvested in each plot with area (35 m^2) were measured for each treatment and replication whilst eliminating boundary rows (Eq. (5)).

$$Y = \sum_{i=1}^{n} \frac{W_p}{A} \times 10,000 \tag{5}$$

2.6. The effects of water and N on fruit quality

Fruit quality parameters were estimated in terms of its size (length and diameter) and moisture content. This was conducted during each round of harvesting, whereby 30 representative fruit samples were randomly taken from each treatment. The fruit length and diameter were measured by a vernier calliper. Fruit moisture content (MC), an important indicator of fruit quality as it indicates its freshness, the condition necessary for the market, was measured destructively. Fruits were harvested from the 6 monitoring plants of each plot and kept in labelled bags. The fresh weight of the fruits was measured immediately after harvesting using a Kern DS (Max. 8100 g, d =0.1 g) digital weighing balance. Samples were then cut, into two parts to enhance drying, oven dried at a temperature 70 °C until there observed no further change in weight. Fruit water content (FWC) were then measured from the relationship of fresh (W_f) and dry (D_f) fruits weights as indicated in Eq. (6).

$$FWC = \frac{W_f - D_f}{W_f} \times 100\% \tag{6}$$

2.7. Water-use and agronomic N-use efficiencies

For each season, the crop water efficiency were estimated using fresh yield (Y_t, t/ha) harvested per treatment with its corresponding total amount of water irrigated (I_{gross}, m^3/ha) (Eq. (7)) (Gaveh et al., 2011). The Agronomic N efficiency (NUE) was calculated using the difference between the fresh yield obtained in the F100, 75 or 50 % N treatment and yield obtained in the 0% N treatment and divided by the N applied ($N_{applied}$, kg/ha) in the N treatment (Eq. (8)) (Badr et al., 2012)).

$$WUE = \frac{Y_t}{I_{gross}} \tag{7}$$

$$NUE = \frac{(Y_{,t} - Y_{,0})}{N_{applied}} \tag{8}$$

2.8. Statistical analysis

Statistical analysis was conducted through the analysis of variance (ANOVA) using the general linear model (GLM) using water and nitrogen as fixed factors. Normality and homogeneity of variance were checked and parameters transformed if necessary. The analysis was performed using R-software (R Core Team, 2018) platform. Mean separation was performed using the Least Square Difference (LSD) procedure with alpha level of 5%. The correlation analysis (R^2) was also conducted to assess the contribution of growth variables on yield using ggplot and ggpubr packages in R-studio.

3. Results

3.1. The response of crop growth to water and N

A sharp increase in plant height was observed between 30 and 45 days in all water treatments and maximum plant height was reached approximately 90 days after planting (Fig. 2d–f).

Plant growth parameters such as plant height and LAI were influenced by the amount of water and nitrogen applied within a cropping season. The 0 N treatment resulted in a significantly lower height compared to the other fertilizer treatments whilst maximum plant height was achieved in the F100 and F75 treatments. The average plant height measured at 45 days after transplanting was significantly influenced by the water ($p < 0.01$) and N application ($p < 0.001$) strategies (Table 2). Aside from the 0 N application treatment, the average plant height ranged from 55.0 to 61.2 cm in function of the N applied and was found to be insignificantly different between the 100 % and 80 % irrigation treatment (Table 2). The lowest levels of plant height were observed for treatments where 0 nitrogen was applied and ranged from 26.2 cm (I60F0) to 30.1 cm (I80F0). Treatments which received only 60 % of the irrigation water requirement also showed the lowest plant height regardless of the level of N applied.

The plant LAI also increased with time to the crop maturity with lowest value recorded for none N treatment (F0) throughout the season. Within the I100 and I80 treatments, the canopy LAI had a slight difference in both F100, F75 and F50 within the season (Fig. 2d–f). For the treatments receiving lowest levels of water (I60), the LAI increased for F100, F75 and F50 was uniform within the first 60 days. Beyond 60 days after planting, the plant LAI for F50 and F0 started to decline. The average plant LAI measured at 60 days after transplanting showed a similar response as the plant height. LAI showed a significant effect depending on the water ($p < 0.001$) and the amount of N applied ($p < 0.001$) and its interaction ($p < 0.01$). The highest LAI was observed for I100F100 (1.9) and I100F75 (1.9) (Table 2). All N treatments in combination with 100 % and 80 % of the irrigation requirement were not found to be significantly different with the exception when 0% N was applied. As with plant height lowest LAI were recorded for 0% N application especially when only 60 % of the irrigation water requirement was applied.

3.2. The response of African eggplant yield performance to water and N

The number of fruits per plant was significantly influenced by the amount of N applied ($p < 0.01$) but not by the amount of water or its interaction. Only for I100 a significant difference was found between the F0 and the other 3 fertilizer application strategies (Table 2). For F100 providing 100 % of the irrigation water requirement resulted in significantly higher number of fruits compared to the other two irrigation strategies. For F75 both 100 % and 80 % of the irrigation requirement resulted in significantly higher number of fruits. On contrary to the number of fruits per plant, the total eggplant yield did show an interaction effect of water and N application ($p < 0.001$). Highest eggplant yield was observed for the treatments which either received 100 % or 80 % of the estimated irrigation requirement in combination with 100, 75 or 50 % of the N requirement (Table 2). The lowest total yields were observed for treatments which received either 100 % of the irrigation requirement but 0% of N or a combination of only 60 % of the irrigation requirement and 0% if the N applied.

The fruit yield response could be predicted based on plant growth variables measured at different levels of water and N combination. The highest correlation was found between crop yield and LAI measured 60 days after transplanting ($R^2 = 0.8$, $p < 0.0001$) (Table 3). The correlation between fruit yield and average plant height measured at 85 days

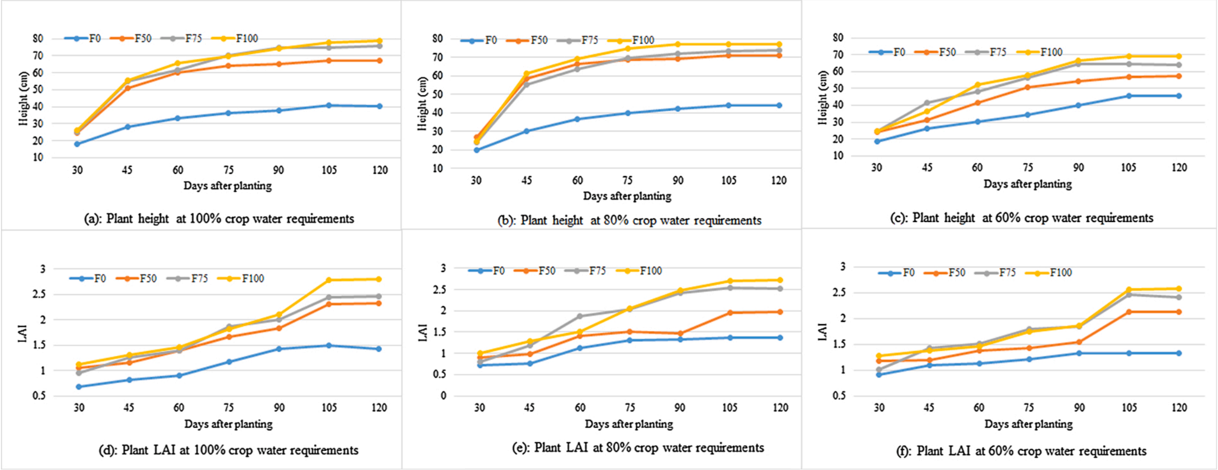

Fig. 2. (a-f): Plant height (a-c) and LAI (d-f) at critical growth stages for 100%, 80% and 60% of ET at different fertilizer treatments.

Table 2
Average plant and crop performance indicators over two seasons as influenced by N and water application treatment.

Treatment	Plant height (cm)	LAI	Fruit number per plant	Fruit length (cm)	Fruit diameter (cm)	Moisture content (%)	Yield (t/ha)	WUE (kg/m^{3})	NUE (kg/kg)
Irrigation water									
I100	50.3^{a}	1.6^{a}	115^{a}	5.5^{a}	3.5^{a}	91.6^{a}	49.9^{a}	18.3^{b}	150.7^{a}
I80	51.1^{a}	1.6^{a}	99^{ab}	5.1^{b}	3.5^{a}	90.5^{a}	47.2^{a}	21.7^{a}	71.1^{b}
I60	33.9^{b}	1.3^{b}	75^{b}	5.3^{a}	3.4^{a}	86.2^{b}	31.1^{b}	17.6^{b}	64.8^{b}
Nitrogen fertilizer									
F100	52.9^{a}	1.7^{a}	104^{a}	5.6^{a}	3.4^{ab}	89.7^{ab}	52.4^{a}	23.7^{a}	108.4^{b}
F75	50.6^{a}	1.65^{ab}	117^{a}	5.4^{a}	3.5^{a}	90.7^{a}	50.7^{a}	22.5^{a}	135.6^{a}
F50	48.7^{a}	1.5^{b}	98^{a}	5.4^{a}	3.5^{a}	89.3^{ab}	42.6^{b}	19.1^{b}	138.1^{a}
F0	28.2^{b}	1.2^{c}	66^{b}	4.8^{b}	3.38^{b}	88^{b}	25.2^{c}	11.6^{c}	
Water and N combinations (Water x N)									
I100F100	61.2^{a}	1.9^{a}	135^{ab}	5.9^{a}	3.6^{ab}	90.99^{abc}	63^{a}	23.03^{a}	161.6^{b}
I100F75	55.2^{a}	1.9^{a}	147^{a}	5.9^{a}	3.7^{a}	93.6^{a}	64.3^{a}	23.51^{a}	223^{a}
I100F50	56.2^{a}	1.6^{bc}	114^{abcd}	5.5^{abc}	3.49^{bc}	92.43^{ab}	49.9^{bc}	18.23^{bc}	218.1^{a}
I100F0	28.4^{c}	1.2^{ef}	66^{ef}	4.6^{d}	3.1^{e}	89.26^{bcd}	22.6^{fg}	8.26^{d}	
I80F100	61.1^{a}	1.6^{bc}	88^{cdef}	5.3^{abc}	3.4^{cd}	91.09^{abc}	51.1^{bc}	23.52^{a}	66.3^{e}
I80F75	55^{a}	1.7^{ab}	124^{abc}	5.1^{bcd}	3.5^{abc}	92.5^{ab}	55.2^{ab}	25.43^{a}	110.8^{c}
I80F50	58.4^{a}	1.6^{bc}	103^{bcde}	5^{bcd}	3.5^{abc}	87.27^{cde}	47.9^{bc}	22.06^{ab}	107.2^{cd}
I80F0	30.1^{bc}	1.5^{cd}	77^{def}	4.8^{cd}	3.6^{ab}	91.09^{abc}	34.5^{de}	15.89^{c}	
I60F100	36.3^{bc}	1.6^{bc}	90^{cdef}	5.4^{abc}	3.2^{de}	87.11^{cde}	43.1^{cd}	24.47^{a}	97.3^{cde}
I60F75	41.5^{b}	1.3^{de}	79^{def}	5.3^{abc}	3.3^{d}	86.09^{de}	32.5^{e}	18.42^{bc}	73de
I60F50	31.5^{bc}	1.4^{d}	77^{def}	5.7^{ab}	3.5^{abc}	88.2^{cd}	29.9^{ef}	16.97^{c}	88.9^{cde}
I60F0	26.2^{c}	1.1^{f}	53^{f}	4.9^{cd}	3.4^{cd}	83.53^{e}	18.8^{g}	10.67^{d}	
Significance:									
Water (W)	**	**	NS	**	NS	*	**	NS	**
Nitrogen (N)	***	***	**	**	NS	NS	***	***	***
W x N	NS	**	NS	NS	***	NS	**	*	***

Values with the same letter within the column are not statistically different at $p<0.05$. *, ** and *** = Significant at 0.05, 0.01 and 0.001 probability levels, respectively. NS = Not significant.

Table 3
Correlation (R^2) between fruit yield and plant height, LAI and number of fruits per plant.

Variable	R^2	p-value	Equation
Plant height at 45 days (cm)	0.6	8.1×10^{-8}	$y = 7.3 + 0.78x$
Number of fruits per plant	0.6	7.3×10^{-8}	$y = 9.8 + 0.34x$
LAI at 60 days	0.8	8.3×10^{-13}	$y = -34 + 50x$

after transplanting ($R^2 = 0.6$; $p < 0.0001$) as well as yield and number of fruits per plant ($R^2 = 0.6$, $p < 0.0001$) were also found significant (Table 3).

3.3. The effect of water and N on fruit quality

Fruit quality parameters such as fruit size (length and diameter) and moisture content responded differently at different levels of water and N. Fruit length varied between 5.9 cm and 4.6 cm, fruit diameter between 3.7 cm and 3.1 cm and moisture content between 83.5 % and 93.6 %. Independent irrigation and N application had no significant influence on fruit diameter while the fruit length were influenced by water, N and their interaction. An interaction between water and nitrogen was observed on the fruit diameter ($p < 0.001$) and moisture content ($p < 0.05$) (Table 2). For I100 the application of 100 %, 75 % or 50 % of the N resulted in significantly longer eggplants than when no nitrogen was applied. Under the same irrigation regime application of 100 % and 75 % of N application also resulted in longer fruits compared to the F50 fertilizer treatment. For the other two irrigation treatments no significant difference was observed between the different fertilizer treatments. The fruit moisture content on the other hand, was influenced by irrigation water ($p < 0.05$) with insignificant influence of N. The I60 treatment had the lowest fruit moisture content.

3.4. Water-use and agronomic nitrogen-use efficiencies at different water and N rates

Different levels of water and N combinations, resulted into varying water and N use efficiencies. The results have shown that, I80F75 had the highest water use efficiency (25.43 kg/m^3), followed by I60F100 (24.47 kg/m^3 then I80F100 (23.52 kg/m^3) and I100F75 (23.51 kg/m^3) (Table 2). Medium levels of water-use efficiencies were recorded for treatments I80F50 (22.06 kg/m^3) and I60F75 (18.42 kg/m^3) with insignificant difference between them. Treatments with lowest water use efficiency were I100F0 (8.26 kg/m^3) and I60F0 (10.67 kg/m^3). These results show that, the 80 % of water supply with 75 % of N resulted into best crop water-use efficiency. Therefore, I80F75 was selected as the treatment with the highest water-use efficiency.

For the agronomic N use efficiency, analysis was conducted for F100, F75 and F50 N treatments as F0 had no N application (Table 2). The results showed that both water, N and their interaction had a positive influence on the NUE. Applying 100 % of the crop water requirement (I100) resulted into the highest significant N-use efficiency (150.7 kg/kg). The fertilizer rates of 75 % and 50 % of the total N applied, resulted into highest N use efficiency (135.6 kg/kg and 138.1 kg/kg). The highest agronomic N use efficiency was recorded for I100F75 (223.0 kg/kg) and I100F50 (218.1 kg/kg) (Table 2) whilst the lowest N use efficiency was found for I80F100 (66.3 kg/kg) and I60F75 (73.0 kg/kg) The lowest N use efficiency was associated with application of low levels of water in combination with higher rates of N. Thus, lower rates of water limit the N uptake signficantly under drip systems. On the other hand, in order to attain best N use efficiencies, in drip system under tropical sub-humid condition areas, full irrigation levels with lower levels of N is recommended. Therefore, I100F75 was regarded as the optimum water and N combination.

4. Discussion

4.1. Effect of water and nitrogen application on the crop and yield performance of African eggplant

Water and Nitrogen are important inputs to agricultural performance of African eggplant. This study showed the impacts of different N and water application rates on crop performance, fruit yield and quality as well as water-use and N-use efficiencies.

The crop performance varied significantly at different treatments. F0 instance, the response of increased plant height at 100 % and 80 % levels of irrigation, in combination with 100 %, 75 % and N rates (Table 2) can be explained by the importance of water availability to enhance fertilizer response to crop growth (Gaveh et al., 2011; Díaz-Pérez and Eaton, 2015). When only 60 % of the irrigation water requirement was applied, water was a limiting factor in translating fertilizer rates F100, F75 and F50 into increased plant height and biomass (i.e. LAI) production. Based on the plant height and LAI, water application could be reduced to 80 % of the irrigation requirement in combination with 75 % of the N application. Similar findings were observed by Amiri et al. (2012) where the highest plant height was observed in treatments with higher rates of irrigation in combination with 65 % of crop N requirements.

A positive correlation was found between LAI or plant height and fruit yield. Hence, fruit yield showed a similar response as those observed for plant height and LAI. The highest level of water (I100) in combination with F100 and F75 resulted into significant higher yield. Attaining yields at highest level of irrigation indicates that there is an opportunity for a yield increase at similar levels of nitrogen. Similar findings were reported by Mirdad (2011) and Amir et al. (2012) who found an increase in eggplant yield as water amounts and N increased. Furthermore, under I60 and F100, eggplant yield was found to be similar as under the F50 and I100 or F100, F75 and F50 under I80. This supports the trade-offs between N and water and its subsequent translation into yield. However, by increasing the water requirement to I100 and reducing fertilizer to F75 an increase of 33 % in eggplant yield can be obtained. If one would only apply 80 % of the irrigation requirement F75 would result in a 22 % yield increase.

4.2. Effect of water and nitrogen application on fruit quality, WUE and NUE

The fruit length response to water and nitrogen was similar to the other crop growth and yield performance indicators whereas no significant differences were observed for the fruit diameter. In this case similar fruit length could be attained at I80 compared to I100 under F100. Similar results were pointed out by Kirnak et al. (2002) who concluded that, eggplant can be produced at 90 % replenishment without a significant reduction in fruit size. The positive effect of deficit irrigation on fruit size (Patanè et al., 2011; Silveira et al., 2020) was supported in this study for 80 % of the crop water requirement. Furthermore, deficit irrigation (I60) with any N combination resulted into low fruit moisture content. Overall, the application of I80 under 75 % of the N application did not result in a significant reduction of overall fruit quality. However, if one was to further decrease irrigation application and combine this with further lower levels of N application one would significantly affect fruit quality and likely therefore marketability of the produce.

Whilst lower N application influenced fruit quality and WUE, higher NUE were reported. Overall, WUE was highest under I100, I80 or I60 in combination with F100 and F75. However, WUE dropped significantly under F50 whilst NUE increased. This further supports earlier studies where deficit amounts of water and N positively effects crop performance. Gaveh et al. (2011) recommended the use of 80 % of the crop water requirement to translate in highest WUE while the higher NUE with lower N application is supported by Zotarelli et al. (2009) who observed high N use-efficiency when N is a limiting factor in tomatoes. If the absolute highest average WUE (I60) would be chosen this would result in the lowest NUE. On the other hand, the combination of the lowest level of 60 % or 80 % water applied with the higher level of N (100 % or 75 %) resulted to lowest N-use efficiency. This is because deficit irrigation limits plant water uptake consequently prohibiting efficient N uptake by the plant.

5. Conclusions

Strategies to enhance African eggplant production through improved water and nitrogen management was assessed during two irrigation seasons. The study evaluated the effect of irrigation water and N on crop growth variables and yield, fruit quality, WUE and NUE. Plant height, LAI and number of fruits per plant was good indicators of the end of season yields. The study showed the importance of combining different irrigation performance indicators which responds to different levels of water and nitrogen to evaluate and assess suitable irrigation and fertilizer strategies for African eggplant. Based on the crop performance, yield, fruit quality, WUE and NUE different optimal water and fertilizer strategies can be defined. Minimizing trade-offs between the various indicators and taking into account the cost involved in pumping water as well as those for buying fertilizer, the optimal application for African eggplant would likely be around 80 % of the total irrigation requirement and 75 % of the N requirement in sandy clay loam soils under sub-humid conditions.

CRediT authorship contribution statement

Paul Reuben Mwinuka: Conceptualization, Data curation, Methodology, Writing - original draft, Writing - review & editing. **Boniface P. Mbilinyi:** Conceptualization, Supervision, Investigation, Data curation. **Winfred B. Mbungu:** Supervision, Methodology, Investigation, Writing - review & editing. **Sixbert K. Mourice:** Supervision, Methodology, Writing - review & editing, Validation. **Henry F. Mahoo:** Project administration, Investigation. **Petra Schmitter:** Writing - review & editing, Validation.

Declaration of Competing Interest

The authors report no declarations of interest.

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