



Cowpea evapotranspiration modeling using the FAO-56 dual crop coefficient approach for climate-resilient agriculture under deficit irrigation conditions

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Abstract

This study evaluated the effects of different irrigation methods, varying levels of water deficit, and irrigation intervals on transpiration, soil evaporation, crop growth, and yield of cowpea (*Vigna unguiculata*) under field conditions. The assessment was conducted using the food and agriculture organization-56 dual crop coefficient method across seven irrigation treatments. In the I1, I2, and I3 treatments, irrigation was applied through a drip irrigation system at 100%, 80%, and 60% of crop evapotranspiration (ET_c), respectively. In contrast, in the I4, I5, and I6 treatments, irrigation was provided at 100% of ET_c when soil moisture depletion reached 45%, 60%, and 75% of the management allowed depletion threshold, respectively. The I7 treatment consisted of conventional furrow irrigation applied at four-day intervals. The results revealed that variable irrigation intervals in the I4, I5, and I6 treatments resulted in seasonal soil evaporation (E) savings of 17.4%, 29.9%, and 42.8%, respectively, compared to the treatments receiving frequent irrigation at two-day intervals. Furrow irrigation (I₇) doubled the evaporation losses as compared to drip irrigation. Under deficit irrigation in I2 and I3, transpiration (T) decreased by 18.5% and 42.7%, while ET_c was reduced by 13.2% and 30.6%, respectively. Conversely, only 4.8% and 16.2% reductions in transpiration were observed under I5 and I6, respectively. The non-frequent irrigation regime in I4, I5, and I6 decreased seasonal ET_c by 5.0%, 12.0%, and 23.8%, respectively, whereas furrow irrigation (I₇) increased ET_c by 28.1%. The highest growth and yield attributes were observed in drip-irrigated I1 and I4 treatments, as confirmed through spectral signatures and vegetation indices. The maximum yield of cowpea (11.57 tons per hectare) was recorded in I4, which was statistically on par with I1 and I7. The lowest yield was observed in the severely water-stressed I3 and I6 treatments. Deficit irrigation in I2 and I3 significantly improved the Water Productivity (WP, kg/m³)–Yield per unit of total crop evapotranspiration, Transpiration Use Efficiency (TrUE, kg/m³)–Yield per unit of transpiration, Irrigation Water productivity (IWP, kg/m³)–Yield per unit of irrigation water applied and Biomass Transpiration Productivity (WPT_r, kg/m³)–Biomass per unit of transpiration. The study highlights the potential of deficit irrigation strategies (I2 and I3) to enhance water productivity and efficiency, while non-fixed irrigation intervals (I4, I5, and I6) contribute to reducing soil evaporation losses. Drip irrigation at 100% ET_c with a non-fixed irrigation interval (I4) emerged as the most effective treatment, optimizing both yield and water conservation. These findings have significant implications for improving irrigation management in water-scarce regions.

Keywords Water deficit · Irrigation interval · Dual crop coefficient · Evaporation · Transpiration · Cowpea

Introduction

Climate change threatens the sustainability of ecosystems through severe constraints on water resources, with a corresponding increase in food and fiber production to meet the expected population growth in the coming years (Kendall

and Pimentel 1994; Singh et al. 2014; Surendran et al. 2014). Globally, more than 70% of withdrawn freshwater is used in agriculture (Hamdy et al. 2003; Pimentel et al. 2004). Most of this water may be lost before it reaches the roots of the plant (Wallace 2000). Therefore, using water in agriculture should be precisely managed, minimizing water losses that can be used to cultivate more crops in the coming years (Bouman 2007; Molden et al. 2010; Ward and Pulido-Velazquez 2008; Surendran et al. 2021).

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At present, water scarcity restricts water use, especially for irrigation. In many areas, there is insufficient water to fully meet the water requirements of the growing crops, especially during the dry season (Pereira et al. 2002; Falkenmark and Molden 2008). Therefore, irrigation management strategies should be developed under water deficit conditions to minimize the negative effects of water stress on crop growth and productivity (Feres and Soriano 2007; Zin El-Abidin et al. 2017). Deficit irrigation could provide better survival for crops without affecting crop productivity (Bloch et al. 2006; Mattar et al. 2020). Improvement of water productivity under deficit irrigation has been successfully confirmed in many crops (Geerts and Raes 2009; Zhang 2003; Ma et al. 2015; Li et al. 2019; Zin El-Abidin et al. 2019; Mattar et al. 2021). Research questions on efficient use of water require the proper method of irrigation, irrigation timing, and accurate assessment of crop water requirements (CWR) (Aghdasi et al. 2010; Khorsand et al. 2019). The dual crop coefficient model in the FAO-56 method addresses the computation of crop evapotranspiration (ET_c) by simulating the crop transpiration (T) and the soil evaporation (E) separately (Zhang et al. 2013; Alberto et al. 2014; Barker et al. 2018). In this method, the reduction in soil moisture due to plant transpiration and soil evaporation can be calculated separately (Allen et al. 1998). Other than the single crop coefficient model, the dual crop coefficient takes account of the effect of the irrigation system, soil properties, irrigation intervals and crop cover on ET_c (Rosa et al. 2012; Zhao et al. 2013). While optimal transpiration rate is essential for ideal plant growth and crop productivity (Flowers and Yeo 1989; Bessembinder et al. 2005), the evaporation is unproductive depletion, so minimizing the soil evaporation reduces the CWR without affecting crop productivity, which means more crop production for each drop of water or higher water productivity (Droppelmann et al. 2000). Although both processes go hand in hand, evaporation from the soil surface can be restricted by soil mulching, subsurface irrigation, and a non-frequent irrigation interval (Wallace 2000; Allen et al. 2005a; Wang et al. 2009).

High-frequency irrigation prevents periodic water stress, when compared to low-frequency irrigation (Radin et al. 1989). Increasing the irrigation interval results in a drier soil surface, which could produce less evaporation from the soil surface, especially through the early growth stage when the crop cover is incomplete (Zhang et al. 2013; Freeman et al. 1976; Sepaskhah and Kamgar-Haghighi 1997; Allen et al. 2005b). To avoid water stress, irrigation should be applied at or before the depletion of the maximum allowable soil moisture to maintain transpiration at its standard rate (Allen et al. 1998). The dual crop coefficient model is capable of treating water restrictions in both volume and timing (Rosa et al. 2012). Studying the effects of different

patterns of water saving strategies in terms of intensity, duration, and fluctuation may lead to a better understanding of the consequences of water stress and recovery after rehydration. Considering these aspects, this field study aimed to evaluate the role of irrigation method, deficit irrigation, and irrigation intervals for partitioning soil evaporation and transpiration, and assessing the growth and yield of cowpea using the FAO-56 dual crop coefficient method.

Materials and methods

Location, meteorological, crop and soil data

The field experiment was conducted at the experimental farm of Land and Water Management Research Group, Center for Water Resources Development and Management (CWRDM) located at Kottamparamba ($11^{\circ} 17' 07''$ N, $75^{\circ} 52' 15''$ E, 60 m asl), Kozhikode, Kerala, India, during 2017–18. The climate of the experimental site is tropical. The historical average annual rainfall is 3205 mm on average, with a short dry season from December to March. The field experiment was started at the beginning of the dry season, depending on irrigation with ineffective rainfall during the whole season. The daily values of maximum and minimum temperature ($^{\circ}$ C), mean relative humidity (RH%), and wind speed (km/day) during the experiment period were recorded at the weather station of CWRDM near the experimental site at a height of 2.0 m above the ground (Fig. 1). In general, Soil pH was 6.97, with EC 207.86 μ S, high in OC and available nutrients of P and K, with a Field capacity of $0.244 \text{ m}^3 \text{ m}^{-3}$ and Permanent Wilting point as $0.183 \text{ m}^3 \text{ m}^{-3}$. The soil physical and chemical properties are presented in Supplementary Table 1.

Seeds of cowpea Bali 265 were sown on November 29th 2017 at 20 cm distance in 30 cm raised beds of 60 cm width. One lateral of the drip irrigation system with 4 lph emitters spaced at 40 cm was installed on each beds of that one emitter could cover two plants. The recommended cultural practices were followed in all the plots.

Experimental design and irrigation treatments

The study included seven irrigation treatments (I_1 to I_7 , Supplementary Table 2) with three replicates, which were randomly arranged in a completely randomized block design (CRBD). ET_c of cowpea was modeled based on the FAO-56 dual crop coefficient method under different soil water conditions to determine the quantity of applied water (AW). In I_1 , I_2 and I_3 treatments, 100%, 80% and 60% of ET_c were applied through drip irrigation at 2 days interval, respectively. In I_4 treatment, irrigation was scheduled on the day,

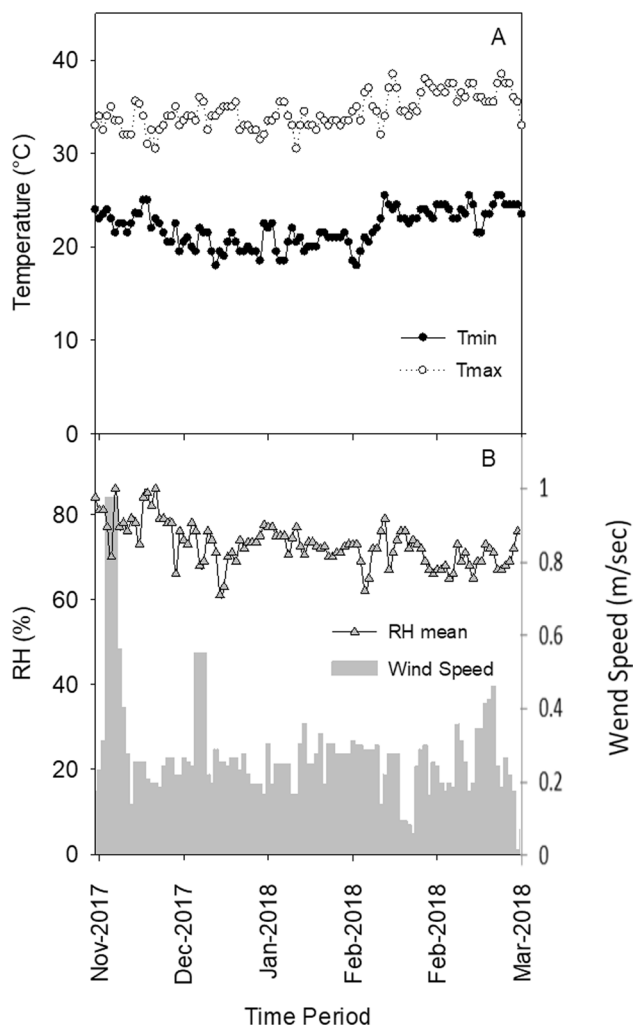


Fig. 1 Meteorological features during the experimental period from December 2017 to March 2018 **A** Daily minimum and maximum air temperatures (Tmin and Tmax, °C), **B** daily average relative humidity (RH mean, %) and wind speed (m/sec)

when available soil water (*TAW*), was depleted of 45%, the maximum allowable level of soil water depletion for cowpea (*p*) (Allen et al. 1998). The soil water depletion in the *I*₄ treatment was always kept below the water stress threshold of cowpea. So, *ET_c* in *I*₄ was modeled under standard conditions with no water stress. Then, the total *ET_c* was fully applied in the next irrigation through drip irrigation which was assumed to bring back the available soil water depletion to zero. In *I*₅ and *I*₆ treatments, irrigation was scheduled on the same day of depletion of 60% and 75% of *TAW*, respectively. The consumption of water beyond 45% of *TAW* threshold in both the treatments was under water stress. Hence, the water stress coefficient was considered in *ET_c* modeling after depleting 45% of *TAW*. Further, to restore

the available water capacity, the total *ET_c* was fully applied in the next irrigation through drip irrigation. In addition, in *I*₇ treatment, 100% of *ET_c* under standard conditions was applied at 4 days interval through the conventional furrow irrigation system. The general description of the experimental treatments is summarized in Supplementary Table 2.

In short, the treatments included different irrigation systems (drip irrigation in *I*₁, *I*₂, *I*₃, *I*₄, *I*₅ and *I*₆, and furrow irrigation in *I*₇), different irrigation intervals (frequent irrigation at fixed intervals in *I*₁, *I*₂, *I*₃ and *I*₇, and non-frequent irrigation at unfixed intervals in *I*₄, *I*₅ and *I*₆), different irrigation levels [optimal irrigation in *I*₁, *I*₄ and *I*₇, deficit irrigation (moderate) in *I*₂ and *I*₅, and deficit irrigation (severe) in *I*₃ and *I*₆], and different water saving strategies (shortage of applied water in *I*₂ and *I*₃, less evaporation losses in *I*₄, and extra depletion of available soil water in *I*₅ and *I*₆).

Evapotranspiration (*ET_c*)

The evapotranspiration of cowpea was calculated for plants grown under standard conditions (*ET_c*) as follows:

$$ET_c = K_c \times ET_0 = (K_{cb} + K_e)ET_0 \quad (1)$$

Under water stress conditions, the adjusted crop evapotranspiration (*ET_{cadj}*) was calculated as follows:

$$ET_{cadj} = (K_s K_{cb} + K_e)ET_0 \quad (2)$$

where *ET_c* is crop evapotranspiration (mm day⁻¹), *K_c* is dual crop coefficient of FAO-56, *K_{cb}* is basal crop coefficient, *K_e* is soil evaporation coefficient, *ET₀* is reference evapotranspiration (mm day⁻¹), *ET_{cadj}* is crop evapotranspiration under water stress conditions (mm day⁻¹), and *K_s* is water stress coefficient.

Reference evapotranspiration (*ET₀*)

CROPWAT 8.0 has been used for daily *ET₀* calculation (Fig. 2) according to FAO Penman Monteith (Allen et al. 1998). The climatic data (maximum air temperature, minimum air temperature, relative humidity, wind speed and sunshine hours) required for *ET₀* calculation was recorded at the Automatic Weather Station (AWS) of Land and Water Management Research Group, CWRDM located adjacent to the experimental site.

FAO-56 dual crop coefficient (*K_c*)

Dual crop coefficient (*K_c*) comprises of the basal crop coefficients (*K_{cb}*) of cowpea and the soil evaporation coefficient (*K_e*).

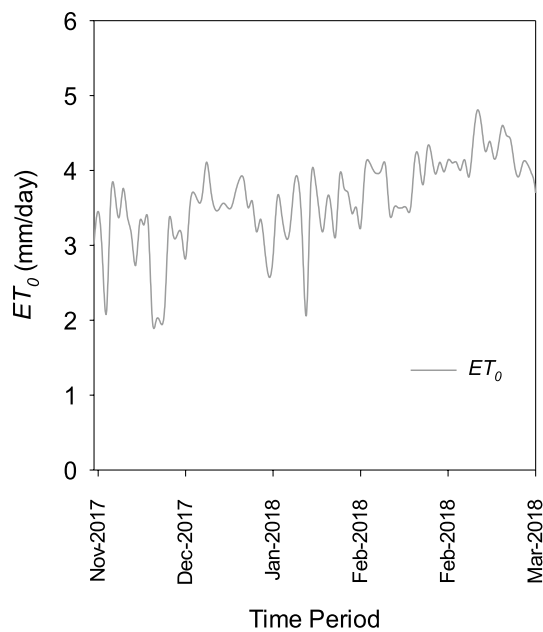


Fig. 2 Reference evapotranspiration (ET_0 , mm day⁻¹) during the experimental period from December 2017 to March 2018

Basal crop coefficient (K_{cb})

Tabulated K_{cb} from cowpea, as recommended by Allen et al. (Allen et al. 1998) is shown in Fig. 3A. For specific adjustment in local climate, the K_{cb} values at mid-season and late-season stages were adjusted using the following equation:

$$K_{cb} = K_{cb(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (3)$$

where $K_{cb(Tab)}$ is tabulated K_{cb} value for cowpea at mid-season and late-season stages (if $K_{cb} > 0.45$), u_2 is wind speed (m.s⁻¹) at 2 m height ($1 \leq u_2 \leq 6$), RH_{min} is minimum relative humidity (%) during the mid and late-season growth stage ($20\% \leq RH_{min} \leq 80\%$), and h is plant height during mid or late-season stage (m).

The values of 55.2% and 1 m s⁻¹ were used for RH_{min} and u_2 , respectively, based on the reference average during the same period of the year. Adjusted basal crop coefficient (K_{cb}) of cowpea under the local conditions of the experiment is presented in Fig. 3A.

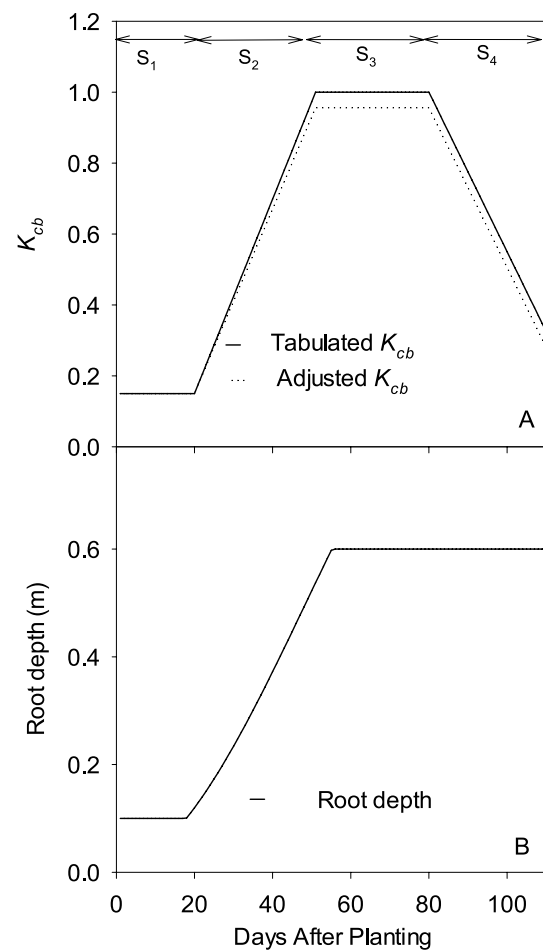


Fig. 3 A Tabulated and adjusted basal crop coefficient, K_{cb} of cowpea (Allen et al. 1998) B Modeled cowpea root depth (m) (Allen et al. 1998; Borg and Grimes 1986; Steduto et al. 2012) at different crop stages, viz. S1 = initial, S2 = crop development, S3 = mid-season, and S4 = late-season

Soil evaporation coefficient (K_e)

The evaporation coefficient from the topsoil was calculated daily for each treatment based on the following equation:

$$K_e = K_r(K_{cmax} - K_{cb}) \leq f_{ew}K_{cmax} \quad (4)$$

where K_r is reduction coefficient of evaporation from the topsoil, K_{cmax} is maximum value of K_c following rain or irrigation, and f_{ew} is exposed and wetted fraction of the soil surface.

According to Allen et al. (Allen et al. 1998), K_{cmax} can be calculated as follows:

$$K_{cmax} = \max \left(\left\{ 1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \right\}, \{K_{cb} + 0.05\} \right) \quad (5)$$

where $\max()$ function selects the highest value of the functions in braces $\{ \}$ that are separated by the comma.

The wetted fraction of soil surface exposed to sunlight (f_{ew}) was calculated from the following equation:

$$f_{ew} = \min(1 - f_c, f_w) \quad (6)$$

where f_c is the approximate fraction of soil surface that were effectively covered by vegetation [0–0.99], $1 - f_c$ is the exposed fraction of soil surface not covered or shaded by vegetation [0.01–1], f_w is the wetted fraction of soil surface by irrigation or precipitation, and $\min()$ function selects the lowest value of $1 - f_c$ and f_w values.

The fraction of covered soil surface (f_c) was calculated as follows:

$$f_c = \left(\frac{K_{cb} - K_{cmin}}{K_{cmax} - K_{cmin}} \right)^{(1+0.5h)} \quad (7)$$

where K_{cmin} is minimum value of K_c for dry bare soil with no ground cover [0.15].

During the initial growth stage of cowpea, K_{cmin} and K_{cb} were equal. Therefore, the difference $K_{cb} - K_{cmin}$ was limited to ≥ 0.01 for numerical stability. The present study was conducted in the dry season. Therefore, wetting of the soil surface was a result of irrigation and differed based on the irrigation system. The field estimate for f_w was 0.3 and 0.8 for drip irrigation and furrow irrigation, respectively. Under drip irrigation, most of the wet soil may be shaded, since it occurs beneath the canopy. In order to estimate the fraction of wetted soil surface that was effectively exposed to sunlight under drip irrigation, f_w values were multiplied by $[1 - (2/3)f_c]$. The f_c and f_{ew} equations were applied daily to match with the daily change in K_{cb} .

Reduction coefficient of soil evaporation (K_r) The evaporation of water from the wet soil exposed to sunlight is assumed to take place in two stages. The first stage starts after watering and attaining field capacity from the topsoil, during which, the evaporation occurs at its maximum rate and is determined only by energy availability at the soil surface ($K_r = 1$). This stage continues until the cumulative depth of evaporation (D_e) become equal to the depth of readily evaporable water (REW). The second stage starts after losing all REW from the topsoil and the value of K_r begins to fall linearly to become 0 at the end of this stage. The K_r value during the second stage was calculated based on the following equation:

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \text{ for } D_{e,i-1} > REW \quad (8)$$

where is $D_{e,i-1}$ cumulative evaporation depth from the topsoil at the end of previous day [mm], REW is readily evaporable water [mm], and TEW is total evaporable water [mm].

According to Allen et al. (Allen et al. 1998), TEW can be calculated as follow:

$$TEW = 1000(\theta_{fc} - 0.5\theta_{wp})Z_e \quad (9)$$

where θ_{fc} is soil water content at field capacity [m^3m^{-3}], θ_{wp} is soil water content at wilting point [m^3m^{-3}], and Z_e is depth of the topsoil that is subject to drying by evaporation.

In the current experiment, θ_{fc} and θ_{wp} of the experimented soil were 0.244 and 0.183 m^3m^{-3} , respectively. The values used for Z_e and REW were 0.12 m and 8 mm, respectively (Allen et al. 1998). K_r value was calculated daily based on the daily value of $D_{e,i-1}$ for each irrigation treatment.

Cumulative evaporation depth (D_e) The daily water balance of the soil evaporation layer was worked out on a separate Excel sheet by using the following equation:

$$D_{e,i} = D_{e,i-1} - (P_i - RO_i) - \frac{I_i}{f_w} + \frac{E_i}{f_{ew}} + T_{ew,i} + DP_{e,i} \quad (10)$$

where $D_{e,i}$ is cumulative depth of evaporation at the end of day i [mm], $D_{e,i-1}$ is cumulative depth of evaporation at the end of day i-1 [mm], P_i is precipitation on day i [mm], RO_i is precipitation runoff from the soil surface on day i [mm], I_i is depth of irrigation on day i [mm], E_i is evaporation on day i (i.e., $E_i = K_e ET_0$) [mm], $T_{ew,i}$ is transpiration depth from the soil surface layer on day i [mm], and $DP_{e,i}$ is deep percolation loss from the topsoil layer on day i [mm].

The values of P_i and RO_i were zero during the entire season, since the amount of precipitation was not significant, and $T_{ew,i}$ was assumed to be zero, as suggested by Allen et al. (Allen et al. 1998). A daily water balance of the topsoil layer was worked out for each treatment. At the beginning of the growing season, all the treatments were sufficiently irrigated to ensure field capacity moisture content in the topsoil layer. The depth of evaporation at the first day $D_{e,1}$ was assumed as zero. The $DP_{e,i}$ values were ignored in the calculation procedure by imposing a minimum limit of D_e equal to zero.

Water stress coefficient (K_s)

The coefficient of water stress was calculated based on the following equations:

$$K_s = \frac{TAW - D_{r,i-1}}{TAW - RAW} \text{ for } D_{r,i-1} > RAW \quad (11)$$

$$TAW = 1000(\theta_{fc} - \theta_{wp})Z_r \quad (12)$$

$$RAW = p(TAW) \quad (13)$$

where $D_{r,i-1}$ is cumulative depletion depth from root zone at the end of previous day [mm], RAW readily available water [mm], TAW is total available water [mm], Z_r is effective root depth [m], p is maximum allowable soil water depletion fraction for no stress.

Borg and Grimes (Borg and Grimes 1986) equation was used for modeling effective root depth at initial and crop development stages (Fig. 3B) as follows:

$$Z_{r,i} = Z_{r,m} \left[0.5 + 0.5 \sin \left(3.03 \frac{DAP}{DTM} - 1.47 \right) \right] \geq 0.1 \quad (14)$$

where $Z_{r,i}$ is effective root depth on day i , $Z_{r,m}$ is maximum effective root depth, DAP is days after planting, and DTM is days to vegetative maturity.

The maximum effective root depth for cowpea is 0.60 m (Allen et al. 1998), which can be attained by the end of the crop development stage and continues till the end of the season (Fig. 3B). The minimum value for effective root depth at crop initiation is 0.10 m (Steduto et al. 2012). p was adjusted to (p_{adj}) to match with low ET_c as follows (Allen et al. 1998):

$$p_{adj} = p + 0.04(5 - ET_c) \quad (15)$$

Cumulative depletion depth (D_r)

The daily balance of soil water within the effective root depth was calculated using the following equation:

$$D_{r,i} = D_{r,i-1} - (P_i - RO_i) - I_i - CR_i + ET_{c,i} + DP_i \quad (16)$$

where $D_{r,i}$ is root zone depletion at the end of day i [mm], $D_{r,i-1}$ is root zone depletion at the end of the previous day, $i-1$ [mm], CR_i is capillary rise from the groundwater table on day i [mm], and DP_i is deep percolation on day i [mm].

CR_i was assumed to be zero as suggested by Allen et al. (Allen et al. 1998), when the bottom of the root zone is more than 1 m above the water table. In the present study, the irrigation treatments for all treatments were within water-holding capacity of the soil. Hence, excess water was not subjected to deep percolation ($DP_i = 0$). To initiate root zone water balance, all treatments were irrigated at the beginning of the growing season with sufficient water to reduce the depth of initial depletion in the root zone to zero.

$$\text{Crop biomass (kg ha}^{-1}\text{)} = \text{plant fresh weight (kg ha}^{-1}\text{)} + \text{crop yield (kg ha}^{-1}\text{)} \quad (17)$$

$$\text{Harvest index (HI)} = \text{crop yield (kg ha}^{-1}\text{)} / \text{crop biomass (kg ha}^{-1}\text{)} \quad (18)$$

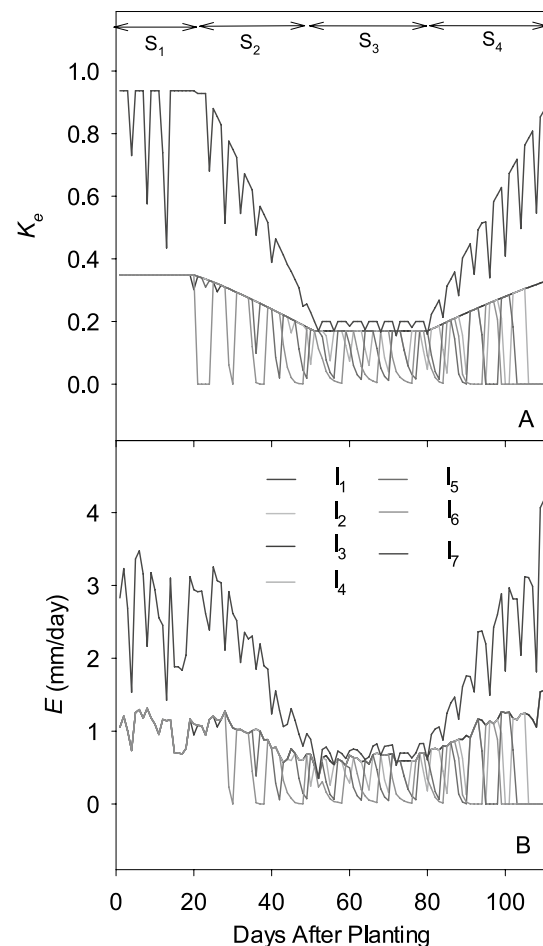


Fig. 4 **A** Simulated soil evaporation coefficient (K_e) and **B** Soil evaporation (E , mm/day) under different treatments (I1-100% ET_c at two days interval through drip irrigation; I2-80% ET_c at two days interval through drip irrigation; I3-60% ET_c at two days interval through drip irrigation; I4-100% ET_c at 45% depletion of available soil moisture through drip irrigation; I5-100% adjusted ET_c at 60% depletion of available soil moisture through drip irrigation; I6 -100% adjusted ET_c at 75% depletion of available soil moisture through drip irrigation; I7-100% ET_c at 4 days irrigation interval through furrow irrigation) at different crop stages, viz. S1 = Initial, S2 = crop development, S3 = mid-season, and S4 = late-season

Yield attributes

Harvesting of cowpea green pods started 51 days after planting and continued till March 18, 2018, the end of the season (110 days after planting). The following parameters were calculated as follows:

Spectral measurements and indices

A spectroradiometer (Field spec FR 350–2500 nm, ASD Inc., Boulder, CO, USA) was used for hyper spectral measurements from the field. The instrument measures the spectral reflectance between 350 and 2500 nm with a spectral resolution of 2 nm. Measurements were taken at a height of roughly 0.9 m above the canopy cover with a 25-degree field of view, resulting in a fixed area. Five duplicate measurements were taken and averaged to get a single set of spectral reflectance. The reflectance was taken from the white reference (polytetrafluoroethylene (PTFE) and cintered halon reference panel) prior to capturing the spectra for each sample. The data captured from the device was processed for splice correction and the mean was calculated for the different samples. To remove the water absorption bands at 1350 nm–1400 nm and 1800 nm–2000 nm, the exported ASCII file was viewed so that those specific wavelengths are manually removed. The edited ASCII file was imported into the ENVI platform, and the spectra are illustrated. Several spectral indices were calculated at different wavelengths that are sensitive to different properties related to water stress levels. The formula used to calculate these indices is given in Supplementary Table 3.

Water productivity and efficiency indices

In order to evaluate the effect of the irrigation treatments on water use, water efficiency indices, i.e., water productivity (WP, kg m⁻³), irrigation water productivity (IWP, kg m⁻³), transpiration use efficiency (TrUE, kg m⁻³), biomass water productivity (WP_{ET}, kg m⁻³), and biomass transpiration productivity (WP_{Tr}, kg m⁻³) were calculated as described by Steduto et al. (Steduto et al. 2012) and Kemanian et al. (Kemanian et al. 2005).

$$WP = \frac{Y}{ET_c} \quad (19)$$

$$IWP = \frac{Y}{IW} \quad (20)$$

$$TrUE = \frac{Y}{T} \quad (21)$$

$$WP_{ET} = \frac{B}{ET_c} \quad (22)$$

$$WP_{Tr} = \frac{B}{T} \quad (23)$$

where Y is green yield (kg ha⁻¹), B is crop biomass (kg ha⁻¹), IW is irrigation water (m³ ha⁻¹), ET_c is water

consumption or evapotranspiration (m³ ha⁻¹), and T is transpiration water (m³ ha⁻¹).

Statistical analysis

Analysis of variance (ANOVA) was performed for the experimental data by Microsoft excel software following the procedure described by Gomez and Gomez (Gomez and Gomez 1984). The significance level used in the F test was $P=0.05$. Critical differences values were calculated wherever the 'F' test was found to be significant.

Results and discussion

Modeling of soil water and water consumption

Soil evaporation (E)

Simulation of soil evaporation losses showed a clear difference between growth stages, irrigation methods, irrigation intervals, and water saving strategies (Fig. 4A). K_e and E (mm d⁻¹) were relatively high during the initial stage of growth, when the plants were too young to cover the soil surface, and decreased slightly during the crop development stage, reaching a minimum value during the mid-season stage, and then, increased in the late-season stage (Fig. 4). Soil evaporation increases when crop cover is low and high energy is available at the soil surface for evaporation (Zhang et al. 2013; Zhao et al. 2013; López-Urrea et al. 2009).

The irrigation method showed clear difference on soil evaporation. Due to the higher wetted fraction of soil surface under furrow irrigation (0.8), K_e and E were superior in I₇, compared to drip irrigation (I₁ to I₆), especially during the initial and late-season stages.

The soil evaporation responded also to irrigation interval. Frequent irrigation at 2-days interval suggested maximum values for K_e and E in I₁, I₂ and I₃ treatments, even with 20% and 40% water deficits at I₂ and I₃, respectively. However, cyclic declines in K_e and E values were observed with infrequent irrigation in I₄, I₅ and I₆ treatments. The lowest K_e and E values were recorded at I₆, followed by I₅, and I₄. Increasing the soil moisture depletion threshold to 45%, to 60% and 75% in I₄, I₅ and I₆, respectively, increased the corresponding irrigation interval and decreased soil evaporation accordingly (Fig. 5A). The irrigation interval increased as the crop grew up and its roots deepened to absorb more water from the soil. Infrequent irrigation gave the evaporated topsoil additional time to dry, which limited evaporation losses (Zhang et al. 2013; Freeman et al. 1976; Sepaskhah and Kamgar-Haghighi 1997; López-Urrea et al. 2009).

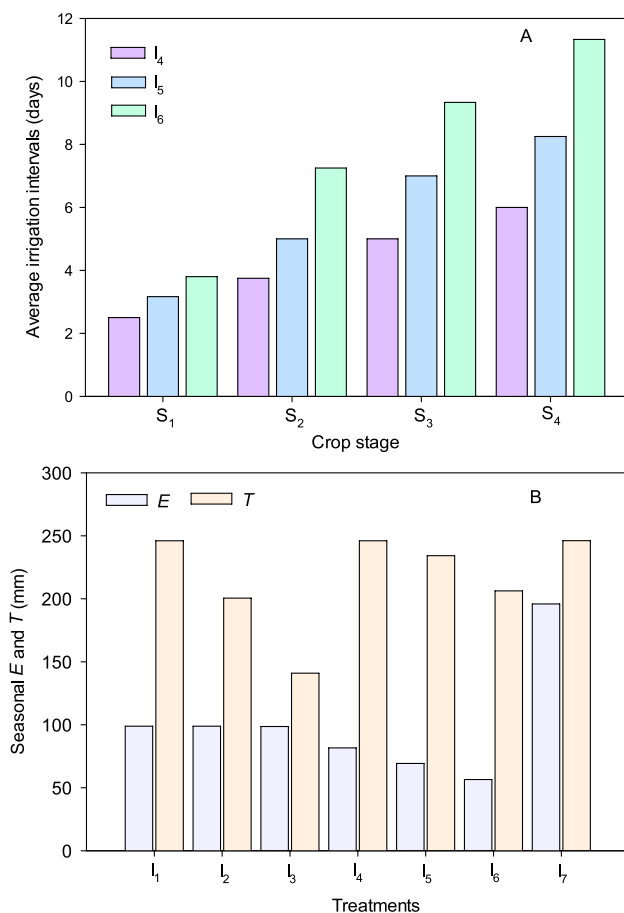


Fig. 5 **A** Average irrigation interval for unfixed irrigation intervals treatments (I₄-100% ETc at 45% depletion of available soil moisture through drip irrigation; I₅-100% adjusted ETc at 60% depletion of available soil moisture through drip irrigation; I₆-100% adjusted ETc at 75% depletion of available soil moisture through drip irrigation) at different crop stages viz. S₁=Initial, S₂=crop development, S₃=mid-season and S₄=late-season. **B** Simulated seasonal soil evaporation (E, mm) and transpiration (T, mm) of cowpea as influenced by irrigation method, irrigation interval and water saving strategies under different treatments (I₁-100% ETc at two days interval through drip irrigation; I₂-80% ETc at two days interval through drip irrigation; I₃-60% ETc at two days interval through drip irrigation; I₄-100% ETc at 45% depletion of available soil moisture through drip irrigation; I₅-100% adjusted ETc at 60% depletion of available soil moisture through drip irrigation; I₆-100% adjusted ETc at 75% depletion of available soil moisture through drip irrigation; I₇-100% ETc at 4 days irrigation interval through furrow irrigation)

The simulated seasonal soil evaporation (E, mm) is shown in Fig. 5B. Furrow irrigation in the I₇ treatment increased seasonal evaporation losses (E) by about 100% over drip irrigation treatments. The surface evaporation loss clearly increased under furrow irrigation as the soil wetted area reached 80%, while only 30% of the soil surface under plant canopies was wetted under drip irrigation. Araujo et al. (Araujo et al. 1995) reported a similar water status in the two

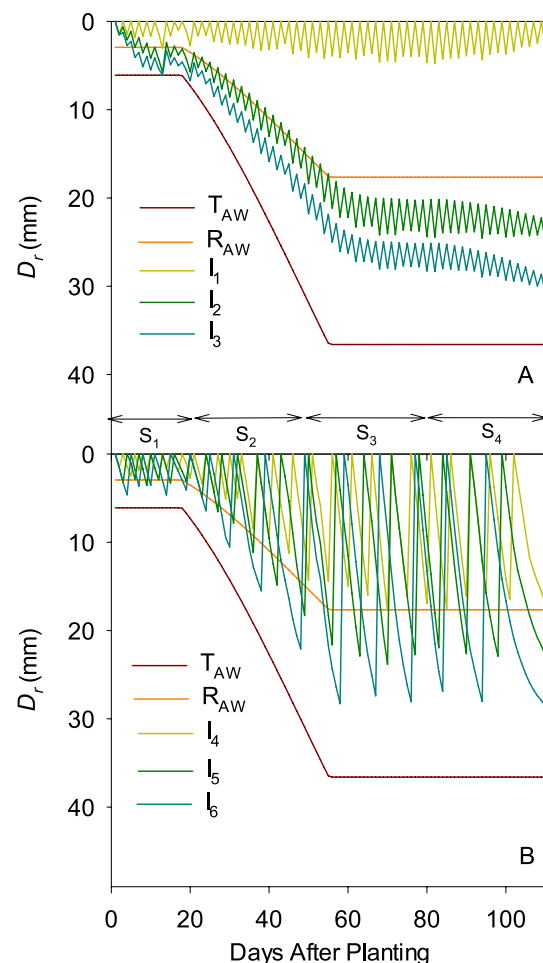


Fig. 6 Simulated cumulative depletion depth (D_r) during the growth of cowpea as influenced by irrigation method, irrigation interval and water saving strategies compared with total available water (TAW) and readily available water (RAW) with **A** I₁-100% ETc at two days interval through drip irrigation; I₂-80% ETc at two days interval through drip irrigation; I₃-60% ETc at two days interval through drip irrigation and **B** I₄-100% ETc at 45% depletion of available soil moisture through drip irrigation; I₅-100% adjusted ETc at 60% depletion of available soil moisture through drip irrigation; I₆-100% adjusted ETc at 75% depletion of available soil moisture through drip irrigation at different crop stages viz. S₁=Initial, S₂=crop development, S₃=mid-season, and S₄=late-season

irrigation systems. The irrigation system influences E, especially with respect to the wetted fraction of the soil surface (f_w), which affects the estimation of the f_{ew} fraction and thus the K_e values (Rosa et al. 2012). Deficit irrigation in I₂ and I₃ showed no decrease in seasonal E, compared to I₁, while a significant decline in seasonal E was observed under infrequent irrigation treatments. Extending the irrigation interval at I₄, I₅ and I₆, respectively, resulted in 17.4%, 29.9%, and 42.8% savings in seasonal E, compared to the 2-days irrigation interval in I₁, I₂ and I₃ treatments (Fig. 5B).

Cumulative depletion depth (D_r)

Fig. 6 A and B presents cumulative depletion depth (D_r) during the growth of cowpea as influenced by irrigation method, irrigation interval and water saving strategies compared with total available water (T_{AW}) and readily available water (R_{AW}). In I_1 , I_4 and I_7 treatments, 100% of standard irrigation requirements were scheduled, while keeping the cumulative depletion depth (D_r) below the maximum allowable soil water depletion fraction (p) to prevent any water stress ($K_s = 1$) and to ensure optimum transpiration over the whole season, as suggested by Rosadi et al. (Rosadi et al. 2005).

In I_2 and I_3 treatments with a 20% and 40% deficiency in standard soil water depletion replenishment, respectively, D_r was accumulated with crop growth and an increasing pattern was recorded in D_r (Fig. 6A), since the applied irrigation water in both the treatments was insufficient to compensate the soil water consumption by evaporation and transpiration. Root growth during the development stage led to an extension of the root zone and additional combined depths of available soil water, which helped the I_2 plants to maintain D_r within or close to p till the end of the development stage. However, at I_3 under severe water deficit, D_r exceeded RAW from the initiation of the crop until the end of the season. In plants growing under water deficit, root growth is usually less restricted than that of branches, or it can even be enhanced (Sharp et al. 1989). Increases in the rooting depth during water deficiency is a clear benefit of maintaining an adequate water supply (Sponchiado et al. 1989; Sharp et al. 2004).

Applied irrigation water in I_4 , I_5 and I_6 treatments were calculated to compensate the estimated value of D_r to replenish the field capacity after each irrigation ($D_r = 0$). Irrigation was then inhibited until 45% (p), 60% and 75% of TAW was depleted from I_4 , I_5 and I_6 treatments, respectively, (Fig. 6B). The RAW curve presents the water stress threshold (p). Hence, soil water absorption beyond RAW depletion was under stress.

Transpiration (T)

According to Allen et al. (Allen et al. 1998), transpiration (T) under water stress conditions is a function of reference evapotranspiration, crop coefficient and water stress coefficient (K_s). In the present study, K_s was simulated using Eq. (11) for water stress treatments, where the cumulative depletion depth (D_r) continuously (as in I_2 and I_3) or periodically (as in I_5 and I_6) exceeded the maximum allowable soil water depletion fraction (p).

Accordingly, the K_s values decreased significantly ($K_s < 1$) under the I_2 and I_3 treatments compared to the unstressed condition (Fig. 7A). 40% water deficiency in I_3

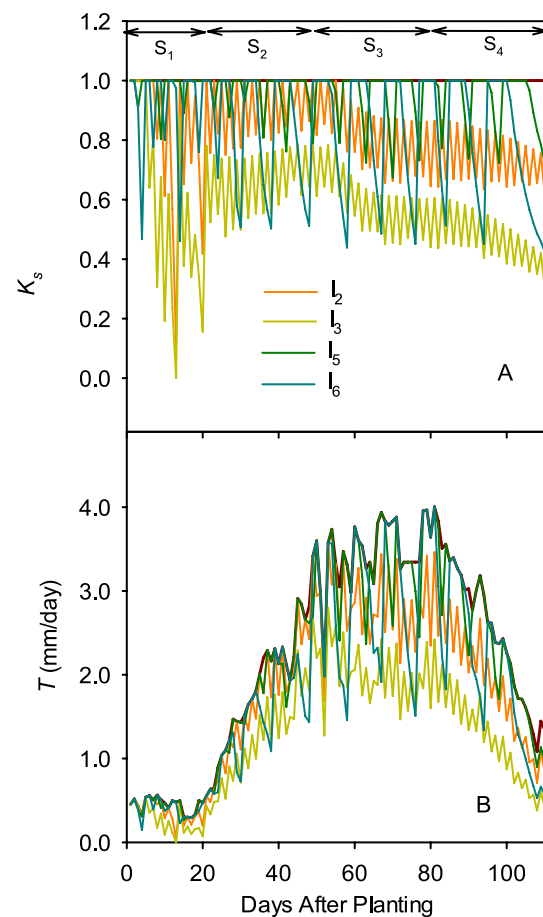


Fig. 7 A Simulated water stress coefficient (K_s), “dark red bold line” indicates non-stress conditions in comparison with stressed conditions under I_2 -80% E_{Tc} at two days interval through drip irrigation; I_3 -60% E_{Tc} at two days interval through drip irrigation; I_5 -100% adjusted E_{Tc} at 60% depletion of available soil moisture through drip irrigation; I_6 -100% adjusted E_{Tc} at 75% depletion of available soil moisture through drip irrigation and B Crop transpiration (T , mm/day), “dark red bold line” indicates potential transpiration compared with above treatments as influenced by irrigation method, irrigation interval and water saving strategies during the growth period of cowpea at different crop stages, viz. S1=Initial, S2=crop development, S3=mid-season, and S4=late-season

resulted in lower K_s values and suggested intensive water stress conditions compared to I_2 , where only 20% water deficiency was applied. The K_s values during the initial growth stage showed a sharp decrease in both the treatments due to the concentration of roots in the surface layer with higher exposure to evaporation at the initial stage. At the initial stage, evaporation of soil water from the bare surface layer further contributed to soil water depletion (Lyra et al. 2016). This reinforces the importance of avoiding water stress in the initial stage of crop growth (Machado et al. 2009; Ferreira et al. 2013). A marked improvement in the K_s values of I_2 and I_3 treatments were seen during the crop development stage, when root growth was high. This is consistent

with previous studies that showed a lesser effect of water stress during the vegetative stage in cowpea (Turk et al. 1980; Labanauskas et al. 1981; Shouse et al. 1981; Ahmed and Suliman 2010). During the mid-season and late-season stages, the K_s values for both treatments showed a descending pattern until the end of the growing season. Accordingly, the lack of water in the I_2 and I_3 treatments suggested lower values of T compared to the potential T under non-stressed condition (Fig. 7B), while the decrease in T was more severe under I_3 treatment. The effect of water stress on T temporarily decreased after each irrigation in the I_2 treatment during the initial and development stages of the crop, while severe water deficit in I_3 indicated continuous water stress and low T during the entire season.

Accordingly, in I_4 , all water was depleted under no stress and hence, so K_s was equal to one and no decrease in T was recorded during the whole season. However, in I_5 and I_6 , the depletion of TAW was from 45 to 60% and from 45 to 75%, respectively, under stress, which suggested intermittent and rotated reductions in K_s (Fig. 7A) and, accordingly, in T (Fig. 7B). This state of intermittent water deficit can give stressed plants a rest period to recover after rehydration (Lopez et al. 1987; Souza et al. 2004; Rivas et al. 2016). Increasing the water depletion threshold to 75% of the TAW in I_6 resulted in severe water stress, which extended for a longer duration, compared to I_5 . Where plants were irrigated when 60% of the TAW was depleted.

Non-stressed condition in I_1 , I_4 and I_7 treatments resulted in a standard transpiration rate, which was 246.1 mm during the entire season (Fig. 5B). While 20% and 40% shortage of water in I_2 and I_3 treatment, respectively, resulted in a severe seasonal transpiration deficit of 18.5% and 42.7% in I_2 and I_3 , respectively. However, only 4.8% and 16.2% decrease in seasonal transpiration were due to the extension of the irrigation interval at I_5 and I_6 , respectively.

Crop evapotranspiration (ET_c)

Fig. 8 shows the simulated values of daily evapotranspiration (ET_c) for all treatments. Application of 100% ET_c at a 2-day irrigation interval through drip irrigation in I_1 did not impose any restrictions on water use and permitted the plants to consume the standard ET_c , which on an average, registered 1.5, 3.4, 4.1, and 3.6 mm day⁻¹ during the initial, development, mid-season, and late-season stages, respectively, and 344.9 mm during the whole season. For furrow irrigation, I_7 registered a 28.1% increase in ET_c over I_1 due to higher E losses, especially during the initial and late-season stages. In contrast, a 20% and 40% water deficit in I_2 and I_3 presented 13.2% and 30.6% reductions in ET_c , respectively, which resulted totally from a severe retraction of T without any saving in E losses (Fig. 8A). Irrigation at p in I_4 provided sufficient moisture continuously in the

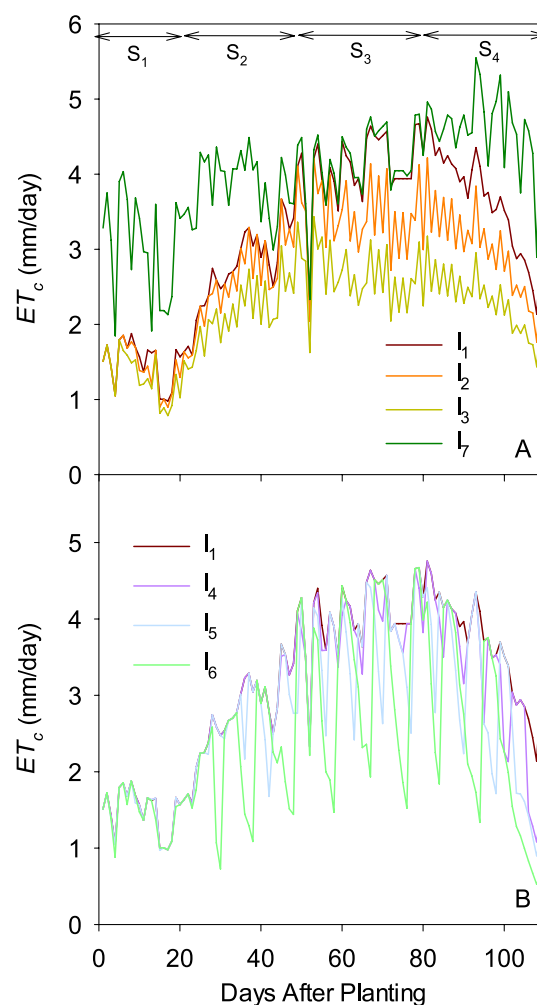


Fig. 8 Simulated actual evapotranspiration of cowpea (ET_c) during the growing season as influenced by irrigation method, irrigation interval and water saving strategies under **A** I_2 -80% ET_c at two days interval through drip irrigation; I_3 -60% ET_c at two days interval through drip irrigation; I_7 -100% ET_c at 4 days irrigation interval through furrow irrigation compared with I_1 -100% ET_c at two days interval through drip irrigation and; **B** I_4 -100% ET_c at 45% depletion of available soil moisture through drip irrigation; I_5 -100% adjusted ET_c at 60% depletion of available soil moisture through drip irrigation; I_6 -100% adjusted ET_c at 75% depletion of available soil moisture through drip irrigation compared with I_1 -100% ET_c at two days interval through drip irrigation for clear representation at different crop stages viz. S1 = Initial, S2 = crop development, S3 = mid-season and S4 = late-season

soil for standard transpiration and extended the irrigation interval, which reduced the evaporation losses and reduced the seasonal ET_c by 5.0%, when compared to frequent drip irrigation in I_1 . Increasing ET_c of cowpea due to frequent application of irrigation was previously reported by Phogat et al. (Phogat et al. 1984). The extra increase in the irrigation intervals for I_5 and I_6 over the depletion of maximum allowable soil moisture suggested intermittent water stress conditions and obtained a 12.0% and 23.8% reduction in

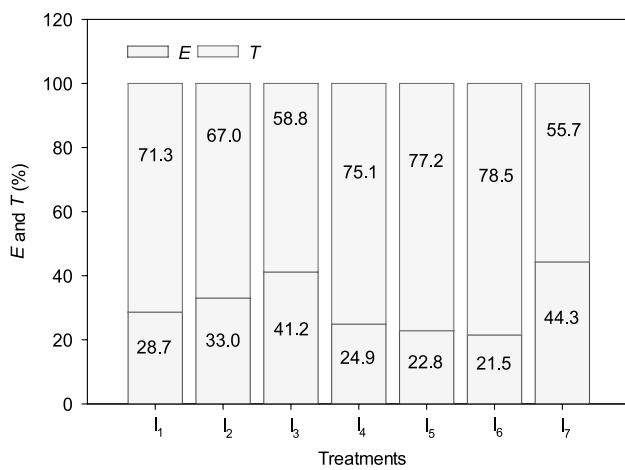


Fig. 9 Fraction (%) of seasonal soil evaporation (E) and transpiration (T) as influenced by irrigation method, irrigation interval and water saving strategies under different treatments (I1-100% ET_c at two days interval through drip irrigation; I2-80% ET_c at two days interval through drip irrigation; I3-60% ET_c at two days interval through drip irrigation; I4-100% ET_c at 45% depletion of available soil moisture through drip irrigation; I5 -100% adjusted ET_c at 60% depletion of available soil moisture through drip irrigation; I6-100% adjusted ET_c at 75% depletion of available soil moisture through drip irrigation; I7-100% ET_c at 4 days irrigation interval through furrow irrigation)

ET_c, respectively (Fig. 8B), which was a result of lower *T* and *E* values.

Soil evaporation fraction (E%)

E% Was counted as 28.7% of ET_c in I₁ under drip irrigation. While for furrow irrigation in I₇, *E*% reached 44.3% of ET_c. However, in I₂ and I₃, under water deficits, *E*% losses registered 33.0 and 41.2% of ET_c, respectively, while, for non-frequent drip irrigation in I₄, I₅, and I₆, *E*% listed 24.9, 22.8, and 21.5%, respectively (Fig. 9). The dual crop coefficient model suggested a marked increase in *E*% under furrow irrigation system due to the higher wetted fraction of soil surface, which resulted in higher *E* losses, when compared to drip irrigation. Despite frequent irrigation in I₂ and I₃, which did not reduce the *E* losses, the shortage of water in both the treatments caused a severe reduction in *T*. Accordingly, ET_c, produced higher *E*% in I₂ and I₃ as compared to I₁. In contrast, a marked decrease in *E*% was recorded under I₄ treatment due to increase in the irrigation interval, which produced a drier soil surface and lower *E* losses, as compared to frequent irrigation at a 2-day interval. The additional elongation in irrigation interval in I₅ and I₆ showed a slight decrease in *E*%, despite an extra reduction in *E* being recorded. The accompanying reduction in *T* due to the water stress kept the fraction of *E* without much change (Fig. 9).

Table 1 Effect of irrigation method, irrigation interval and water saving strategies under different treatments on growth and yield of cowpea

Treatment	Plant height (cm)	Number of leaves	Leaf Area Index (m ² m ⁻²)	Leave dry weight (g)	Stem dry weight (g)	Root dry weight (g)	Fresh Weight (g plant ⁻¹)	Biomass (ton ha ⁻¹)	Harvest index	Yield (ton ha ⁻¹)
I1	187.8 ^a	46.3 ^a	0.75 ^a	18.13 ^{ab}	34.0 ^a	3.7	262.0 ^a	32.61 ^a	0.33	10.78 ^{ab}
I2	156.3 ^{bc}	41.3 ^{ab}	0.68 ^{ab}	18.75 ^a	28.3 ^{ab}	3.9	251.3 ^a	31.46 ^a	0.34	10.52 ^b
I3	141.3 ^c	27.0 ^b	0.53 ^b	13.11 ^b	20.7 ^b	4.2	170.0 ^{bc}	21.91 ^c	0.36	7.74 ^c
I4	188.7 ^a	47.7 ^a	0.85 ^a	18.33 ^{ab}	28.4 ^{ab}	3.8	264.7 ^a	33.62 ^a	0.34	11.57 ^a
I5	163.0 ^b	44.3 ^a	0.78 ^a	18.01 ^{ab}	29.3 ^{ab}	3.7	232.7 ^a	29.59 ^a	0.35	10.21 ^b
I6	125.7 ^c	24.7 ^b	0.44 ^b	11.42 ^b	20.3 ^b	3.4	155.3 ^c	20.60 ^c	0.38	7.66 ^c
I7	157.7 ^{bc}	29.7 ^b	0.55 ^b	14.36 ^b	23.5 ^b	3.8	212.0 ^b	28.53 ^b	0.38	10.87 ^{ab}

Cowpea performance

Table 1 presents the effects of irrigation method, irrigation interval, and water saving strategies on the growth attributes and cowpea yield. Growth attributes such as plant height, leave number, LAI, leave and stem dry weight, fresh weight, and biomass of cowpea showed a significant retraction under severe water stress in I_3 and I_6 treatments, when compared to well-irrigated plants through drip in I_1 and I_4 treatments. In addition, well-irrigated plants through conventional furrow irrigation in the I_7 treatment registered a significant reduction in the above-mentioned growth attributes as compared to the I_1 and I_4 treatments. While non-significant differences were recorded among moderately water-stressed plants in I_2 and I_5 treatments and well-irrigated plants in I_1 and I_4 treatments with respect to leave number, LAI, leave dry weight, stem dry weight, fresh weight, and biomass of cowpea. However, the plant height of moderately water-stressed plants in I_2 and I_5 treatments was significantly lower as compared to I_1 and I_4 treatments. In contrast, a non-significant difference was recorded in the dry weight of root and HI among different treatments. Moreover, full recovery of soil water consumption at p through drip irrigation in I_4 recorded the highest yield of cowpea ($11.57 \text{ ton ha}^{-1}$), which was on par with the other well-irrigated treatments through drip at a 2-day irrigation interval in I_1 ($10.78 \text{ ton ha}^{-1}$) and via conventional furrow irrigation in I_7 ($10.87 \text{ ton ha}^{-1}$). The yield of cowpea obtained under moderate water stress in I_2 and I_5 treatments was on par with I_1 and I_7 and statistically lesser than I_4 , while the lowest yield of cowpea was recorded under severe water stress conditions in I_3 and I_6 treatments. Retraction in growth and yield of cowpea under severe water stress was previously recorded in several studies (Phogat et al. 1984; Farouk and Amany 2012; Lima and Lobato 2017). Optimal water supply is essential for normal plant growth and productivity. Continued or intermittent water stress similarly constrains the growth and performance of cultivated crops more than any other environmental factor (Shao et al. 2009; Anupoj and Kambhammettu 2020).

A comparison of means was obtained from Fisher's least significant difference (LSD) test. Means with the

same alphabet (as superscript) are not significantly different ($P < 0.05$) based on Fisher's least significant difference (LSD) test. I_1 -100% ETc at a 2-day interval through drip irrigation; I_2 -80% ETc at a 2-day interval through drip irrigation; I_3 -60% ETc at a 2-day interval through drip irrigation; I_4 -100% ETc at a 45% depletion of available soil moisture through drip irrigation; I_5 -100% adjusted ETc at a 60% depletion of available soil moisture through drip irrigation; I_6 -100% adjusted ETc at a 75% depletion of available soil moisture through drip irrigation; I_7 -100% ETc at a 4-day irrigation interval through furrow irrigation (Table 2).

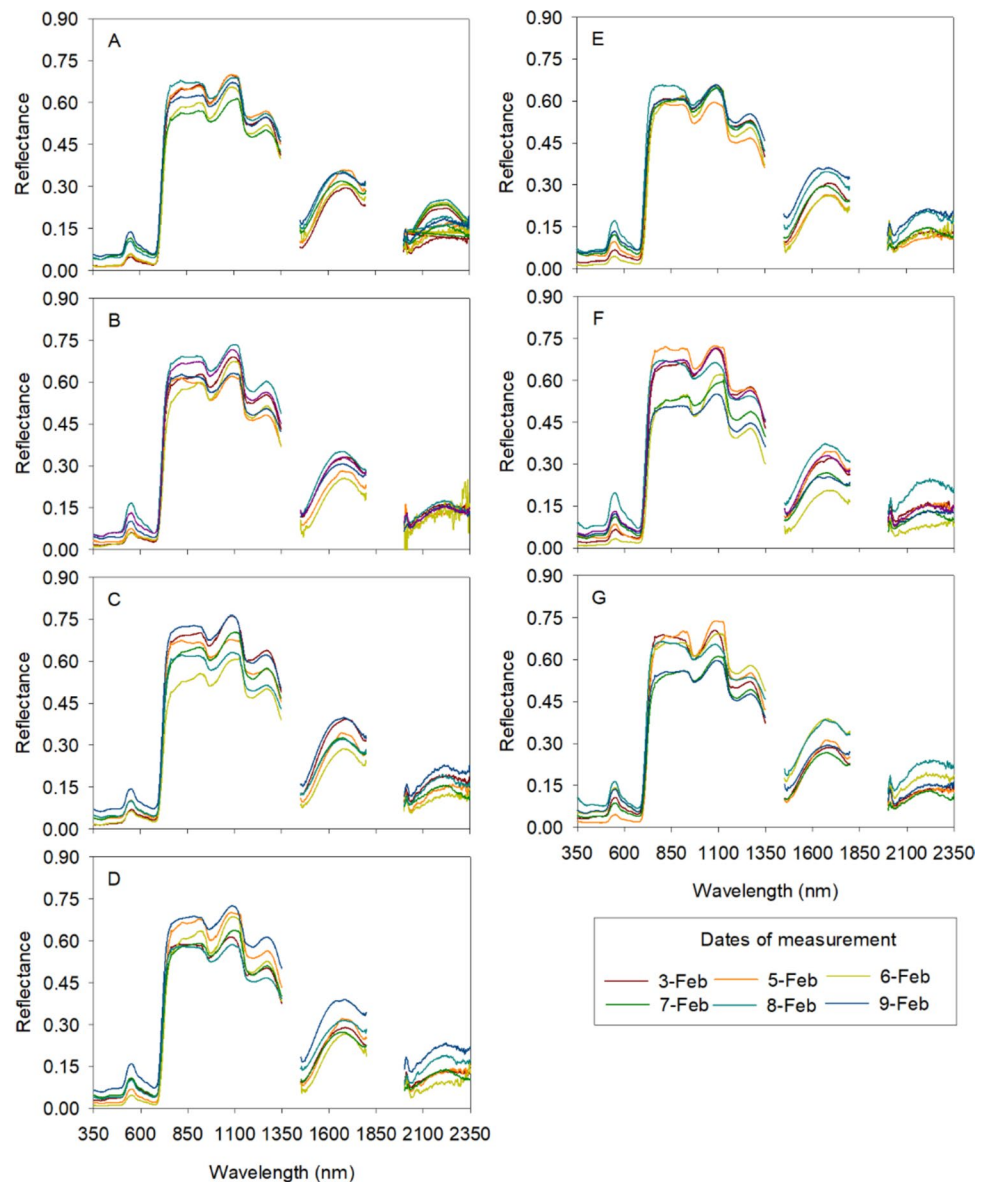
Spectral reflectance and its relation with water stress

Spectral reflectance data were captured from cowpea and analyzed to understand the effects of irrigation method, irrigation interval, and water saving strategies. For interpretation purposes, seven-day continuous spectral signature is shown in Fig. 10. The results confirm the impact of water stress on specific treatments such as I_3 and I_6 , which were exposed to severe water stress. In the case of I_1 and I_4 , a constant pattern of reflectance was observed in the wavelength range of 1450 to 2500, which indicates that leaf water status was optimal for the entire observation period (between February 3 and 9). In the case of I_2 , I_3 , I_5 , and I_6 , during the observation, the reflectance varied according to the irrigation frequency, and when irrigated, the reflectance was minimal, i.e., when the leaf water status is optimal, and when cowpea suffered stress due to a lack of moisture, the spectral reflectance was maximum, showing the leaf water deficit, which is indicated by indices (Supplementary Table 4). In the case of I_5 , spectral reflection of the short-wave infrared region is steadily increasing and, eventually, leading to a water deficit situation, which is recovering once the plants are irrigated. In the case of I_7 , even though a constant pattern of reflectance was observed in the wavelength range of 145–2500, when compared with I_1 and I_4 , light variation was observed in spectral reflectance, which might be due to the fact that the I_7 interval is once every 4 days, hence

Table 2 Effect of irrigation method, irrigation interval and water saving strategies under different treatments on water use of cowpea

Treatment	WP (kg m-3)	TrUE (kg m-3)	IWP (kg m-3)	WPET (kg m-3)	WPTTr (kg m-3)
I1	3.18 ^b	4.38 ^b	2.86 ^b	9.46 ^a	13.25 ^b
I2	3.88 ^a	5.25 ^a	3.49 ^a	10.51 ^a	15.69 ^a
I3	3.81 ^a	5.49 ^a	3.42 ^a	9.15 ^a	15.55 ^a
I4	3.74 ^a	4.70 ^b	3.36 ^a	10.26 ^a	13.66 ^a
I5	3.65 ^a	4.36 ^b	3.28 ^a	9.75 ^a	12.64 ^b
I6	3.28 ^b	3.71 ^c	2.95 ^b	7.84 ^b	9.99 ^c
I7	2.58 ^c	4.42 ^b	1.81 ^c	6.46 ^b	11.60 ^{bc}
LSD (0.05)	0.38	0.52	0.34	1.52	2.26

Fig. 10 Leaf spectral reflectance of cowpea crop under different treatments I1 -100% ETc at two days interval through drip irrigation **A**; I2 -80% ETc at two days interval through drip irrigation **B**; I3 -60% ETc at two days interval through drip irrigation **C**; I4 -100% ETc at 45% depletion of available soil moisture through drip irrigation **D**; I5 -100% adjusted ETc at 60% depletion of available soil moisture through drip irrigation **E**; I6 -100% adjusted ETc at 75% depletion of available soil moisture through drip irrigation **F**; I7 -100% ETc at 4 days irrigation interval through furrow irrigation **G** at different dates of measurements during mid-season stage



there may be a slight water deficit. Several indices worked out also showed a similar trend of water deficit and were positively correlated with the yield obtained. For instance, Water Index, NDVI, RVI, DVI, LAI, SAVI, VI, etc. were significantly correlated with the yield obtained (data not shown). These results confirm our findings that these spectral reflectance data can be used as a tool for predicting yield response and may also help to identify water stress in plants (Chaturvedi et al. 2019).

Water utilization by cowpea

Improving water productivity has been a challenging task for scientists across the globe (Koech and Langat 2018; Hatfield and Dold 2019). The results of WP, TrUE, IWP, WP_{ET}, and WP_{Tr} are presented in Table 2. Among the frequent

drip-irrigated treatments, moderate and severe water stress in I₂ and I₃ treatments gave significantly higher WP (3.88 and 3.81 kg m⁻³, respectively), TrUE (5.25 and 5.49 kg m⁻³, respectively), IWP (3.49 and 3.42 kg m⁻³, respectively), and WP_{Tr} (15.69 and 15.55 kg m⁻³, respectively), when compared to well-irrigated treatment I₁, while, non-significant difference was recorded in WP_{ET} between I₁, I₂, and I₃ treatments. Among the well-irrigated treatments, drip irrigation at *p* in the I₄ treatment showed significantly higher WP (3.74 kg m⁻³), IWP (3.36 kg m⁻³), and WP_{Tr} (13.66 kg m⁻³) as compared to frequent-irrigated treatments via drip in I₁ and via conventional furrow irrigation in I₇. However, I₁ and I₄ were statistically on par with respect to TrUE (4.38 and 4.70 kg m⁻³, respectively) and WP_{ET} (9.46 and 9.75 kg m⁻³, respectively), and significantly superior over I₇ in WP_{ET}. Increasing irrigation frequency reduced the WP of cowpea

due to proportionally greater evaporation losses and more water requirements (Phogat et al. 1984; Üzen et al. 2018). Irrigation at 75% depletion of TAW in I_6 recorded significantly lower WP (3.28 kg m^{-3}), TrUE (3.71 kg m^{-3}), IWP (2.95 kg m^{-3}), WP_{ET} (7.84 kg m^{-3}), and WP_{Tr} (9.99 kg m^{-3}) as compared to I_4 , where irrigation was scheduled at 45% depletion of TAW, while irrigation at 60% depletion of TAW in I_5 did not significantly differ in WP, TrUE, IWP, and WP_{ET} as compared to I_4 (Phogat et al. 1984; Üzen et al. 2018; Ma et al. 2018). The results showed that crop water productivity is an important index to evaluate water saving and to obtain higher output or value for each drop of water used (Üzen et al. 2018; Ma et al. 2018; Ding et al. 2013; Çetin and Uygan 2008; Cetin and Kara 2019; Cetin and Akinci 2021).

A comparison of means was obtained from Fisher's least significant difference (LSD) test. Means with the same letter are not significantly different ($P < 0.05$) on the basis of Fisher's least significant difference (LSD) test. WP: water productivity, TrUE: transpiration use efficiency, IWP: irrigation water use efficiency, WP_{ET} : biomass water productivity, and WP_{Tr} : biomass transpiration productivity I_1 -100% ETc at a 2-day interval through drip irrigation; I_2 -80% ETc at a 2-days interval through drip irrigation; I_3 -60% ETc at a 2-day interval through drip irrigation; I_4 -100% ETc at a 45% depletion of available soil moisture through drip irrigation; I_5 -100% adjusted ETc at a 60% depletion of available soil moisture through drip irrigation; I_6 -100% adjusted ETc at a 75% depletion of available soil moisture through drip irrigation; I_7 -100% ETc at a 4-day irrigation interval through furrow irrigation.

Conclusions

The study demonstrated that daily simulation of soil evaporation and crop transpiration using the FAO-56 dual crop coefficient method effectively highlighted the influence of irrigation strategies on water use efficiency and cowpea growth. The highest soil evaporation was recorded at the initial growth stage, and the minimum value was registered during the mid-season stage. Furrow irrigation doubled the evaporation losses, when compared to drip irrigation. Frequent irrigation at 2-day interval showed the maximum evaporation rate even with 20% and 40% shortage of water, whereas stretching the irrigation interval by irrigation at 45%, 60%, and 75% depletion of available soil moisture registered 17.4%, 29.9%, and 42.8% savings in seasonal evaporation as compared to frequent irrigation, respectively. The research clearly demonstrated that extending irrigation intervals based on soil moisture depletion levels can substantially reduce evaporation losses. The seasonal ET_c of non-stressed cowpea plants at 2-day interval was 344.9 mm under drip

irrigation and 442.0 mm under conventional furrow irrigation. Irrigation with a 20% and 40% water deficit through drip showed 13.2% and 30.6% reductions in ET_c , respectively. Drip irrigation at 45%, 60%, and 75% depletion of available soil moisture decreased the seasonal ET_c by 5.0%, 12.0%, and 23.8% as compared to frequent drip irrigation at a 2-day interval. Soil evaporation fraction ($E\%$) was 28.7% under drip irrigation at 2-day interval and 44.3% under conventional furrow irrigation. Frequent drip irrigation with a 20% and 40% water deficit increased $E\%$ to 33.0 and 41.2%, respectively, while the lowest $E\%$ values of 24.9%, 22.8%, and 21.5% were obtained by irrigation at 45%, 60%, and 75% depletion of available soil moisture.

Well-irrigated cowpea plants through drip recorded the highest growth, while significant reductions in growth attributes of cowpeas were registered under conventional furrow irrigation. Severe water stress also reduced the growth of cowpea as compared to well-irrigated plants through drip. The highest yield of cowpea ($11.57 \text{ tons ha}^{-1}$) was obtained by drip irrigation at 45% depletion of available soil moisture, while the lowest yield of cowpea was recorded under severe water stress conditions. Drip irrigation with a 20% and 40% water deficit significantly improved WP, TrUE, IWP, and WP_{Tr} . To conclude, deficit irrigation (non-frequent drip irrigation at 45% depletion of available soil moisture) showed significantly higher WP, TrUE, IWP and WP_{Tr} . This strategy not only maximized cowpea yield (reaching up to 11.57 tons per hectare) but also reduced non-beneficial soil evaporation and improved overall water productivity. In contrast, conventional furrow irrigation and severe water stress conditions were associated with reduced growth attributes and lower yields. In conclusion, the findings suggest for the adoption of deficit drip irrigation, especially at 45% depletion of available soil moisture, as a sustainable and efficient water management strategy. This approach significantly enhances water use efficiency and crop productivity while conserving water resources, making it an ideal practice for cowpea cultivation, particularly in water-scarce regions. Future research could further explore the applicability of these strategies across different crops and agro-climatic conditions to generalize the benefits of optimized irrigation scheduling.

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