Journal of Agriculture and Food Research 10 (2022) 100384

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Yield, mineral content and root growth response of jute mallow (*Corchorus olitorius* L.) to planting density and water availability

Sibongiseni Mgolozeli [a,b,*], Eyob Habte Tesfamariam [a], Yacob Beletse [b]

[a] University of Pretoria, Private Bag X20, Hatfield, 0028, South Africa
[b] Agricultural Research Council - Vegetable and Ornamental Plant Institute, Private Bag X293, Pretoria, 0001, South Africa

ARTICLE INFO

Keywords:
Biomass yield
Irrigation
Nutritional value
Plant population
Plant available water

ABSTRACT

Current trends in agriculture dictate an urgent need for the reduction of input resources while maintaining high biomass yield of good quality. The overall aim of the study was to investigate the interactive effects of planting density and water availability on growth, development, total biomass yield and quality of jute mallow. It was hypothesized that up to 20% of the crop irrigation water requirement could be saved through deficit irrigation without compromising biomass production and nutritional value. To achieve the stated aim, three planting densities: low (100 000 plants.ha^{-1}); medium (167 000 plants.ha^{-1}); and high (330 000 plants.ha^{-1}) were tested in a two-year field trial. Each of these planting densities received three irrigation strategies: full irrigation (irrigation to field capacity (FC)); medium stressed (irrigation to 80% plant available water (PAW)); and stressed (irrigation to 60% PAW). All treatments were replicated three times in a randomized complete block design layout. Irrigation was applied every fifth day for all treatments under nitrogen non-limiting conditions. Results showed that high leaf area index (LAI), stomatal conductance (gs), total fresh yield, and mineral content (Zn and K) were attained at the medium planting density of 167 000 plants.ha^{-1} under the medium stress (irrigation to 80% PAW) strategy. Consequently, 20% less than is needed to fill the root zone to FC was saved. Hence, the hypothesis was accepted. On the other hand, the irrigation strategy of irrigation to FC increased the length and dry mass of the roots.

1. Introduction

Food insecurity is one of the biggest challenges in Sub-Saharan Africa (SSA) which are expected to aggravate under the envisioned climate change if agricultural production continues in business as usual. Water shortage and land degradation are the two main causes of food insecurity in SSA among other factors. Maseko et al. [1] states that “South Africa faces challenges of food insecurity at household levels due to nutrient deficiencies such as vitamin A, iron, zinc, and vitamin C.” The Food and Agricultural Organization (FAO, 2012) defined food security as “a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets the dietary needs and food preferences for an active and healthy life”. Approximately 70% of South African land surfaces have been affected by varying intensities and types of erosion [2] and left about 60% of soils with less than 0.05% of soil organic matter [3]. According to Labadarios et al. [4]; among 1–9 year old SA children: 64% have low serum retinol (vitamin A) levels, 45% have low zinc status and 28% are anaemic while 13% have poor iron status. To address these food and nutritional insecurity related challenges in the SSA, several mitigation and adaptation measures have been proposed including but not limited to the use of drought tolerant breeds, implementation of water harvesting techniques and reclamation of degraded lands. Besides, there is a growing recognition and demand for traditional food crops due to their potential role as nutraceuticals, functional food and as dietary supplement to improve health quality especially in rural areas [5].

Many farmers practicing in marginal lands including rural households for sustenance [6] have used Jute mallow with several traditional crops as stable food. Jute mallow is a traditional leafy vegetable crop harvested from the wild in the tropical and subtropical regions [7,8] with higher nutritional value than some of the popular vegetables such as cabbage, spinach and other leafy vegetable crops (Oelofse and Van Aberbake, 2012; [9]. The crop is planted directly from seeds or by transplanting seedlings. Generally, seeds are sown one to two cm deep uniformly in raised beds at a rate of five to six kg per hectare, and thinned after full germination to achieve plant spacing of 0.5 m between

---

* Corresponding author. University of Pretoria, Private Bag X20, Hatfield, 0028, South Africa.
E-mail address: steinger23@gmail.com (S. Mgolozeli).

https://doi.org/10.1016/j.jafr.2022.100384
Received 27 April 2022; Received in revised form 26 August 2022; Accepted 3 September 2022

rows and 0.2 m between plants to give a plant density of 100 000 plants. ha^{-1} [10]. Seedlings are often transplanted to the field when they reach a height of 0.1 m with an average of eight leaves per seedling [11,12]. Jute mallow is known for its sturdy natural fibre and serve as important food for many families in Asia, Middle East and Africa [13]. According to Jansen van Rensburg et al. (2009), cooked Jute mallow has mucilaginous texture and is highly favoured by people in the northern parts of South Africa. Generally, jute mallow is among many indigenous vegetable species, which are gaining international recognition due to their potential role to food and nutritional security as well as income generation option for smallholder farmers [6]. It is grown for its edible leaves, which are rich sources of pro-vitamin A (β-carotene), calcium, thiamine, niacin, folate, riboflavin, zinc and iron [8,13,14]. According to Tovihoudji et al. [6]; the leaves of jute mallow plays an important role in nutrition and food security and they contain an average of 15% dry matter, 4.8 g of protein, 259 mg of calcium, 4.5 mg of iron, 4.7 mg of vitamin A, 92 μg of folates, 1.5 mg of nicotinamide and 105 mg of ascorbic acid per 100 g of leaves. The leaves of jute mallow could play an important role in the prevention of a number of malnutrition-triggered diseases, especially in children who live in rural areas, as the number is higher compared to those living in urban areas [15]. Besides the higher nutritious value, Jute mallow's ecological adaptation to various environmental and climatic conditions such as heat stress and resistance to pest and diseases [1] informed the choice of jute mallow for this study. Jute mallow is a shallow-rooted crop with an adventitious root system [8,16], which grows in semi-arid to humid regions that receive an annual rainfall of 600 mm to 2000 mm and temperatures above 15 °C [7,17].

This crop is sensitive to water stress, but recovers easily with the availability of water [16,18]. In the arid and semi-arid regions of Sub-Saharan Africa, where the long-term mean annual rainfall is less than 600 mm, supplemental irrigation is required for optimal jute mallow production [7,19]. Based on personal communication with South African smallholder farmers, stress or deficit irrigation could be applied by leaving room for rain without compromising Jute mallow biomass yield to (i) Save up 20% of irrigation water and (ii) Minimize nitrate leaching due to an increase in root volume and depth. Jute mallow is among the least studied leafy vegetables despite its high nutritional value and ecological adaptation capabilities. There is a paucity of information in South Africa with regard to the effect of water stress, radiation use efficiency, planting density and nitrogen fertilization on crop quality and production [5,7]. Agronomic and cultural practices for maximum biomass yield production and high nutritional value of the crop are not fully understood. The objective of this study was to determine the interactive effects of planting density and water availability on the nutritional value, total biomass yield and root growth response of jute mallow under nutrient non-limiting conditions. The recommended planting density of 100 000 plants ha^{-1} [10] is too little for maximum biomass yield under irrigated Nitrogen non-limiting conditions. Therefore, it was hypothesized that the biomass yield of Jute mallow can be attained by increasing planting density from 100 000 to 167 000 or 330 000 $plants.ha^{-1}$. It was also hypothesized that up to 20% of the crop irrigation water could be saved by irrigating the crop to 20% less than what is needed to fill the root zone to Field Capacity through deficit irrigation without compromising biomass production and nutritional value.

2. Materials and methods

2.1. Study site description and crop management

A two-year (2012/13 and 2013/14 seasons) field trial was conducted under a rain shelter at the Agricultural Research Council–Vegetable and Ornamental Plant Institute (ARC–VOPI) in Roodeplaat (25°35′ S, 28°21′ E, altitude 1165 m), which is located about 35 km north east of central Pretoria. The soil at the study site is red sandy clay loam and is classified as Hutton [20] with a depth of more than 1.2 m. Textural analyses of the top 1 m soil depth are presented on Table 1.

The soil is fairly well drained with moderate water-holding capacity. The soil contains 2344 mg kg^{-1} and 56 mg kg^{-1} of Iron (Fe) and Zinc (Zn), respectively. Other selected chemical properties of the study site determined prior to planting are presented on Table 2. The amount of water, which was applied in both growing seasons, is shown in Table 3.

Weather data was collected from an automated weather station located 100 m from the experimental site. This weather station consisted of an LI 200X pyranometer (LiCor, Lincoln, Nebraska, USA) for measuring solar radiation, an electronic relative humidity and temperature sensor (Model 083E Relative Humidity and Temperature Sensor), to measure relative humidity and temperatures, an electronic cup anemometer (MET ONE, Inc. USA) to measure wind speed, an electronic rain gauge (RIMCO, R/TBR tipping bucket rain gauge, Rauchfuss Instruments Division, Australia) to measure rainfall and a CR 10X datalogger for data storage (Campbell Scientific Inc., USA). The mean weekly maximum and minimum temperature, two-weekly cumulative rainfall, mean weekly solar radiation, and mean weekly evapotranspiration (ETo) are presented in Fig. 1.

2.2. Experimental layout and treatments

A field study was established under a rain shelter for two consecutive seasons (2012/13 and 2013/14). Plots of 5.2 m^2 (2 m × 2.6 m) were arranged in a randomized complete block design (RCBD) comprising three replications of a two-factor experiment. The two factors were planting density and irrigation. Five extra plots were included for destructive sampling and back-up for unforeseen errors in the main plots.

The planting treatments consisted of three densities: low (P1) = 100 000 $plants.ha^{-1}$ (0.2 m × 0.5 m), medium (P2) = 167 000 $plants.ha^{-1}$ (0.2 m × 0.3 m) and high (P3) = 330 000 $plants.ha^{-1}$ (0.2 m × 0.15 m). Irrigation was applied every fifth day according to the soil water deficit computed from site calibrated neutron probe readings (Model 503 DR CPN Hydroprobe; Campbell Pacific Nuclear, CA) to a depth of 0.6 m. The irrigation strategies included irrigating to refill the profile to FC (W1); irrigating to refill the profile to 80% of PAW (W2); and irrigating to refill the profile to 60% of PAW (W3).

2.3. Crop management

Seedlings were established in shade nets using Hygromix® growth medium on trays and lightly covered with vermiculite for easy germination. The seedlings were transplanted to the rain shelter once they reached a height of 0.1 m, with an average of eight leaves per seedling. After transplanting, the seedlings were irrigated with 10 mm daily for the first week to avoid seedling death. Nitrogen (N) was applied in split with 40% of the annual recommended rate (100 kg ha^{-1}) applied at transplanting, 20% after first harvest, 20% after second harvest, and the last 20% after the third harvest in the form of limestone ammonium nitrate (LAN). Wetting front detectors (WFD) were installed at both 30 and 60 cm depth below the soil surface to monitor nitrate concentration in leachate. During the first growing season (2012/13), the concentration of nitrate in leachate collected by WFDs was so high at transplanting

Table 1
Soil textural analyses of the experimental Hutton soil form at ARC–VOPI Roodeplaat, Pretoria.

Soil Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural Classification
0–20	70	8	22	Sandy clay loam
20–40	66	8	26	Sandy clay loam
40–60	66	8	26	Sandy clay loam
60–80	62	6	32	Sandy clay loam
80–100	62	6	32	Sandy clay loam

Table 2
Selected soil chemical properties of the top 0.40 m soil layer of the study site at ARC-VOPI Roodeplaat, Pretoria, 2012/13.

Soil depth	N–NO3-	N–NH4+	P	K	Ca	Mg	Na	pH
cm	mg kg-1							(H2O)
0–40	21.05	4.79	84.4	234.5	912	148.5	38.8	7.40

Table 3
Total irrigation water applied during the first and second season at ARC-VOPI Roodeplaat, Pretoria.

Irrigation Treatments	2012/2013	2013/2014
100%FC	192 mm	189 mm
80%PAW	165 mm	166 mm
60%PAW	114 mm	126 mm

time. This was attributed mainly to low consumption by plants because the roots were not well established. Consequently, the fertilizer application ratio during the second growing season was revised to 20% of the total annual application at transplanting; 25% after first harvest; 30% after the second harvest; and the remaining 25% after the third harvest.

2.4. Sampling and sample analyses

Four harvests per season were made for both growing seasons. The first harvest was made three weeks after transplanting. The second, third and fourth harvests were made every third to fourth week following each harvest. The samples from each plot were randomly harvested 0.2 m above the soil surface. The collected plant samples were partitioned into stems and leaves, and total fresh biomass was measured as the sum of the two. The samples were oven dried at 70 °C for 48 h to determine total dry aboveground biomass. Additional samples were collected during the maximum vegetative period (second harvest) of each season for selected mineral content analyses (K, P, Zn, and Fe). The nutrient concentration of a plant is at its peak during the maximum vegetative period [21]. The study on mineral content focused on Zn and Fe because of the widely reported deficiency symptoms in women and children in rural areas in SSA (Wenhold et al., 2012; [22].

The mineral content analyses were conducted on a 200 g fresh composite sample per treatment, which consisted of leaves and young tender stems (edible fresh biomass). The plant samples were analysed for P, Fe and Zn after wet acid digestion, using an inductively coupled plasma optical emission spectrometer (ICP-OEC) (SpectroFlame Modula; Spectro, Kleve, Germany), following standard procedures (Non-Affiliated Soil Analyses Work Committee, 1990). Similarly, plant sample K content was analysed using an ammonium acetate extraction method following standard procedures (Non-affiliated Soil Analyses Work Committee, 1990). Leaf area index was measured weekly with a plant canopy analyser (LAI-2200) by taking one reading above and four readings below the canopy. The four readings below were made between rows (starting at the bottom right corner diagonally to the top left corner of the plot). Stomatal conductance was measured weekly from three plants per plot and three leaves per plant, using a steady state leaf porometer device (SC-1 leaf porometer, Decagon Devices). Chlorophyll content measurements were done at similar time intervals using a chlorophyll content meter (Opti-Sciences CCM-200, USA).

The Fv/Fm ratio was determined for each treatment as the chlorophyll fluorescence component using Handy Plant Efficiency Analyser (Handy PEA) (Hansatech Instruments Ltd., King's Lynn, Norfolk, UK). This ratio is correlated directly with total leaf N and chlorophyll content [23], and hence is often used as an estimate for total biomass yield [24]. Leaf blades of sample plants were dark-adapted using Handy PEA suitable clamps for 30 min i) to allow relaxation of fluorescence quenching associated with thylakoid membrane energization; and ii) to bring all the centres of photosystem II (PSII) to an open stage [23,24]. A single measurement per plant (fully expanded leaf disc) was made in three plants per plot for all treatments.

A 1.1 m long clear acrylic tube was installed vertically at an angle of 45° with 0.1 m of the tube protruding above the soil surface as per recommendations by Iversen et al. [25] and Villordon et al. [26]. The acrylic tubes were installed between plants within a row by digging a hole with an auger of similar diameter to ensure snug fit. The bottom openings of the tubes were capped to prevent water entry. Similarly, the

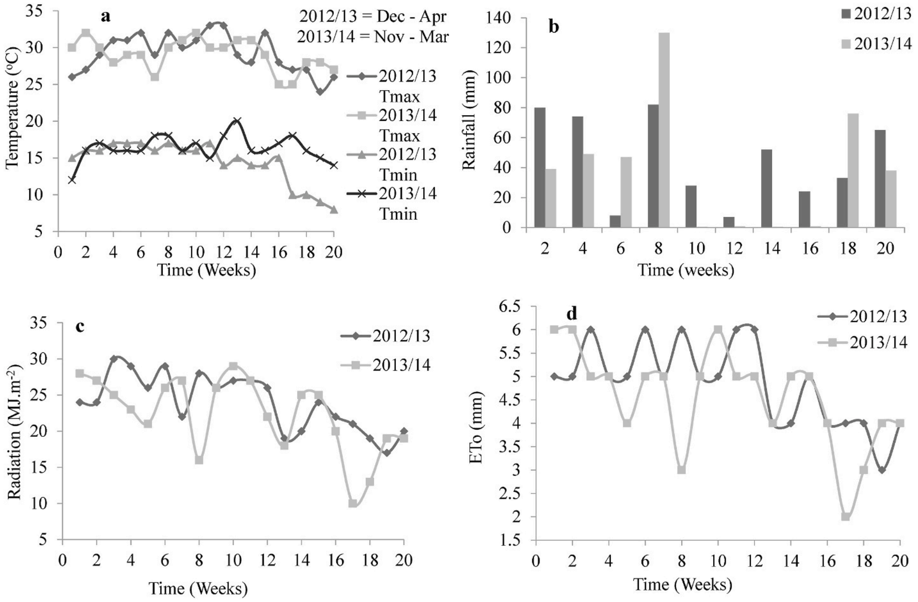

Fig. 1. Mean weekly maximum and minimum temperatures (a), rainfall (b), radiation (c) and evapotranspiration (d) during the 2012/13 and 2013/14 growing seasons at ARC–VOPI, Roodeplaat, Pretoria.

upper openings of acrylic tubes were closed when not in use to prevent the entry of water and dirt.

A root scanner (CI-600 Root Scanner, CID Bio-Science, Camas, WA, USA) was inserted into each tube to measure root growth every 0.2 m increments up to 0.8 m depth. This tool scans 360° in the inner surface of the acrylic tube, and is used in conjunction with a portable laptop to capture and store root images at 300 dpi resolution. Various resolutions could be used, but higher resolution (up to 1000 dpi) measurements take longer [25]. The measurements for non-destructive root samples were made during the maturity stage of the crop, two weeks before the termination of the trial. The root images were analysed using CI-600 Root Snap software, which provides average and total root length (mm), root diameter (mm), root volume (mm^3) and root area (mm^2). Because of limited funds, measurements were made in only two replicates for each treatment. Root length was calculated using the following formula to compensate the angle used for acrylic tube installation:

$$\mathrm{RL} = \mathrm{RL_i} \times \mathrm{Cos}\ \theta \tag{1}$$

where RL (mm) is the actual rooting length, RL$_i$ (mm) is the angled root length and θ (^{o}) is the tube angle [27].

At the end of each trial, three root samples were carefully taken per plot using spades, and the roots were washed with tap water. Average value of the three samples was used as representative root length and root dry weight per plot. Root length was measured with a ruler. Root fresh mass was determined immediately after the destructive sampling using a suitable weighing balance with a resolution of ±0.00 g. Root dry mass was determined by oven drying the fresh root samples at 70 °C for 48 h.

2.5. Statistical analyses

Fresh biomass, dry biomass, mineral nutrients, root length and root dry matter were subjected to analysis of variance (ANOVA) using a two factor (three planting density by three water levels) randomised block design of the linear model of the Statistical Analysis System (SAS) software for Windows v 9.3 (Statistical Analysis System, Inc., 2002). Difference between treatment means were separated using least significant difference (LSD) at $p < 0.05$.

3. Results

3.1. Total fresh and oven dried biomass yield

When data was combined for both years, there was an insignificant means ($P < 0.05$) year × spacing × irrigation interaction effect on total fresh and total dry biomass yield. However, there was a significant ($P < 0.05$) spacing × irrigation interaction for both total wet and total dry biomass yield (Table 5). This was primarily attributed to magnitudinal differences in total biomass between the two growing seasons. Similar trend showing an increase in total fresh (Fig. 2a and c) and total dry biomass yield (Fig. 2b and d) of jute mallow with an increase in planting density indicates that there were some significant interactions among treatment means despite the varying climatic conditions between the two experimental years.

Table 4

Water productivity (kg.m-3) from the irrigation and planting density treatments at ARC–VOPI Roodeplaat, Pretoria.

Treatments	100 (10)3 Plants.ha-1	167 (10)3 Plants.ha-1	330 (10)3 Plants.ha-1
2012/2013 seasonrowhead			
100%FC	0.25 kg.m-3	0.29 kg.m-3	0.29 kg.m-3
80%PAW	0.23 kg.m-3	0.30 kg.m-3	0.30 kg.m-3
60%PAW	0.14 kg.m-3	0.13 kg.m-3	0.17 kg.m-3
2013/2014 seasonrowhead			
100%FC	0.14 kg.m-3	0.27 kg.m-3	0.25 kg.m-3
80%PAW	0.11 kg.m-3	0.28 kg.m-3	0.25 kg.m-3
60%PAW	0.10 kg.m-3	0.18 kg.m-3	0.16 kg.m-3

In both experimental years, the yields from medium (P2 = 167 000 plants.ha^{-1}) and higher planting density (P3 = 330 000 plants.ha^{-1}) at full (W1 = FC) and medium (W2 = 80%PAW) irrigation levels were significantly ($P < 0.05$) higher than the yield from lower planting density (P1 = 100 000 plants.ha^{-1}). During the 2012/13 growing season, the highest value of 19.0 t ha^{-1} (Figs. 2a) and 3.2 t ha^{-1} (Fig. 2b) for total harvestable fresh and oven dried biomass yield, respectively, were recorded under P3W2. However, the total harvestable fresh and dry biomass yields of jute mallow were relatively higher at medium planting density of 167 000 plants.ha^{-1} compared with 330 000 plants. ha^{-1}during the 2013/14 growing season.

Table 4 shows the crop water productivity or water use efficiency for each treatment and was calculated using the following equation [19];

$WUE = \frac{M_b}{Cw} kg/m^3$ Where WUE is water use efficiency in kg/m^3, M_b is sum of fresh weight of leaves, roots and stems in kg, and Cw is cumulative amount of water used in m^3. The crop water use was estimated using soil water balance equation as follows;

$$Cw = \mathrm{I} + \mathrm{P} + \Delta \mathrm{s} + \mathrm{D} + \mathrm{R}$$

Where Cw = crop water use (mm), I = Irrigation (mm), P = Precipitation (mm), Δs = Change is soil moisture storage (mm), D = Drainage (mm), and R = Runoff (mm). Since a rain shelter was used, precipitation, drainage and runoff were negligible. The results from the current study show that water productivity of Jute mallow increases with the increase in planting density (Table 4).

3.2. Mineral content

When data were combined for both years, there was a significant mean ($P < 0.05$) year × spacing × irrigation effect on phosphorus and iron. There was, however, no significant mean ($P < 0.05$) year × spacing × irrigation effect for potassium and zinc. There was highly significant mean ($P < 0.001$) spacing × irrigation effect for all mineral nutrients (Table 6). The lowest Zn contents of 28.6 mg kg^{-1} and 26.5 mg kg^{-1} for the 2012/13 and 2013/14 growing seasons, respectively, were recorded at the lowest planting density, which received 60% PAW irrigation treatment (Fig. 3a and b). The highest values of 48.8 mg kg^{-1} for 2012/13 and 44.2 mg kg^{-1} during the 2013/14 growing season were recorded at medium planting density of 167 000 plants per hectare combined with 80% PAW irrigation treatment (P2W2).

Pertaining the Fe content, the highest value of 421.5 mg kg^{-1} was recorded at 100 000 plants.ha^{-1} and 80% PAW treatment combination. Generally, 80% PAW produced higher Fe content in all planting densities compared with other irrigation treatments (Fig. 3c). The lowest Fe content (224.7 mg kg^{-1}) of jute mallow was recorded at 167 000 plants. ha^{-1} and 60% PAW treatment combination. For all planting densities, the lowest value of Fe was recorded where 60% PAW irrigation treatment was applied.

Similarly with the Fe content analysis results, the year had a significant effect on treatment combination (planting density and irrigation) on the P content of jute mallow. The results indicate that an increase in water availability improves the P content of jute mallow leaves at all planting densities. However, there was a decline in P content from 80% PAW to FC under 100 000 plant.ha^{-1} planting density (Fig. 3d). The highest significant value of 0.7% for P was recorded under both medium (167 000 plants.ha^{-1}) and higher (330 000 plants.ha^{-1}) planting densities that received full irrigation treatment (FC). The lowest significant value of 0.3% was recorded under both the lowest planting density and higher planting density that received severe stressed water treatment (60% PAW).

Table 5
Combined analysis of variance table over the two years for total fresh mass and total dry biomass yield.

Source of Variation	Total Fresh Mass			Total Dry Mass		
	df	Mean squares	Pr > F	df	Mean squares	Pr > F
Year	1	53.0046296	<.0001	1	3.63481667	<.0001
Error (a)	32	1.176296	<.0001	32	0.02839653	<.0001
Spacing	2	356.1785185		2	8.83890556	
Year*Spacing	2	13.7029630	0.0002	2	0.43120556	<.0001
Irrigation	3	124.5256944	<.0001	3	2.41637917	<.0001
Year*Irrigation	3	9.5586574	0.0004	3	0.19048287	0.0012
Spacing*Irrigation	3	16.8328241	<.0001	3	0.34661713	<.0001
Year*Spacing*Irrigat	3	0.5961574	0.6804	3	0.03744676	0.2854
Error (b)	52	23.809288		52	0.54689744	

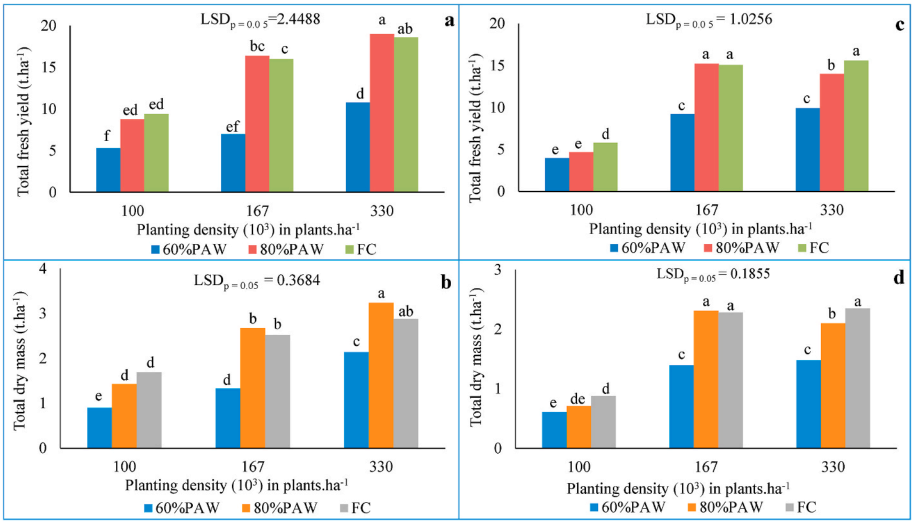

Fig. 2. Mean (a) fresh and (b) oven dry biomass yield for 2012/13 growing season and (c) fresh and (d) dry biomass yield for 2013/14 growing season. Means with the same letter are not significantly different ($P < 0.05$). FC = field capacity, PAW = plant available water.

Table 6
Combined analysis of variance table for both years of potassium, phosphorus, iron and zinc.

Source of Variation	Potassium (%)			Phosphorus (%)		Iron (Fe)	Zinc (Zn)	
	df	Mean squares	Pr > F	Mean squares	Pr > F	Mean squares Pr > F	Mean squares	Pr > F
Year	1	2.20826667	<.0001	0.00125185	0.5337	14474.4074 < .0001	250.9066667	<.0001
Error (a)	32	0.42176720	<.0001	0.00316204	<.0001	734.4699	12.664468	<.0001
Spacing	2	1.05680000		0.13055000		14825.9074 < .0001	247.0468519	
Year*Spacing	2	0.27740000	0.0028	0.00545741	0.1942	5744.0185 0.0017	0.3350000	0.9739
Irrigation	2	0.91570556	<.0001	0.31748889	<.0001	63288.9630 < .0001	200.4051852	<.0001
Year*Irrigation	2	0.54527222	0.0001	0.01742963	0.0088	1434.7407 0.1583	37.6155556	0.0656
Spacing*Irrigation	4	0.19458056	<.0030	0.07338056	<.0001	10626.1852 < .0001	101.0857407	<.0001
Year*Spacing*Irrigat	4	0.03101389	0.5362	0.01014352	0.0253	5193.6852 0.0003	27.0338889	0.0993
Error (b)	52	0.15181795		0.02676311		4963.0783	37.659943	

3.3. Root growth

When data was combined for both years, there was no significant ($P > 0.05$) spacing × irrigation interaction effect on root length and root dry matter (Table 7). However, the treatment means on year × spacing interaction on root length and year × irrigation interaction effects on root dry matter was significant ($P < 0.05$). The results indicate that for the 2012/13 growing season, there was no clear trend to show whether the interactive effect of planting density and water availability increased or decreased the root length of jute mallow (Fig. 4a). Comparison between the treatment show that the highest root length value of 24.2 cm was recorded under the medium planting density of 167 000 plants. ha^{-1}, which received FC water treatment. The lowest root length of 18.1 cm was recorded under the medium planting density that received the severe stressed water treatment of 60% PAW. For the 2013/14 growing season, the root length of jute mallow was generally higher at the lowest and medium planting densities compared with the highest planting density of 330 000 plants.ha^{-1} (Figs. 4b–9). The highest value of 17.0 cm was recorded at the lowest planting density, which received FC water treatment. The lowest value of 6.0 cm was recorded under the highest planting density at both medium (80% PAW) and FC water treatment.

For both growing seasons, a similar growth pattern showing an increase in planting density was observed to decrease root dry weight of jute mallow (Fig. 4c and d). This is probably attributable to moisture and nutrient resource competition among crops. For the 2012/13 growing season, the highest value of 3.1 g.plant^{-1} for root dry matter was recorded under the lowest planting density, which received severe stressed (60% PAW) irrigation treatment. The lowest value of 1.0 g.

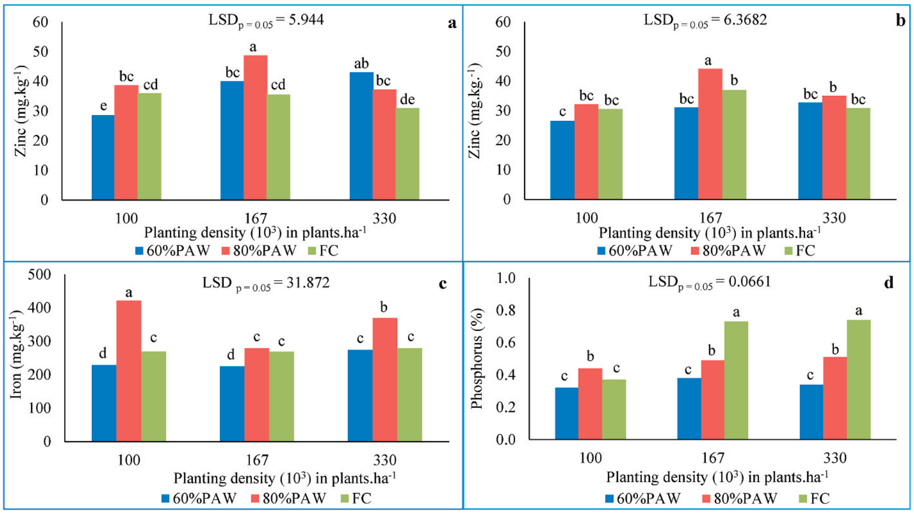

Fig. 3. The interactive effect of planting density and water availability on zinc a) (2012/13) and b) (2013/14 growing season) as well as the combined seasons for iron c) and d) phosphorus. The results for 2012/13 and 2013/14 seasons for both Iron and Phosphorus were combined because there was an interaction effect ($P < 0.05$) as shown in (Table 4). FC = field capacity, PAW = plant available water.

Table 7

Combined analysis of variance table for both years for root length and root dry matter using destructive method.

Source of Variation	Root length			Root Dry Matter		
	df	Mean squares	Pr > F	df	Mean squares	Pr > F
Year	1	1529.606667	<.0001	1	0.40907407	0.1803
Error (a)	34	5.509869	<.0001	34	0.21865468	<.0001
Spacing	2	103.605000		2	9.31629630	
Year*Spacing	2	65.360556	0.0001	2	0.29851852	0.2690
Irrigation	2	12.573818	0.0683	2	0.53932828	0.0520
Year*Irrigation	2	15.640631	0.1012	2	1.92363636	0.0055
Spacing*Irrigation	4	10.998125	0.1173	4	0.18618056	0.5027
Year*Spacing*Irrigat	0	–	–	0	–	–
Error (b)	52	13.437821		52	0.62685185	

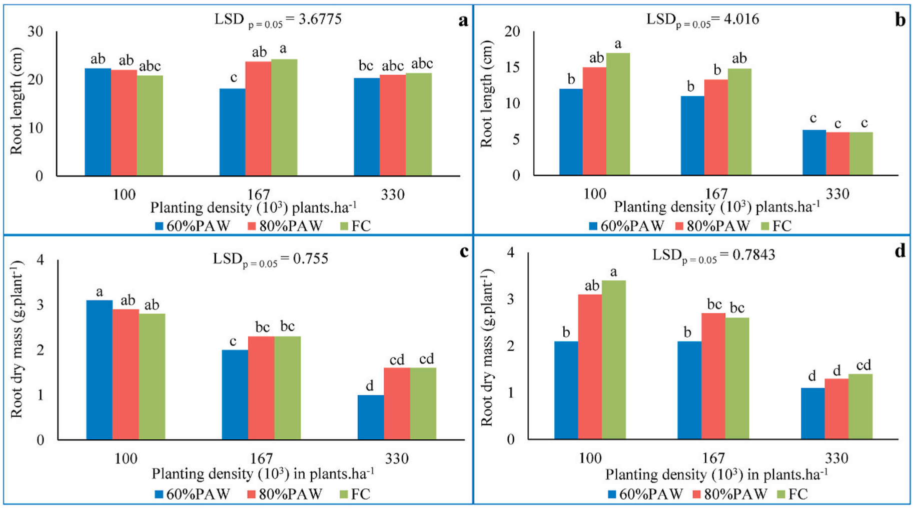

Fig. 4. Interactive effect of planting density and water availability on root length during the (a) 2012/13 and (b) 2013/14 growing seasons and root dry mass during the (c) 2012/13 and (d) 2013/14 growing seasons using destructive method. FC = Field capacity, PAW = plant available water.

plant^{-1} was recorded at the highest planting density, which received severe stressed irrigation treatment. For the 2013/14 growing season, the highest value of 3.4 g.plant^{-1} was recorded under the lowest planting density, which received FC treatment, while the lowest value of 1.1 g.plant^{-1} was recorded at the highest planting density of 330 000 plants.ha^{-1}, which received severe stressed irrigation treatment.

When data were combined for both years, there was a significant ($P < 0.05$) year × spacing × irrigation interaction effects for root growth parameters except for root diameter when using the non-destructive method (Table 8). Generally, root volume was significantly ($P < 0.05$)

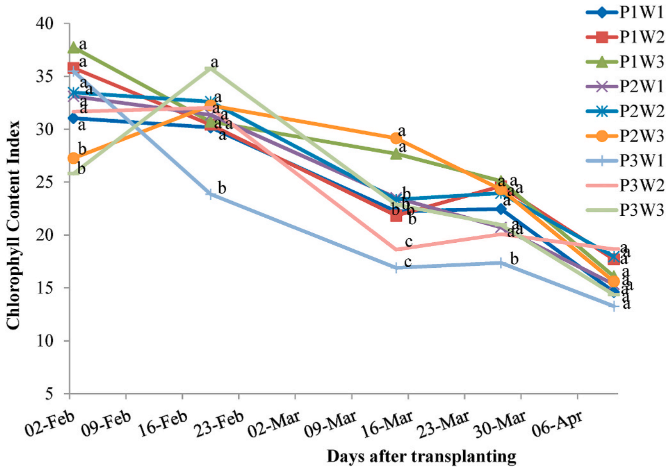

Fig. 5. Crop aging effect on Chlorophyll Content Index (CCI) of Jute mallow under three planting densities exposed to three irrigation regimes during the 2013/14 growing season. Means with the same letter are not significantly different within the same planting date.

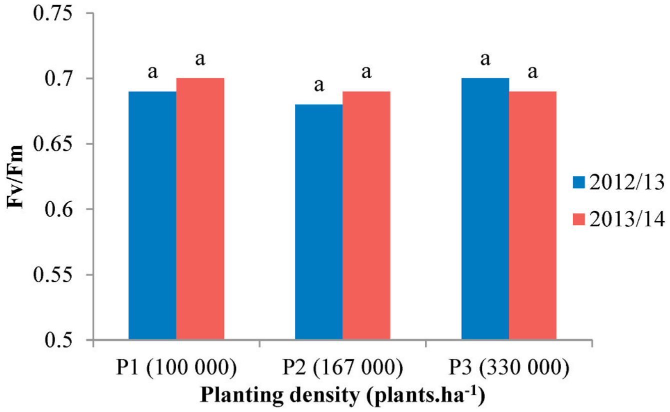

Fig. 6. The effect planting density on leaf Chlorophyll Fluorescence (Fv/Fm) during the 2012/13 and 2013/14 growing season. Means with the same letter are not significantly different from each other at P < 0.05. LSD2012/13 = 0.02, LSD2013/14 = 0. 03.

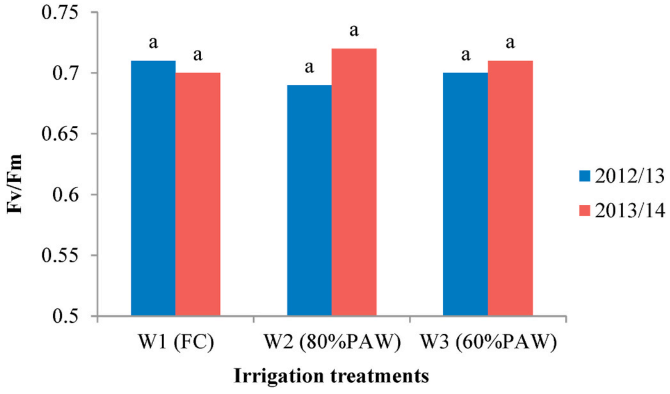

Fig. 7. Irrigation effect on leaf Chlorophyll Fluorescence (Fv/Fm) during the 2012/13 and 2013/14 growing season. Means with the same letter are not significantly different from each other at P < 0.05. LSD2012/13 = 0.02, LSD2013/14 = 0. 03.

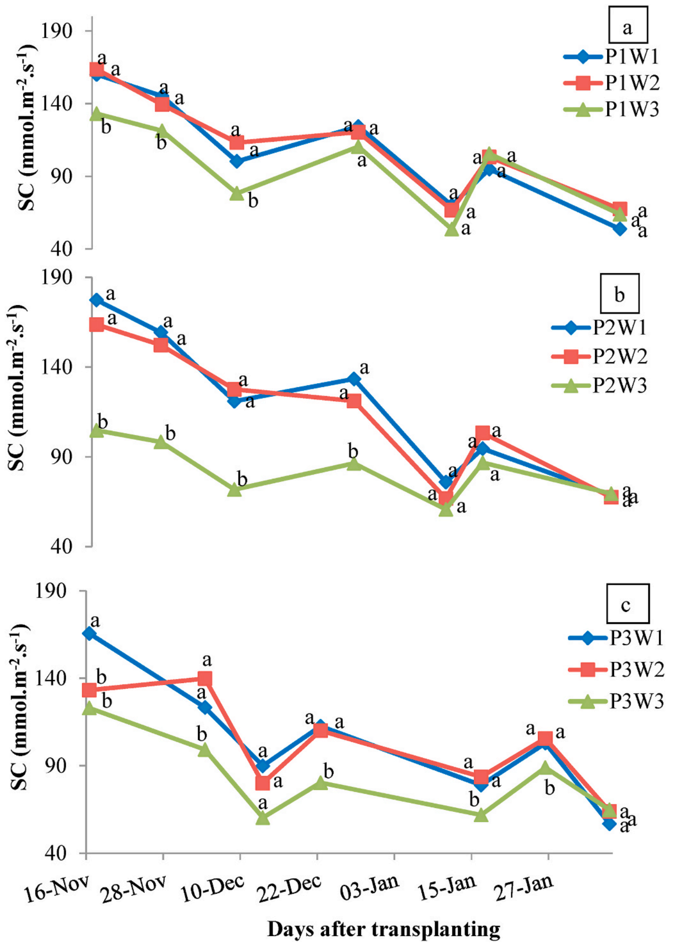

Fig. 8. Stomatal conductance of Jute mallow at different planting densities: low planting density of 110 000 plants.ha-1 (a), medium planting density of 167 000 plants.ha-1 (b), and high planting density of 330 000 plants.ha-1 (c) during the 2013/14 growing season.

higher at the full irrigation treatment (FC) than other irrigation treatments at all planting densities. The results indicate that the root volume improves with an increase in soil water availability at all planting densities. Comparison between the treatments show that the highest significant value of 4031.4 cm^{-3} was recorded under P2W3, and the lowest value of 1521.5 cm^{-3} was recorded under P1W1 treatment combination.

Pertaining to the effect of soil water availability on root length, the results show that root length of jute mallow decreased as the soil water availability rose at all planting density, except at medium planting density of 167 000 $plants.ha^{-1}$, which showed the opposite of the trend with other planting densities. Comparison between the treatments show that the highest significant value of 16.5 cm was recorded at the lowest planting density that was subjected to severe water stress conditions (P1W3) and the lowest value was of 10.4 cm was recorded at P3W3 treatment combination. Pertaining to the effect of spacing and water availability on root diameter, the results showed no clear trend whether the root diameter decreases or increase as the planting density or water availability increases. However, comparison between the treatments show that the highest value of 1.25 mm was recorded under P2W1 treatment combination, while the lowest value of 0.8 mm was recorded under P3W3 treatment combination.

The differences between the severe stressed (60%PAW) and FC water treatments were not apparent under the highest planting density (330 000 $plants.ha^{-1}$), but significantly lower compared to the medium stressed (80% PAW) water treatment. However, the root images scanned

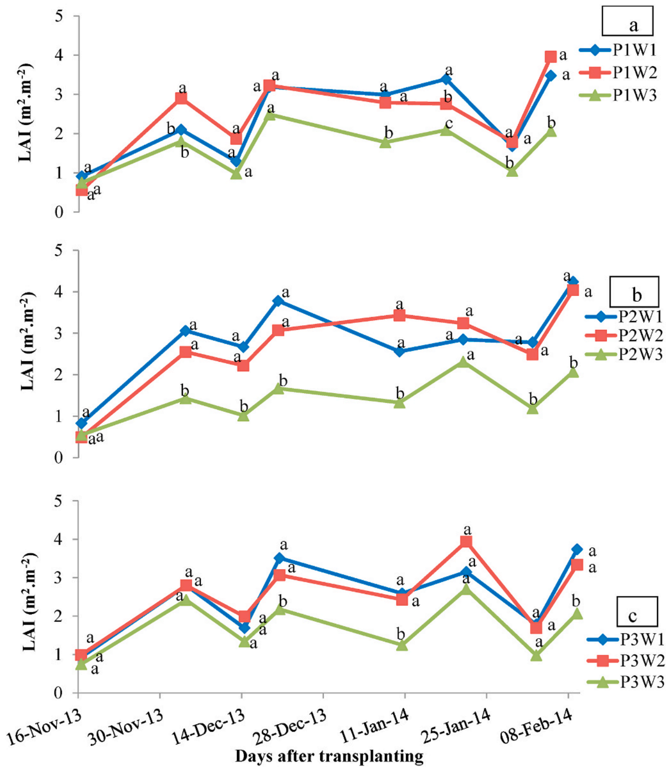

Fig. 9. Leaf Area Index response to harvesting as affected by water availability at low planting density of 100 000 plants.ha-1 (a), medium planting density of 167 000 plant.ha-1 (b) and high planting density of 330 000 plants.ha-1 (c) during the 2013/14 growing season.

at depth 0.4 m appear to show differences in root distribution as affected by water availability at high planting density. It would have been interesting to compare all the images scanned at different increment depth from the same day and treatment to see the general overview or picture of the complete root system of a single crop. However, the angle at which the tubes are installed do not allow such observations and the other challenge is that the scanner shows only those roots that are in contact with the tube.

3.4. Leaf to stem ratio of total fresh and dry biomass yield

When data were combined for both years, there was no significant ($P > 0.05$) year × spacing × irrigation interaction effects on all plant yield parameters. However, there were significant ($P < 0.05$) spacing × irrigation interaction effects on all plant yield parameters, the only exception was on dry leaf to stem ration. Comparison between the two experimental years shows that the fresh and dry aboveground biomass of jute mallow was higher in 2012/13 than the 2013/14 growing season. In contrast, the leaf: stem ratio of the fresh biomass was higher in 2013/14 than in 2012/13. The highest fresh mass of harvestable leaves was obtained from P3W2 (9.1 t ha^{-1}) in 2012/13 and P2W2 (8.83 t ha^{-1}) in 2013/14. Harvestable fresh stem mass was highest for treatment P3W2 (9.9 t ha^{-1}) in 2012/13 and P3W3 (7.5 t ha^{-1}) in 2013/14. In contrast, the lowest fresh and dry mass of both leaves and stems was harvested from the lowest planting density (P1) irrigated to 60% PAW. Generally, treatments P3W1 and P3W2 provided higher leaf: stem ratio compared with all other treatment combinations.

4. Discussion

The increase in total fresh and oven dry biomass yield of Jute mallow attributed to greater planting density shows that the low planting density of 100 000 plants.ha^{-1} prescribed by Palada and Crossman [10] is too low for optimal yield under irrigation. Generally, the total harvestable fresh and dry biomass yields were significantly ($P < 0.05$) higher at medium planting density of 167 000 plants.ha^{-1} compared with 330 000 plants.ha^{-1}during the 2013/14 growing season. This is attributed to the combined effect of lower stomatal conductance and LAI of the high planting density compared with the stomatal conductance and LAI of medium planting density at 80% PAW and FC irrigation levels. This is in line with the literature, because plant growth and biomass yield increased as the leaf area and stomatal conductance improved [28,29]. In addition, the increase in competition for natural resources such as radiation, moisture and nutrients as planting density was increased from 167 000 plants.ha^{-1} to 330 000 plants.ha^{-1}, lead to lower yields for 330 000 plants.ha^{-1} during the 2013/14 growing season. The plot area (5.2 m^2) chosen for this study was determined based on the size of a rainout shelter for purposes of accommodating all the needed treatments and replications for scientific research. Nonetheless, results from the current studies are extrapolable to bigger fields although the expected results from such big fields will depend on the homogeneity of the soils, nutrient application, and irrigation managment practices, which has to be sunchronised with the natural rainfall.

The higher temperatures that prevailed during 2013/14 might have led to a reduction in total fresh and oven dried biomass yield compared to similar treatments during the 2012/13 growing season mainly due to reduced stomatal conductance caused by reduced leaf area index. Although there were significant ($P < 0.05$) differences between the medium and high planting densities during the 2012/13 season, the biomass yield differences were only magnitudinal in the 2013/14 growing season. The insignificant biomass yield response to an increase in planting density from 167 000 to 330 000 plants ha^{-1} is attributed mostly to N deficiency, because the highest planting density had low chlorophyll content compared with the medium planting density for most of the 2013/14 growing season. Based on the findings from this study, the (P2W2) treatment would be preferred over (P3W1 and P3W2) as it saved 20% of the water used by the crop without compromising biomass yield. The medium and higher planting densities of Jute mallow as indicated in this study (Table 4) are more water efficient and therefore have high crop water productivity compared to lower planting densities. Water use efficiency or crop water productivity was

Table 8
Combined analysis of variance table over the years for root length, root volume and root diameter using non-destructive method.

		Root Length (cm)		Root Volume (cm3)		Root Diam (mm)	
Source	DF	MS	Pr > F	MS	Pr > F	MS	Pr > F
Rep	3	6.3536111	<.0014	2.26516944	0.2919	0.013211	<.0001
Error (a)	16	2.8036111		0.19921319		0.013123	
Spacing	2	57.085833	<.0001	3.94360833	<.0001	0.540003	<.0001
Year*Spacing	2	23.850277	0.0030	4.12010278	<.0001	0.224336	0.0001
Irrig	2	4.3780556	0.2375	8.91302431	<.0001	0.055714	0.0219
Year*Irrig	2	6.7050000	0.1067	2.09603542	0.0005	0.171047	0.0001
Spacing*Irrig	4	23.651388	0.0014	1.49800347	0.0023	0.008903	0.5779
Year*Spacing*Irrig	4	11.751111	0.0228	4.50008125	<.0001	0.030903	0.1105
Error (b)	34	10.555703		2.08431193		0.0754346	

authenticated as an index to assess food production per unit of water used [30]. In comparison with crop water productivity values of most alien vegetable crops (such as onion, broccoli, butternut, cucumber and tomato) shown in a study by Nyathi [30]; Jute mallow is not only superior but can play a major role in addressing nutritional food security.

In addition, Jute mallow since it contains higher values of Iron and Zinc than most alien vegetable used [30] and can help to fight food insecurity more especially in water scarce rural areas plagued with hidden hunger (deficiency of micronutrients). Soil water content affects crop nutrient availability and mobility strongly within the soil profile. Potassium is one of the macro nutrients needed by crops in higher quantities, similar to N, and is transferred to the crop tissue largely via passive nutrient uptake in solution form [31]. The interaction between spacing and irrigation is probably attributable to the differences in crop aboveground biomass response to the availability of water, which leads to the differences in crop K content owing to dilution effects [32]. For Zn, all treatment combinations were slightly significantly different, but the results indicate that a treatment combination of medium planting density and medium stressed irrigation (P2W2) would be a better cultivation practice for jute mallow. This is because the latter treatment combinations produced higher Zn content for both growing seasons than other treatment combinations. Zn is one of the essential micronutrients that play an integral role in combating human immune system dysfunctions and dwarfism [33]. In addition, Zn is highly involved in plant physiological mechanisms to tolerate drought stress. Gadallah [34] observed that soybean plants supplemented with Zn had improved root growth at various water stress levels. The initial characterization of soil in the study sites indicates that both Zn and Fe were relatively adequate in the soil, which was also reflected on the Jute mallow leave analysis.

The demands for Zn and Fe supplements, to some extent, could be met by marketing jute mallow adequately to combat malnutrition-related diseases in women and children in South Africa, especially in rural areas [22]; Wenhold et al., 2012). Wenhold et al. [22] stated that 'Iron is an essential micronutrient needed for transferring oxygen from lungs to tissues, and for electron enzyme transport.' It also plays a pivotal role in the prevention of anaemia [35]. Nutrient availability for crop uptake by plant roots from the soil is affected by the availability of water, because most of the nutrient uptake takes place during water uptake [19]; Pedersen et al., 2009). The results obtained under the destruction method indicates that root length and root dry mass were significantly ($P < 0.05$) increased under water non-limiting conditions relative to medium and high water stress treatments. This response to water availability contradicts the normal plant physiological response mechanism to tolerate or avoid drought stress. The plant would generally respond to moisture stress by increasing root biomass in contrast to shoot biomass [36–38]. This response mechanism allows the plant to explore deeper soil layers for more nutrients and water for uptake. For the non-destructive method, root length Jute mallow increased with the decline in plant available water in line with the literature [36–38], with exception on the medium planting density, which showed that root length increased with rise in water availability. Additionally, the results for root volume showed the opposite of the general literature regarding water availability. The daily increase in lateral and downward root penetration can be a function of the soil water stress factor [39,40]. Root growth and morphology are of immense importance in optimizing the rate of water uptake. Moreover, fine younger roots adsorb more water than older roots owing to high oxygen consumption capacities caused by high capillarity, surface area and volume compared with older roots [8,16]. The root dry weight increased significantly as the plant water availability improved. These findings were in line with those by Yang et al. [41] and Liu et al. [42] for jatropha and cotton plants, respectively.

5. Conclusions

The results of this study indicate farmers can save up to 20% of water by applying deficit/stress irrigation (P2W2) technique without compromising the biomass yield and nutritional value of jute mallow. Assuming the irrigation water of R2.03 per cubic meter per hectare, and using 270 m^3 ha^{-1} saved during the first season, a farmer can save up to R548,10 per hectare irrigated in monetary terms. South Africa is a water scarce country and therefore, deficit irrigation technique could help retain water sources for longer terms. Since jute mallow is grown for its edible fresh biomass, farmers would be advised to use the treatment combination of 167 000 plants.ha^{-1} and 80% PAW (P2W2) since the highest fresh mass of harvestable leaves was obtained P2W2 (8.83 t ha^{-1}) in 2013/14 season. In addition, the mineral content (Zn, Fe, P and K) of jute mallow was significantly higher under P2W2 than all other treatment combinations. The findings of this research indicate that the highest values of Zn and K attained under P2W2 treatment was attributed to efficient use of water and N with less competition for resources and minimal N leaching losses. Moreover, the crop water productivity values were higher in P2W2 in 2013/14 season compared to all other treatments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by Agricultural Research Council, Vegetable and Ornamental Plant Institute and Citrus Academy Bursary Fund.

References

[1] I. Maseko, T. Mabhaudhi, S. Tesfay, T.H. Araya, M. Fezzehazion, C.P. Du Plooy, African leafy vegetables: a review of status, production and utilization in South Africa, Sustainability 10 (2017) 1–16.
[2] J.J. Le Roux, T.S. Newby, P.D. Summer, Monitoring soil erosion in South Africa at a regional scale: review and recommendations, South African Journal of Soil Science 103 (1) (2007) 329–335.
[3] C.M. Swanepoel, L.H. Swanepoel, H.J. Smith, A review of conservation agriculture research in South Africa, S. Afr. J. Plant Soil 34 (2018) 297–306.
[4] D. Labadarios, R. Swart, E.M.W. Muander, H.S. Kruger, G.J. Gericke, P.M. N. Kuzwayo, P.R. Ntsie, N.P. Steyn, I. Schloss, M.A. Dhansay, P.L. Jooste, A. Dannhauser, J.H. Nel, D. Molefe, T.J.vW. Kotze, Executive summary of national food consumption survey – fortification baseline (NFCS-FB-I), S. Afr. J. Clin. Nutr. 21 (2005) (2008) 245–300.
[5] N.R. Dlamini, T. Moroka, L. Mlotshwa, J. Reddy, G. Botha, Indigenous Edible Plants as Source of Nutrients and Health Benefitting Components (Nutraceuticals), 2010. Available on, https://pdfs.semanticscholar.org/1faa/3385218af4f06bdb4dcdf5556ef45ccc2474.pdf. (Accessed 21 May 2014).
[6] G.P. Tovihoudji, C.P. Djogbenou, P.B.I. Akponikpe, E. Kpadonou, C.E. Agbanagba, D.G. Dagbenonbakin, Response of Jute mallow (Corchorus olitorius L.) to organic manure and inorganic fertilizer on a ferruginous soil in North-eastern Benin, J. Appl. Biosci 92 (2015) 8610–8619.
[7] W.S.J. van Rensburg, W. Van Averbeke, R. Slabbert, M. Faber, P. Van Jaarsveld, I. Van Heerden, F. Wenhold, A. Oelofse, African leafy vegetables in South Africa, WaterSA 33 (3) (2007) 317–326.
[8] M.S.C. Olubunmi, O.O. Surukite, O.B. Anthony, O.S. Rachael, Effects of intrapopulation competition on morphological and agronomical characters of jute plant (*Corchorus olitorius. L.*), J. Basic Appl. Sci. 5 (2009) 1–6.
[9] A.H. Naim, K.M. Ahmed, F.E. Ahmed, Effect of chicken manure on growth and yield of Jute mallow (Corchorus olitorius L.) under rain-fed conditions of Sudan, Open Access Library Journal 2 (2015) 1–9.
[10] M.C. Palada, S.M.A. Crossman, Planting density affects growth and yield of bush okra, Proceedings of the 34th Annual Meeting of the Caribbean Food Crop Society (1998). http://203.64.245.61/fulltext_pdf/E/1991-2000/e00368.pdf. (Accessed 28 March 2012).
[11] S.A. Ayanlaja, S.O. Owa, M.O. Adigun, B.A. Senjobi, A.O. Olaleye, Leachate from earthworm castings breaks seed dormancy and preferentially promotes radicle grow in jute, Horticulture 36 (1) (2001) 143–144.
[12] V.E. Emongor, T. Mathowa, S. Kabelo, The effect of hot water, sulphuric acid, nitric acid, gibberellic acid and ethephon on the germination of Corchorus (*Corchorus tridens*) seed, J. Agron. 3 (3) (2004) 196–200.
[13] C.C. Nwangburuka, O.J. Olawuyi, K. Oyekale, K.O. Ogunwenmo, O.A. Denton, E. Nwankwo, Growth and yield response of *Corchorus olitorius* in the treatment of *Arbuscular mycorrhizae* (AM), Poultry manure (PM), Combination of AM-PM and inorganic fertilizer (NPK), Adv. Appl. Sci. Res. 3 (3) (2012) 1466–1471.
[14] L.A. Ogunkanmi, W.O. Okunowo, O.O. Oyelakin, B.O. Oboh, O.O. Adesina, K. O. Adekoya, O.T. Ogundipe, Assessment of genetic relationships between two

species of jute plants using phenotypic and RAPD markers, Int. J. Bot. 6 (2) (2010) 107–111.

[15] F. Wenhold, J. Annandale, M. Faber, T. Hart, Water use and nutrient content of crop and animal food products for improved household food security: a scoping study, Water Research Commission. WRC Project No (2012). TT 537/12.

[16] A.A. Ogunrinde, J.T. Fasinmirin, Soil moisture distribution pattern and yield of Jute mallow (*Corchus olitorius*) under three different soil fertility management, Proceedings of the Environmental Management Conference, Federal University of Agriculture, Abeokuta, Nigeria (2011). www.unaab.edu.ng. (Accessed 28 March 2012).

[17] O.L. Bamigboye, Effect of Intercropping and Plant Population Density of Jute Mallow (*Corchorus Olitorius*) on the Growth and Yield of Hot Pepper (*Capsicum Frutescens*), 2011. http://www.unaab.edu.ng/ugprojects/2011bagricbamigboyeol.pd f. (Accessed 8 March 2014).

[18] J.I.L. Morison, N.R. Baker, P.M. Mullineaux, W.J. Davies, Improving water use in crop production, Phil. Trans. R. Soc. B. 363 (2008) 639–658.

[19] J.T. Fasinmirin, A.A. Olufayo, Yield and water use efficiency of jute mallow *Corchorus olitorius* under varying soil water management strategies, J. Med. Plants Res. 3 (4) (2009) 186–191.

[20] Soil Classification Working Group, Soil Classification. A Taxonomic System for South Africa, Department of Agricultural Development, Pretoria, South Africa, 1991.

[21] J.L. Halvin, J.D. Beaton, S.L. Tisdale, W.L. Nelson, Soil Fertility and Fertilizers: an Introduction to Nutrient Management, seventh ed., Pearson Prentice Hall, 2005.

[22] F. Wenhold, M. Faber, Nutritional Status of South Africans: Links to Agriculture and Water. Water Research Commission, 2008. WRC Report No TT 362/P/08.

[23] G.C. Percival, I.P. Keary, K. Noviss, The potential of a chlorophyll content SPAD meter to quantify stress in foliar tissue of sycamore (Acer pseudoplatanus), English oak (Quercus robur), and European Beech (Fgus sylvatica), Arboric. Urban For. 34 (2) (2008) 89–100.

[24] X. Zhao, Z. Mao, J. Xu, Gas exchange, chlorophyll and growth responses of Betula Platyphylla seedlings to elevated CO_2 and Nitrogen, Int. J. Biol. 2 (2010), 143-14.

[25] C.M. Iversen, M.T. Murphy, M.F. Allen, J. Childs, D.M. Eissenstat, E.A. Lilleskov, T. M. Sarjala, V.L. Sloan, P.F. Sullivan, Advancing the use of minirhizotrons in wetlands, Plant Soil 352 (1–2) (2011) 23–39.

[26] A. Villordon, D. Labonte, J. Solis, Using a scanner-based minirhizotron system to characterize sweet-potato adventitious root development during the initial storage root bulking stage, Hortic. Sci. 46 (3) (2011) 513–517.

[27] J.A. Torrion, T.D. Setiyon, K.G. Cassman, Soybean root development relative to vegetative and reproductive phenology, Agron. J. 104 (6) (2012) 1702–1709.

[28] A.A. Bakhashwain, A.A. Elfeel, Foliage productivity and quality of valuable medicinal plant (*Clitoria ternatea* L.) as affected by different fertilizers, J. Med. Plants Res. 6 (25) (2012) 4225–4230.

[29] A. Tahery, Measurements of gas exchange characteristics and stomatal conductance of Hibiscus cannabinus infected with Meloidogyne incognita, Ann. Biol. Res. 3 (2012) 280–290.

[30] M.K. Nyathi, Assessment of Nutritional Water Productivity and Improvement Strategies for Traditional Vegetables in South Africa. PhD Thesis, Wageningen University, 2019.

[31] B.V.S. Reddy, P.S. Reddy, F. Bidinger, M. Blummel, Crop management factors influencing yield and quality of crop residues, Field Crop. Res. 84 (2003) 57–77.

[32] S. Umar, Alleviating adverse effect of water stress on yield of sorghum, mustard and groundnut by potassium application, Pakistan J. Bot. 38 (5) (2006) 1373–1380.

[33] A.S. Prasad, Zinc in human health: effect of zinc on immune cells, Mol. Med. 14 (5-6) (2008), 353–257.

[34] A.A.H. Gadallah, Effect of indole-3-acetic acid and zinc on the growth, osmotic potential and soluble and nitrogen components of soybean plants growing under water stress, J. Arid Environ. 44 (4) (2000) 451–467.

[35] F.N. Emuh, Growth and yield performances of *Corchorus olitorius* L. influence by leaves of poultry manure in Niger-Delta, Nigeria, Afr. J. Biotechnol. 12 (19) (2013) 2575–2580.

[36] T.C. Hsiao, L. Xu, Sensitivity of growth of roots versus leaves to water stress: biophysical analysis and relation to water transport, J. Exp. Bot. 51 (350) (2000) 1595–1616.

[37] N.K. Fageria, A. Moreira, The role of mineral nutrition on root growth of crop plants, Adv. Agron. 110 (2011) 251–331.

[38] A.T. Modi, T. Mabhaudhi, Water Use and Drought Tolerance of Selected Traditional Crops, 2013. WRC Report No. 1771/1/13.

[39] J.A. Postma, U. Schurr, F. Fiorani, Dynamic root growth and architecture responses to limiting nutrient availability: linking physiological models and experimentation, Biotechnol. Adv. 32 (2014) 53–65.

[40] J. Wang, C. Xu, S. Gao, X. Han, D. Ju, Effect of water and nitrogen utilized by means of dripping on growth of root and canopy and dry matter distribution in spring wheat, Adv. J. Food Sci. Technol. 5 (4) (2013) 474–481.

[41] Q. Yang, F. Li, F. Zhang, X. Liu, Interactive effect of irrigation frequency and nitrogen addition on growth and water use of, Jatropha curcas. Biomass and Bioenerg 59 (2013) 234–242.

[42] R. Liu, Z. Zhou, W. Guo, B. Chen, D.M. Oosterhuis, Effect of N fertilization on root development and activity of water-stressed cotton (*Gossypium hirsutum* L.) plants, Agric. Water Manag. 95 (2008) 1261–1270.