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Paired-row planting and furrow irrigation increased light interception, pod yield and water use efficiency of groundnut in a hot sub-humid climate

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ABSTRACT

Increasing scarcity of irrigation water calls for enhancing water use efficiency (WUE) of crops, and improved planting method is a potential option. Field experiments were conducted for 3 years to evaluate effects of three planting methods of groundnut viz. flat-bed, ridge and furrow and paired-row at four irrigation regimes viz. 1, 2, 3 and 4 irrigations. Ridge and furrow, and paired-row methods resulted in an increase in pod yield by 13 and 17% and irrigation water saving by 26.7 and 41.7%, respectively compared with flat-bed method. Although highest yield level was similar in ridge and furrow and paired-row methods with four irrigations, irrigation water was 28.4% less in the latter than the former. In the three irrigation x paired-row method, pod yield reduced by only 3.8%, whereas water saving was 26.9% compared to the four irrigations x paired-row method. Better root dry weight, greater intercepted photosynthetically active radiation, chlorophyll fluorescence (Fv/Fm and ΦPS II) and rate of leaf photosynthesis contributed to higher yield and nutrient uptake under paired-row at higher irrigation regime than traditional flat-bed method. Although evapotranspiration (ET) increased with higher irrigation regimes; ridge and furrow and paired-row method decreased ET by 13 and 21%, and increased crop WUE by 32.6 and 48%, respectively over flat-bed. The pod yield (Y)-ET functions were found linear; it has been revealed that the crop will achieve maximum pod yield (2109 kg ha^{-1}) with 359 mm ET under paired-row planting. Computed elasticity of water production and crop yield response factor could well be used for making irrigation decisions. This field study confirmed that paired-row planting and furrow irrigation had increased pod yield, saved water and enhanced WUE of groundnut under hot sub-humid conditions.

1. Introduction

Groundnut (*Arachis hypogaea* L.), also known as 'peanut', is one of the dominant oilseed crops in India. It is cultivated in an area of about 4.77 million ha with 7.40 million tonnes of production in the country. The average groundnut yield is 1268 kg ha^{-1} in Odisha state, in eastern India, which is lower than the national average yield (1552 kg ha^{-1}) (DAC and FW, 2016). Rainy season coincides with the period between June to September. Major reason of lower yield is that the crop is mostly grown under rain-fed condition. Only 25.8% of the area is irrigated. Irrigation is required during dry season especially in the situations of no or little rainfall and no substantial capillary rise. Further, water supply is not adequate to irrigate crops either from reservoir-water through canal system or from groundwater sources. Over-exploitation and depletion of groundwater is alarming and it is a cause of concern. Consequently, water stress is a common phenomenon, which occurs during crop growth, and causes yield reduction. Hence, major challenges are to enhance yield as well as to increase water use efficiency (WUE) of the crop. Furrow making and efficient planting, rather than flat-bed method and irrigation through furrows would save water and bring more area under irrigation.

There is growing need for groundnut irrigation in order to increase its yield, especially due to frequent occurrences of drought, soil moisture deficit or increased soil temperature (Prasad et al., 2010). On the other hand, there has been a rising concern on the availability of water for irrigation because irrigation water withdrawal is under fierce competition from other uses that include industrial purposes, generation of electricity and energy, and domestic consumption (Rijsberman, 2006; Mall et al., 2006). Therefore, freshwater resources should be used for irrigation in the most productive and sustainable manner (Gleick, 2003; Gleick and Palaniappan, 2010); but practical ways and means are not readily available to the growers. Thus, water-limited situations call for crop production with increased WUE (Howell, 2001; Tilman et al., 2002) and water-saving crop management practices. In this regard, advancing agronomic management is essential for increasing yield and WUE of groundnut.

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Previous studies have shown that water stress or drought reduced pod yield and biomass production of groundnut (Lamb et al., 2004; Haro et al., 2008; Songsri et al., 2009; Vaghasia et al., 2010; Shinde et al., 2010; Koolachart et al., 2013; Dang et al., 2013). The underlying reasons of reduced yield were reduced dry weight of roots and WUE (Songsri et al., 2009), impaired pegging and pod formation due to increased soil strength by surface drying (Sadras and Milroy, 1996; Reddy et al., 2003; Haro et al., 2008), affected micro-sporogenesis and fertilization due to increased day temperature beyond 35 °C (Prasad et al., 2001), reduced conductance of stomata and rate of carbon exchange (Nautiyal et al., 1999; Egli and Bruening, 2001), reduced relative leaf water content and cell membrane stability with concomitant reduction in kernel number per plant (Shinde et al., 2010; Dang et al., 2013), decreased chlorophyll biosynthesis (Richardson et al., 2002; Nigam and Aruna, 2008), decreased dry matter production and atmospheric-N fixation (Pimratch et al., 2008). Low yields were also reported due to water-logging because groundnut is sensitive to excess soil moisture (Ibrahim et al., 2002), which caused pest and diseases infestation, for example leaf-miner (*Aproaerema modicella*), leaf-spot disease or commonly called as '*Tikka*' disease (*Cercospora arachidicola*). Thus, previous research findings delved mostly into the basic understanding on water relation in plants and crop physiology. It is important that viable and practical agronomic options that increase pod and biomass yield and save irrigation water are developed.

Information is available on irrigation scheduling and critical growth stages of groundnut, but irrigation water saving technique is required to growers. Patel et al. (2008) suggested for irrigating the crop at 40 mm cumulative pan evaporation, which would give WUE of 4.76 kg ha^{-1} mm^{-1} in Gujarat, India. Chauhan et al. (2013) developed a decision support model which enabled irrigation scheduling to commercial groundnut production. Ratio of irrigation water and cumulative pan evaporation (0.5 to 0.9) was used as criterion for irrigation to summer groundnut in eastern India (Bandyopadhyay et al., 2005). Craufurd et al. (2006) have found a good relationship between groundnut yield and water use with appropriate sowing date and irrigation. Selection of water stress tolerant genotypes (Songsri et al., 2009), application of mulches (Ramakrishna et al., 2006; Zagade and Chavan, 2010), withholding irrigation (Vaghasia et al., 2010), drip irrigation (Zhu et al., 2004) and moving sprinkler (Plaut and Ben-Hur, 2005) have been advocated earlier, but the aim of increasing yield and WUE could not be achieved always. Moreover, mulching and micro-irrigation technologies have not been adopted widely by groundnut farmers in India. Although yield benefits of paired-row (twin-row) planting pattern have been researched and published (Lanier et al., 2004; Sorensen et al., 2007; Culbreath et al., 2008; Ihejirika et al., 2008; Tubbs et al., 2011), this was emphasized mostly to reduce insect-pest and disease incidences, not on water saving.

In India, limited information is available for planting methods on other crops, for example, paired-row for cotton (Aujla et al., 2005), planting of oilseed rape on ridges and beds receiving irrigation through each or alternate furrows (Buttar et al., 2006), sowing of soybean, soybean/maize or soybean/ pigeon pea intercropping on broad-bed and furrows in vertisols (Mandal et al., 2013), but no attempts have been made so far for groundnut with the aim to increase yield and WUE. Improved method of planting and water-saving technique would be required for eastern Indian hot and sub-humid condition. Further, it is essential that pod yield and evapotranspiration (ET) production functions are developed to reveal the dynamic relations on pod yield, ET requirement and WUE. Crop yield response factors (K_y) are important criteria and indices, which reveal complex relationships between water use and crop production. The estimation of these K_y values would be required for this crop to evolve irrigation strategy, especially for the growing condition under hot and sub-humid climate. Earlier, crop coefficient of groundnut and yield response factors (Reddy and Reddy, 1993; Kheira, 2009), and response function with imposed water stress (Jain et al., 1997) have been developed with the aim of irrigation scheduling.

Therefore, attempts were made: i) to study the influence of irrigation regimes and improved planting methods on pod yield, ET, WUE and N-uptake by groundnut, ii) to find out the basis of yield variation using crop growth and physiological parameters viz. root dry weight, interception of photosynthetically active radiation, chlorophyll fluorescence and leaf photosynthesis, iii) to study the changes in soil temperature and soil organic carbon stock, and iv) to develop pod yield-ET production functions to reveal the dynamic relationships of yield, ET and WUE of groundnut under tropical sub-humid condition.

2. Materials and methods

2.1. Description of experimental site

Field experiments were carried out at the Research Farm of the ICAR-Indian Institute of Water Management, Mendhasal, near Bhubaneswar, Odisha, India (20° 18′ N, 85° 41′ E and 97 m msl). Climate is hot i.e., tropical and sub-humid. Weather data and information were recorded from the weather station, which is situated at 1.24 km away from the experiment site. Average annual rainfall is about 1490 mm; out of this about 81% occur during monsoon season i.e., June to September when rice is the predominant crop; whereas post-rainy season period i.e., winter and summer months receive either no or very little rainfall. The season for growing summer groundnut was from the month of January to May.

Rainfall was 49.1 mm in 2008 and 22.4 mm in 2010, and no rainfall was received in 2009 during the crop growing period i.e., mid- January to 1st week of May. Average pan evaporation (E_p) was 4.1, 4.2 and 4.2 mm d^{-1} in 2008, 2009 and 2010, respectively; the maximum E_p was 5.8–6.5 mm d^{-1}, and the minimum was 2.5–2.7 mm d^{-1} over three years. The cumulative E_p was 465.6, 464.9 and 475.7 mm in three years during the cropping period. Winter season (December to February) is short and mild. Air temperature starts increasing in summer months. Average minimum temperature was 13.3, 17.3, 22.1, 24.6 and 26.2 °C in January through May, and average maximum was 28.2, 31.0, 34.1, 36.0, 37.6 °C in corresponding months. In general, there is high probability of occurrence of terminal heat stress in the region during the period which coincides with summer groundnut growing season. However, year-wise variation was minimum in three years of experimentation.

The textural class of the experimental soil was sandy clay loam with 65% sand, 14% silt and 21% clay. Relative sand fractions declined with the increase in soil depth, and clay contents increased. In 60–90 cm, particle size distribution was 62% sand, 12% silt and 26% clay. Soil was slightly acidic with pH 5.6 (soil:water ratio 1:2.5), but non-saline (electrical conductivity 0.31 dS m^{-1}). Initial soil organic carbon (SOC) 4.4 g kg^{-1} was low; available P (5.96 mg kg^{-1}) and K (87 mg kg^{-1}) were also low. Bulk density was 1.43 Mg m^{-3}. Available water ranged from 0.156 to 0.172 m^3 m^{-3} (Page et al., 1982; Klute, 1986; Nelson and Sommers, 1996). Soil moisture regime was '*Typic ustic*' and temperature regime '*hyperthermic*'.

2.2. Treatments, experimental design and crop management

Field experiments were conducted over three consecutive years (2008–2010). The experiment was laid out in a split-plot design with three replications. Treatments consisted of four irrigation regimes in the main-plots: one (I_1) in flowering stage, two (I_2) in flowering and pod development, three (I_3) in vegetative, flowering and pod development and four (I_4) in vegetative, flowering, pod initiation and pod development, and three planting methods in sub-plots as: flat-bed (S_{fb}), ridge and furrow (S_{rf}) and paired-row method (S_{pr}). Irrigations were scheduled in critical growth stages. Physiological and phenological aspects were duly considered. As there was no or little rainfall and no substantial capillary rise of water, it was decided scheduling irrigation

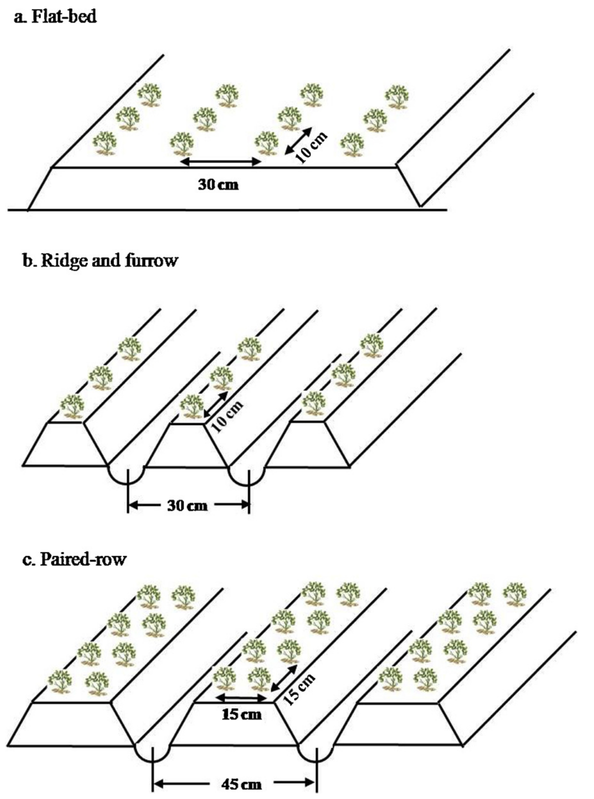


Fig. 1. Schematic diagram of three planting pattern of groundnut used as treatments, a) flat-bed, S_{fb}, b) ridge and furrow, S_{rf}, and c) paired-row method, S_{pr}.

during physiologically important stages. For planting methods, in S_{fb}, spacing was 30 cm row-to-row and 10 cm plant-to-plant; in S_{rf} planting on ridges separated by furrows with same spacing as in S_{fb}, and in S_{pr} method, distance between two rows (paired-row) on the narrow bed was 15 cm and plant-to-plant 15 cm (Fig. 1). Spacing in different methods was designed in such a way that each treatment had uniform density of 30–33 plants per m^2. Irrigation was applied by flood method in S_{fb}, and furrow irrigation in S_{rf} (single rows on ridge separated by furrows) and S_{pr} (paired-row on narrow beds separated by furrows).

Land preparation, manure and fertilizer application, planting etc. were done as per the standard management practices for this crop. Organic manure i.e. farmyard manure was applied at 4.5 tonnes per ha and incorporated before final ploughing and preparing the land by a tractor-drawn plough. The rate of fertilizer-N, P_2O_5 and K_2O was 20, 40 and 40 kg ha^{-1}, respectively; sources were urea, diammonium phosphate and muriate of potash. One pre-sowing irrigation of 65 mm was applied before land preparation for proper germination of seeds and uniform establishment of the crop. Seeds of groundnut (var. TAG 24) was sown on 10–15 January every year as per the treatments. Ridge and furrow (S_{rf}) and narrow bed was made in S_{pr} plots. Other crop management practices were taken up as recommended for this crop *viz.* weeding, hoeing before onset of flowering, measures against infestation by plant diseases and/ or insect-pests during the entire crop period. The crop was harvested manually from 2 to 6 May every year. Pod yield was calculated from net plot area (3.5 m x 4 m) and reported at 15% moisture. The duration of the crop was 110–114 days.

2.3. Measurement methods and calculation procedures

2.3.1. Root dry weight, chlorophyll fluorescence and leaf photosynthesis

Three plants having average growth were selected from each plot for root sampling. Root samples were collected through the monolith method with each sampler centered over the plant (Heeraman and Juma, 1993; Serraj et al., 2004). Samples were washed carefully in a bucket of water, separating all roots by straining. Roots were dried in an oven at 70 °C for 72 h till the constant weight was obtained; then root dry weight was recorded. Three fully matured leaves from the same plant were used to measure chlorophyll fluorescence with a fluorescence monitoring system (model: FMS-2, Hansatech Instruments Ltd., Norfolk, U.K.). The parameters measured were dark-adapted maximum photochemical efficiency (Fv/Fm) and quantum yield of PS II (ΦPS II) at flowering and pod development stages of the crop from each plot. Prior to each set of Fv/Fm measurement, leaves were dark-adapted for a period of 30 min using leaf clips (Souza et al., 2004). The same leaves were also used to measure rate of leaf photosynthesis using a portable photosynthesis system (model: CIRAS-2, PP Systems, U.K.). These measurements were done and recorded during flowering and pod development stages on clear sunny days (solar radiation > 1200 μmol m^2 s^{-1}) between 10:30 and 11:00 h.

2.3.2. Photosynthetically active radiation

Photosynthetically active radiation was measured by a portable line quantum sensor (model EMS-7, SW & WS, Burrage, UK). Measurements were made in five places from each plot on different Julian days coinciding with critical stages of crop growth. Incident (I_0) and transmitted (I_1) radiation was recorded at about 11:00- 12:30 h (± 1 h) on sunny days (Gallo and Daughtry, 1986; Kiniry et al., 2005); I_0 was measured at the top of the canopy and I_1 at the below by placing the sensor across crop rows. The fraction of intercepted PAR i.e. *f*IPAR was calculated as:

$$f\text{IPAR} = (I_0 - I_1)/I_0 \tag{1}$$

2.3.3. Soil parameters and soil temperature

Soil particles i.e., sand, silt and clay fractions were determined using the hydrometer method and soil texture was determined using the USDA classification system. The pH and EC was measured by the digital meters; soil bulk density by core sampling method; field capacity of soil and wilting point using a pressure plate apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands). Soil temperature was measured by manual thermometers (AIC Agro Instruments Pvt. Ltd., Kolkata, India). Thermometers were made of mercury in glass in a rigid brass stem with pointed end for smooth entry into soil, having fuse bulbs for quick response to temperature changes. Measurements were carried out up to 30-cm soil depth during the day-time between 8:00. and 17:00 h with 30-min intervals Soil organic carbon content was determined by Walkley-Black method (Nelson and Sommers, 1982). The SOC stock (Mg ha^{-1}) was then calculated by using SOC content (g g^{-1}), bulk density (Mg m^{-3}) and thickness of soil layer (m) as the following:

$$\text{SOC stock} = \text{SOC content} \times \text{BD} \times \text{soil depth} \tag{2}$$

Nitrogen content in kernel and haulm was analyzed by Kjeldahl method (Horneck and Miller, 1998), and N-uptake was calculated using biomass and N concentration.

2.3.4. Irrigation water, soil moisture and estimation of evapotranspiration

Irrigation was measured by RBC flume (Eijkelkamp, model 13.17.02) in each event of application. Recorded sill heights (mm) were used to determine flow rate. Soil moisture was determined by thermo-gravimetric method before sowing, about 15 days interval during crop growing period and after harvesting. Evapotranspiration (ET) was calculated using the water balance method, as was used earlier also (Mandal et al., 2006):

$$ET = P + I + Cp - Dp - Rf \pm \Delta S \tag{3}$$

where P, rainfall (mm), I, irrigation (mm), Cp, capillary contribution, Dp, deep percolation, Rf, surface runoff and ΔS, the change in soil moisture storage (mm) in the profile (0–90 cm) calculated from soil moisture data on the date of sowing and at harvest. Cp was assumed to be negligible as the groundwater depth was low (> 4 m); as there was no change in moisture storage beyond 90 cm depth, Dp was also considered negligible. Irrigation in each event was not sufficient to saturate entire profile and to cause deep percolation. No runoff occurred because little or no rainfall was received during the cropping period. Thus, ET (mm) was calculated using P, I and ΔS. Crop water use efficiency (WUE) was computed as pod yield (Y) divided by ET, Y in kg ha^{-1}, hence expressed as kg ha^{-1} mm^{-1}, and irrigation water use efficiency (IWUE) was computed as pod yield (Y) divided by cumulative irrigation water (mm).

2.3.5. Pod yield-evapotranspiration relationship

Pod yield and evapotranspiration relationships were developed. The dataset of pod yield and cumulative ET obtained from three years experiment were used for developing these relationships. Regression technique was used separately for three planting methods. It was linear function of the form: Y = a + b ET, where, ‘a’ is the intercept, ‘b’ the slope or the coefficient; Y/ET is the WUE, ∂Y/∂ET is the slope ‘b’ or the marginal water use efficiency (WUE_m) and (∂Y/Y)/(∂ET/ET) i.e., the rate of change of pod yield with respect to the rate of change of ET, is the elasticity of water production (E_{wp}); the expressions (Haxem and Heady, 1978; Liu et al., 2002) are:

$$WUE_m = b \tag{4}$$

$$E_{wp} = \frac{b * ET}{a + b * ET} \tag{5}$$

When ET is maximum (ET_m), Y_m being the maximum yield, the crop yield response factor, K_y of Doorenbos and Kassam (1979) is:

$$K_y = \left(1 - \frac{Y}{Y_m}\right) / \left(1 - \frac{ET}{ET_m}\right) \tag{6}$$

2.4. Statistical analyses

Data were analyzed statistically following analyses of variance (ANOVA) technique as outlined for split-plot design (Gomez and Gomez, 1984). Significance testing was carried out by *F*-test at 5% probability level ($p = 0.05$) for all parameters; then mean differences were compared with computed least significant difference (LSD). Duncan’s range test was used for ranking of both main-plot treatments, sub-plot treatments and interactions means at $p = 0.05$. Regression models of pod yield and evapotranspiration relationships were developed using data analysis software of MS Excel. Coefficients of determination (R^2) were computed and tested statistically.

3. Results and discussion

3.1. Root dry weight

Root dry weight (RDW) increased with the increase in crop growth over the period of study i.e., 30–90 days after planting (DAP). Variation was recorded in different irrigation regimes and planting methods in both the seasons (Fig. 2). Though the differences were similar initially at 30 DAP, RDW varied significantly ($p = 0.05$) afterwards with imposition of irrigation treatments. The interaction between irrigation regime and planting method was not significant on RDW. Maximum RDW was attained with 1.40, 1.43, 1.58 and 1.73 g $plant^{-1}$ in I_1, I_2, I_3 and I_4, respectively. Up to 60 DAP, I_3 and I_4 had similar water regime, hence there was no difference in RDW, and then I_4 showed significantly ($p = 0.05$) higher values than I_3. Further, between I_1 and I_2, the difference was not significant throughout crop growth. Planting methods showed considerable differences also. Maximum RDW was 1.48, 1.55 and 1.58 g $plant^{-1}$ in S_{fb}, S_{rf} and S_{pr}, respectively in the 2008 growing season (2008). Among planting methods, though S_{rf} and S_{pr} showed no significant differences, they were significantly higher than S_{fb} at $p = 0.05$. This trend was similar in the 2009 growing season; hence results were consistent.

Our results indicated that root growth was favored by the optimum irrigation regime as in I_3 and I_4. In general, large root system supports crop to mine water from soil (Puangbut et al., 2009), we have found that soil drying and drought condition hindered root growth as a result of reductions in water supply in I_1 and I_2. However, I_1 had similar RDW to I_2 where water stress was more in the former than the latter; it implied that crop adaptation was more with root growth up to certain extent of decrease in soil moisture. Similar results were also reported (Songsri et al., 2009), where drought reduced RDW of groundnut. Hence, reduced root dry weight might have affected pod yield in lower irrigation regimes and in flat-bed planting. Koolachart et al. (2013) also found adverse impact of soil surface desiccation on root growth and pod yield

3.2. Photosynthetically active radiation intercepted by groundnut crop canopy

Irrigation regimes and planting methods influenced the fraction of photosynthetically active radiation (*f*IPAR) intercepted by groundnut crop canopy (Fig. 3). It was measured in two crop growing seasons (Jan-May 2008 and 2009) out of three years of field experiment. The *f*IPAR was at the minimum at initial stage of the crop, and no significant difference was observed among treatments. Afterwards, significant differences were noted till the last observation on Julian Day (JD) 116 or JD 113. The maximum *f*IPAR was 60% in I_1, 64% in I_2, 68% in I_3 and 71% in I_4; and 61% in S_{fb}, 71% in S_{rf} and 74% in S_{pr} in first crop growing season in 2008. The maximum interception occurred during 60–75 days after sowing i.e., at JD 76–90; this growing period coincided with maximum foliage cover by the crop canopy. With regard to treatments, *f*IPAR was higher in I_3 and I_4 compared with I_1 and I_2. Underlying reason was that the adequate irrigation at I_3 as well as I_4 favored better crop growth and canopy expansion, which intercepted more PAR than the canopy which was grown with inadequate irrigation (I_1 and I_2). Haro et al. (2008) also found variation in light capture by groundnut canopy with the direct effect of water stress. Water stress affected crop growth, hence reduced intercepted PAR.

The *f*IPAR differed significantly among planting methods at $p = 0.05$; it was the highest in S_{pr}, which was statistically similar with S_{fb}. Range of calculated *f*IPAR was 36–61, 41–71 and 45–74% in S_{fb}, S_{rf} and S_{pr}, respectively in the first season (Jan-May 2008); 41–64, 42–70 and 45–72% in corresponding treatments in the second season (Jan-May 2009). The paired-row or the ridge and furrow technique facilitated better crop growing environment than the flat-method. Tubbs et al. (2011) also demonstrated that paired-rows had outperformed single rows in the plant stands and canopy expansion. In paired-row cropping, groundnut might have intercepted more of the incoming radiation by horizontal leaf distribution due to higher extinction coefficient (Kiniry et al., 2005; Awal et al., 2006). Moreover, there was close link of incident PAR with the canopy cover and development due to irrigation and planting methods in groundnut.

3.3. Chlorophyll fluorescence (Fv/Fm & ΦPS II) and rate of leaf photosynthesis (Pn)

Chlorophyll fluorescence (Fv/Fm & ΦPS II) and the rate of leaf photosynthesis differed significantly with irrigation regimes and planting methods at $p = 0.05$. The maximum Fv/Fm, ΦPS II and Pn was obtained in I_4 indicating better physiological functioning of plants with adequate water supply through four irrigation (Table 1). However, with the reduction in water supply, as in I_1 and I_2, ability of plants might have reduced to metabolize only normally. Moreover, imbalance might have occurred between the absorption of light energy by

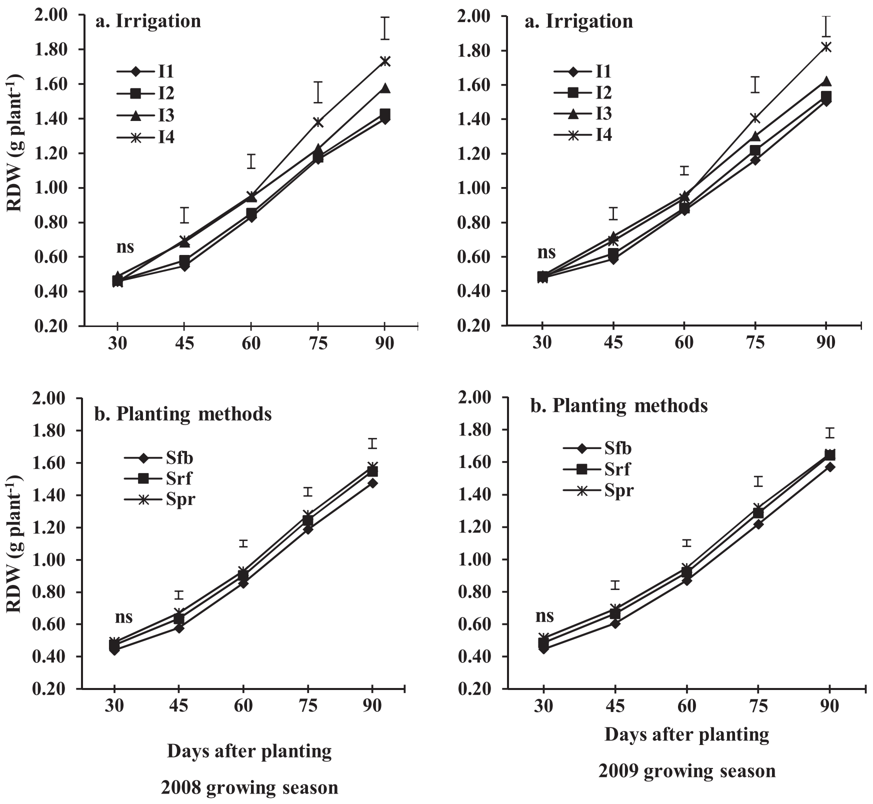


Fig. 2. Root dry weight (RDW) of groundnut plants during 2008 and 2009 growing seasons as influenced by four irrigation regimes, (a): I_1, one; I_2, two; I_3, three, and I_4, four irrigations; three planting methods (b): S_{fb}, flat-bed method at 30 x 10 cm spacing; S_{rf}, ridge and furrow planting at 30 x 10 cm spacing; S_{pr}, paired-row planting at 45 x 15 cm spacing; ns, not significant; vertical lines indicate LSD at $p =$ 0.05.

chlorophyll and the use of energy in photosynthesis (Maxwell and Johnson, 2000; Murchie and Lawson, 2013). A strong and positive relationship was also reported between chlorophyll and photosynthetically active light-transmittance characteristics of leaves (Richardson et al., 2002) and water use by plants (Sheshshayee et al., 2006).

Higher values of Fv/Fm, ΦPS II and Pn were obtained in S_{pr} compared with S_{fb} and S_{rf}; however, Fv/Fm was statistically similar in S_{rf} and S_{pr} in pod development stage, and Pn was similar in these two treatments both in flowering and pod development stage. Better plant growth in S_{pr} and S_{rf} might have managed not to cause photoinhibition (Long et al., 1994) or sustained quenching (Demmig-Adams and Adams,

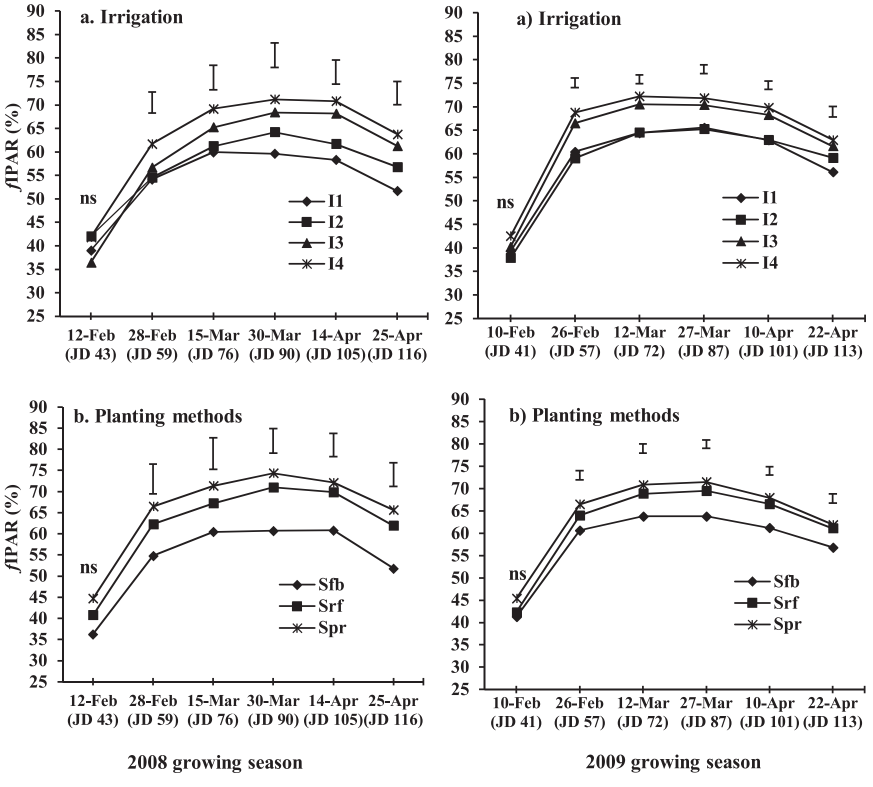


Fig. 3. Fraction of intercepted photosynthetically active radiation (*f*IPAR) by groundnut crop canopy during 2008 and 2009 seasons as influenced by four irrigation regimes, (a): I_1, one; I_2, two; I_3, three, and I_4, four irrigations; three planting methods (b): S_{fb}, flat-bed method at 30 x 10 cm spacing; S_{rf}, ridge and furrow planting at 30 x 10 cm spacing; S_{pr}, paired-row planting at 45 x 15 cm spacing; ns, not significant; vertical lines indicate LSD at $p =$ 0.05.

Table 1
Effects of irrigation regimes and planting methods on some physiological parameters viz. chlorophyll fluorescence (Fv/Fm and ΦPS II) and rate of leaf photosynthesis of groundnut at flowering and pod development stage.

Irrigation and planting methods	F_V/F_m		ΦPS II		Leaf photosynthesis (μmol m^{-2} s^{-1})	
	Flowering stage	Pod development	Flowering stage	Pod development	Flowering stage	Pod development
Irrigation regimes						
I_1: one irrigation	0.747c	0.747c	0.608c	0.578d	16.07b	15.57d
I_2: two irrigation	0.761b	0.755bc	0.611c	0.619c	16.73b	16.53c
I_3: three irrigation	0.781a	0.761b	0.626b	0.634b	21.97a	19.09b
I_4: four irrigation	0.784a	0.793a	0.665a	0.671a	22.77a	22.89a
Planting methods						
S_{fb}: flat-bed method at 30 x 10 cm spacing	0.765b	0.757b	0.618c	0.616c	18.30b	18.07b
S_{rf}: ridge and furrow planting at 30 x 10 cm spacing	0.767b	0.767a	0.627b	0.626b	19.70a	18.60a
S_{pr}: paired-row planting at 45 x 15 cm spacing	0.773a	0.768a	0.638a	0.635a	20.15a	18.90a

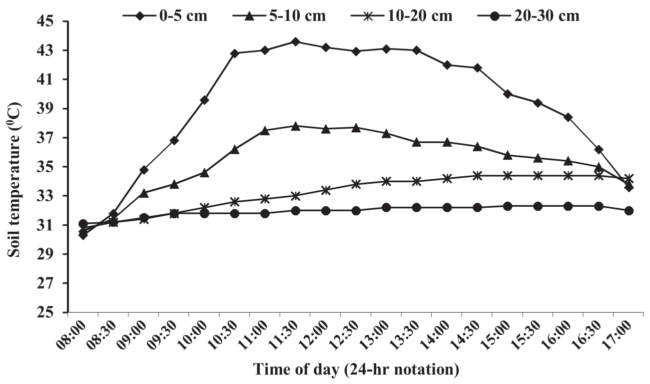
Means in the same column with the same letters are not significantly different by Duncan's multiple range test (DMRT) (at $p =$ 0.05).

2006) compared to flat-bed method (S_{fb}). Consequently there was marginally higher Fv/Fm, ΦPS II and rate of photosynthesis in plant leaves in plots with S_{rf} and S_{pr} than those in S_{fb}.

3.4. Effect of irrigation on soil temperature

Mean values showed that the temperature was higher in dry as compared to irrigated plots (I_4) because of less soil moisture in dry condition (I_1) (Fig. 4). The temperature in the surface soil increased at faster rate than those in other depths; maximum soil temperature was recorded as 43.6 °C in 0–5 cm soil at around 11:30 h on the day under dry condition; whereas in irrigated (I_4) plots we observed gradual increase in soil temperature, and the maximum was 35.8 °C around 11:30 h to 13:30 h. Then, there was decrease in temperature after 13:30 h onwards. In the soil just beneath the surface, maximum temperature was recorded as 37.8 °C in dry and 33.6 °C in irrigated conditions. Temperature variations in lower soil depths i.e., 10–20 cm & 20–30 cm were lesser than surface soil (Fig. 4). Regulation of thermal environment was primarily due to better soil moisture regime upon imposed irrigation (Ramakrishna et al., 2006). Because of high heat capacity of water, different irrigation regimes would likely lead to different soil temperature conditions as was evident in our study. Elevated soil temperature in the pod zone might have detrimental effect to the crop (Davidson et al., 1991; Sorensen and Wright, 2002). Golombek and Johansen (1997) reported that the greatest number of pods was formed at mean soil temperatures between 23 and 29 °C, and 17 and 35 °C were sub- and supra-optimal, respectively. This variation in soil temperature caused differential thermal environment in plots receiving different irrigation regimes. This would form the basis for interpretation of yield differences due to irrigation treatments in present investigation.

a) Dry



b) Irrigated

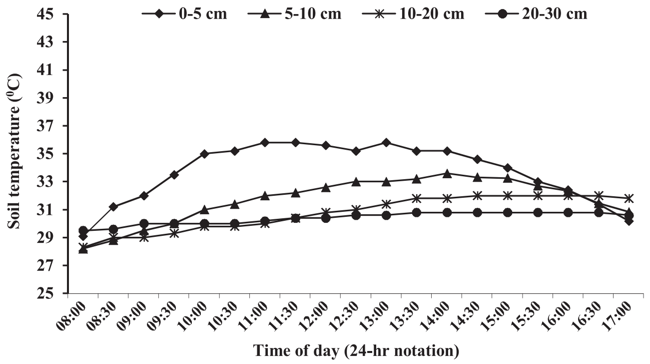


Fig. 4. Variation in soil temperature in 0–5, 5–10, 10–20 and 20–30 cm soil depths within day time (8:00-17:00 h) in groundnut growing plots during pod development stage in (a) dry i.e., drought conditions, and (b) irrigated conditions i.e. with full irrigation.

3.5. Effect of irrigation and planting methods on pod & haulm yield

Across years, pod & haulm yield increased with increase in irrigation regimes. Highest pod yield was obtained in I_4 (1979 kg ha^{-1}) and the lowest in I_1 (1335 kg ha^{-1}). The increase in pod yield was 20, 37 and 48% in I_2, I_3 and I_4, respectively over I_1. Positive response of the crop was obtained to the applied irrigation as there was no rainfall in 2009, and only 27.9 and 21.5 mm in 2008 and 2010 growing seasons, respectively. Hence, maximum pod yield was observed with highest irrigation regime. Similarly, highest pod yield was recorded in S_{pr}, which was 17% higher than S_{fb}, With regard to planting treatments; it was 13% higher in S_{rf} than S_{fb}. The interaction effect between irrigation regimes and planting methods was found significant (Table 2). Across all combination of irrigation regimes and planting methods, pod yield ranged from 1194 to 2056 kg ha^{-1}, being the highest in I_4 x S_{pr} and the lowest in I_1 x S_{fb}. Of course, S_{rf} and S_{pr} showed similar as well as the highest when in combination with I_4. The next best combination was I_3 x S_{pr}, where pod yield was only 3.8% less than that in I_4 x S_{pr}, but with reduction in amount of applied water by 28.4 and 43.1% compared with I_4 x S_{pr} and I_4 x S_{rf}, respectively. This results show that paired-row or ridge and furrow planting with furrow irrigation has led to 13–17% higher pod yield compared to the flat-bed method; paired-row planting saved irrigation water by 41.7% compared to flat-bed method. Although interaction was not significant, haulm yields varied significantly ($p =$ 0.05) due to irrigation regimes and planting methods (Table 3). Haulm yield increased in I_2 (26%), I_3 (39%) and I_4 (45%) over I_1; and 18 and 23% in S_{rf} and S_{pr} over S_{fb}. Number of pods per plant increased to the highest in I_4, which was statistically at par with I_3; similarly it was significantly ($p =$ 0.05) higher in S_{pr} than other planting methods

Table 2

Effect of combination of irrigation regimes and planting methods on groundnut pod yield, crop evapotranspiration (ET) and irrigation water use efficiency (IWUE).

Irrigation treatments	Planting methods	Pod yield (kg ha^{-1})	Irrigation water depth (mm)	Evapo-transpiration (mm)	IWUE (kg ha^{-1} mm^{-1})
I_1: one irrigation	S_{fb}	1194i	79.3g	232.8h	15.86d
	S_{rf}	1381h	57.8h	218.3i	25.98b
	S_{pr}	1429gh	44.9h	203.5j	33.48a
I_2: two irrigation	S_{fb}	1447g	149.4d	300.6e	10.02f
	S_{rf}	1681e	109.4f	263.6g	16.34d
	S_{pr}	1677ef	86.1g	240.9h	20.30c
I_3: three irrigation	S_{fb}	1615f	206.1b	353.8c	8.01fg
	S_{rf}	1907c	147.9d	300.2e	13.36e
	S_{pr}	1977b	123.4e	280.3f	16.40d
I_4: four irrigation	S_{fb}	1830d	291.4a	437.5a	6.34g
	S_{rf}	2051a	217.0b	371.0b	9.51f
	S_{pr}	2056a	168.9c	328.1d	12.33e

S_{fb}, flat-bed method at 30 x 10 cm spacing; S_{rf}, ridge and furrow planting at 30 x 10 cm spacing; S_{pr}, paired-row planting at 45 x 15 cm spacing; Means in the same column with the same letters are not significantly different by Duncan's multiple range test (DMRT) (at $p =$ 0.05).

(Table 3).

The yield increase (both pod and haulm) in paired-row method with furrow irrigation might be attributed to greater interception of PAR, maximum fluorescence efficiency (Fv/Fm and ΦPS II) and net leaf photosynthesis as presented and discussed earlier. Higher irrigation regimes ensured adequate soil moisture in the pod elongation zone, which was actually critical for peg penetration and formation of pods (Reddy et al., 2003). There was a good relation between pod yield and water use by groundnut (Craufurd et al., 2006). Water stress in I_1 and also in I_2 i.e. with inadequate water supply affected crop growth and yield. Yield reduction due to soil water deficit has been reported earlier (Lamb et al., 2004; Haro et al., 2008; Songsri et al., 2009; Shinde et al., 2010). Ratnakumar et al. (2009) also found that water uptake was critical for pod yield. In flat-beds, successive cohorts of pegs might have exposed to desiccated soil surface conditions and evaporative demand, which might have impacted adversely on final pod set. The reasons for better yield in paired-row technique might be credited to plant stands, shortened time to full ground cover, and improved light interception (Sorensen et al., 2007; Tubbs et al., 2011). Previous researchers also reported yield advantages in paired-rows than single row of groundnut (Culbreath et al., 2008; Lanier et al., 2004; Nuti et al., 2008; Sorensen et al., 2004).

3.6. Irrigation water, evapotranspiration (ET) and water use efficiency (WUE)

The irrigation volume (in terms of depth) increased significantly with the increase in irrigation regimes at $p =$ 0.05. Cumulative volume was 60.6, 114.9, 159.1 and 225.8 mm in I_1, I_2, I_3 and I_4, respectively. It increased due to increase in number of total irrigation water applied in different treatments. Conversely, irrigation water decreased in S_{rf} (133.0 mm) and S_{pr} (105.8 mm) over S_{fb} (181.5 mm). Results clearly indicated that there was a significant reduction in irrigation water by 26.7 in S_{rf} and 41.7% in S_{pr}, when compared to S_{fb}. The interaction between irrigation and planting methods was also significant; largest depth (291.4 mm) was obtained in I_4 x S_{fb} combination (Table 2). The trend showed that the depth was more in every combination of irrigation level with S_{fb}, and decreased comparatively in combinations with S_{rf} and the smallest in S_{pr}.

Evapotranspiration increased with higher irrigation regimes due to more water supplies. The trend of interaction between irrigation and planting methods showed similar pattern as in depth of irrigation. Across irrigation regimes, estimated ET decreased by 13% in S_{rf} (288.3 mm) and 21% in S_{pr} (263.2 mm) over S_{fb} (331.2 mm). Both the calculated parameters i.e., crop WUE and irrigation WUE decreased with the increase in irrigation regimes (Tables 2 and 3). Ridge and furrow, paired-row technique saved substantial amount of irrigation water due to having furrow irrigation and consequently increased both crop WUE and IWUE while maintaining similar or more pod yield. Highest WUE of 7.03 kg ha^{-1} mm^{-1} was obtained in S_{pr}, which was 48% higher than the value obtained at S_{fb}; similarly IWUE was about 105% higher in S_{pr} than S_{fb}. In S_{rf} also, WUE and IWUE was 33 and 62% higher than S_{fb}. In previous studies with flat-bed method, reported ET ranged from 356 to 434 mm for summer groundnut in eastern India (Bandyopadhyay et al., 2005), consumptive water use of 795.8 mm with WUE of 4.76 kg ha^{-1} mm^{-1} in Gujarat, western India (Patel et al., 2008). Our results indicated higher WUE than the earlier reports. Thus, our findings demonstrated that substantial increase of WUE could be possible by paired-row method of planting.

3.7. Pod yield-crop evapotranspiration relationship

Regression-based water production functions have been developed. Three year pod yield (Y) and cumulative ET (X) data were used for developing Y-ET relationship for groundnut under three planting treatments (Fig. 5). All functions were best fitted in a linear pattern with quite high and significant coefficient of determination (R^2) at $p =$ 0.05. The intercepts varied among planting treatments; it was the highest with S_{pr} and the lowest in S_{fb}. The slope or the coefficients were found positive; those increased gradually from S_{fb} through S_{pr}. Kheira (2009) also found linear relationship between groundnut yields and seasonal cumulative ET.

These models would help interpret pod yield, ET and WUE of groundnut crop by marginal analysis of water production functions. As the functions were found linear, the changing trend of WUE with ET was directly affected by the intercept. As the intercepts were much higher than zero, WUE decreased with increasing ET in every planting method. From these relationships, it can be quantified that the crop will

Table 3

Effects of irrigation regimes and planting methods on number of pods, haulm yield, crop water use efficiency (WUE) and irrigation water use efficiency (IWUE).

Irrigation and planting methods	Number of pods per plant	Haulm yield (t ha^{-1})	Crop WUE (kg ha^{-1} mm^{-1})	Irrigation WUE (kg ha^{-1} mm^{-1})
Irrigation regimes				
I_1: one irrigation	10.5c	2.67b	6.37a	25.10a
I_2: two irrigation	11.4b	3.37a	6.19a	15.56b
I_3: three irrigation	12.2a	3.70a	6.13a	12.59b
I_4: four irrigation	12.6a	3.86a	5.42a	9.39b
Planting methods				
S_{fb}: flat-bed method at 30 x 10 cm spacing	10.9c	2.96b	4.75c	10.06c
S_{rf}: ridge and furrow planting at 30 x 10 cm spacing	12.5b	3.59a	6.30b	16.30b
S_{pr}: paired-row planting at 45 x 15 cm spacing	13.1a	3.65a	7.03a	20.63a

Means in the same column with the same letters are not significantly different by Duncan's multiple range test (DMRT) (at $p =$ 0.05).

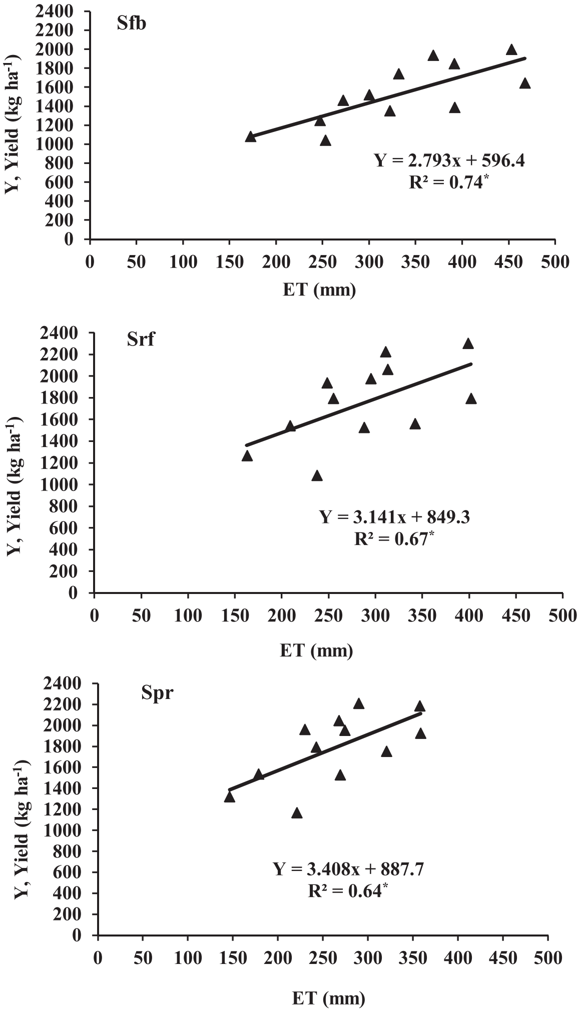


Fig. 5. Evapotranspiration (ET)-pod yield (Y) relationship of groundnut as influenced by three planting methods: S_{fb}, flat-bed method at 30 x 10 cm spacing; S_{rf}, ridge and furrow planting at 30 x 10 cm spacing; S_{pr}, paired-row planting at 45 x 15 cm spacing; R^2, coefficient of determination, *significant at $p = 0.05$.

achieve maximum pod yield of 1902, 2112 and 2109 kg ha^{-1} if the ET requirement (ET_m) of 467, 402 and 359 mm is met under S_{fb}, S_{rf} and S_{pr} treatments, respectively; WUE_m were the same as the slopes i.e., 2.79, 3.14 and 3.41 in corresponding planting methods (Table 4). It implied that the change in pod yield with respect to change in cumulative ET remained constant in any of the three planting methods. It gave a warranty that obtained pod yields would match planting methods. The ratio of relative yield decrease to relative evapotranspiration deficit was the crop yield response factor (K_y). The E_{wp} values were found very close to K_y. It indicated that cumulative crop ET was near to ET_m. The K_y values obtained in our study were very close to the value of 0.70 as was standardized and published in the milestone publication of FAO Irrigation and Drainage Paper No. 33 by Doorenbos and Kassam (1979). For every planting method, K_y was less than 1, which means groundnut crop was tolerant to water deficit and recovered partially from water stress according to yield response factor guidelines. Moreover, the crop exhibited less than proportional reductions in pod yield with reduced irrigation (Steduto et al., 2012). Our results are in conformity with findings of Reddy and Reddy (1993) who reported that, for relative seasonal ET of 0.76 to 0.84, groundnut yield varied from 0.74 to 0.86; whereas by using soil water balance equation to estimate crop ET, Kheira (2009), reported an average K_y of 2.9 for groundnut, which was higher than the 0.7, being maximum seasonal ET 488 mm in his experiment with full irrigation treatment.

The E_{wp} value is analytic to characteristic changes of yield and WUE with varying ET. This parameter indicates the scope of any possible improvement on the pod yield or WUE due to imposed treatment. As per the criterion, yield will increase with increasing ET if $E_{wp} > 0$, conversely yield will decrease if $E_{wp} < 0$; if E_{wp} is equal to 1 both yield and WUE will reach to the maximum level. In this study, the E_{wp} values were greater than zero and less than 1 in every planting methods; it reveals that still there is a scope to increase pod yield of groundnut and it's WUE. The scope was found greater with paired-row planting method where E_{wp} was 0.76, compared with flat-bed (E_{wp} 0.87) and ridge and furrow method (E_{wp} 0.86); the later values were more close to one. This study is similar to and in agreement with our previous findings on water-yield relationship of wheat for central Indian condition (Mandal et al., 2005). Therefore marginal analysis and K_y, which are based on Y-ET relationships, would imply strategic irrigation to meet the ET requirement to increase pod yield and WUE of this crop, more so under limited water availability in a hot and sub-humid condition. Earlier, Jain et al. (1997) also developed water stress response function for groundnut and suggested for use of the same for water saving.

3.8. Soil organic carbon stock, kernel & haulm-nitrogen uptake

Soil organic carbon stock in 0–15 and 15–30 cm soil depth did not vary significantly ($p = 0.05$) due to imposition of irrigation and planting treatments (Table 5), whereas uptake of nitrogen (N) varied significantly ($p = 0.05$). However, it reveals that the SOC stock was more in upper soil layer (0–15 cm) than the lower (15–30 cm). With regard to total SOC stock, it ranged from 20.53 to 21.04 in irrigation treatments and 20.89 to 21.86 Mg ha^{-1} in planting methods. In our earlier studies, similar results on SOC stock were reported for rice-groundnut cropping from the same location (Mandal et al., 2012). It has indicated that the soil environment, in terms of maintenance of soil organic carbon status, has not been deteriorated due to groundnut cropping over three years.

Nitrogen content in kernels and above-ground biomass i.e., haulms of groundnut did not vary significantly ($p = 0.05$) due to different irrigation and planting treatments. Kernel-N content ranged from 2.79 to 3.51% and haulm-N from 1.71 to 2.52%. However, N-uptake by kernel and haulms varied significantly at $p = 0.05$ (Table 5). The kernel-N uptake was significantly the highest in I_4, whereas haulm-N uptake was the highest and similar in I_3 and I_4. With regard to planting treatments, both kernel-N and haulm-N was significantly the highest in S_{pr} at $p =$

Table 4
Crop evapotranspiration production functions, marginal WUE, elasticity of water production and crop response factor of groundnut as influenced by three planting methods.

Planting methods	Linear evapotranspiration production functions	WUE_m (kg ha^{-1} mm^{-1})	E_{wp}	K_y
S_{fb}	$Y = 596.4 + 2.793\,ET$	2.79	0.87 (0.83-0.91)	0.82
S_{rf}	$Y = 849.3 + 3.141\,ET$	3.14	0.86 (0.80-0.89)	0.84
S_{pr}	$Y = 887.7 + 3.408\,ET$	3.41	0.76 (0.74-0.79)	0.73

S_{fb}, flat-bed method at 30 x 10 cm spacing; S_{rf}, ridge and furrow planting at 30 x 10 cm spacing; S_{pr}, paired-row planting at 45 x 15 cm spacing; R^2, coefficient of determination; *significant at $p < 0.05$, Y, pod yield; ET, evapotranspiration; WUE_m, marginal water use efficiency; E_{wp}, elasticity of water production function; K_y, crop yield response factor.

Table 5
Effect of irrigation regimes and planting methods on soil organic carbon stock and N-uptake by groundnut kernel and haulm after completion of three year-cropping.

Irrigation and planting methods	Soil organic carbon stock (Mg ha^{-1})		Kernel-N uptake (kg ha^{-1})	Haulm-N uptake (kg ha^{-1})
	0–15 cm	15–30 cm		
Irrigation regimes				
I$_1$: one irrigation	12.54a	8.50a	24.70d	46.21c
I$_2$: two irrigation	12.36a	8.17a	32.43c	58.45b
I$_3$: three irrigation	12.12a	8.52a	35.01b	69.37a
I$_4$: four irrigation	13.04a	7.88a	39.67a	71.31a
Planting methods				
S$_{fb}$: flat-bed method at 30 x 10 cm spacing	12.30a	9.56a	29.70c	56.97b
S$_{rf}$: ridge-furrow planting at 30 x 10 cm spacing	12.94a	8.46a	32.87b	59.20b
S$_{pr}$ paired-row planting at 45 x 15 cm spacing	12.80a	8.09a	36.28a	67.67a

Means in the same column with the same letters are not significantly different by Duncan's multiple range test (DMRT) (at $p =$ 0.05).

0.05. The underlying reason for variation was the kernel and haulm yield level. As the yield was higher in four irrigation and in paired-row method, even with similar N-content, N-uptake was higher accordingly. Our results and reasons are in conformity with an earlier report (Rami Reddy et al., 1982) that a combination of higher irrigation regime and soil N application had higher uptake due to optimum available moisture and nitrogen to groundnut crop.

4. Conclusions

In this field study, the effect of improved planting methods of groundnut viz. ridge and furrow at 30 x 10 cm spacing and paired-row at 45 x 15 cm spacing was evaluated and compared with traditional flat-bed method with 30 x 10 cm spacing at different irrigation regimes. Improved methods were furrow-irrigated. There was no such technique available to the growers earlier for increasing yield, saving of irrigation water and increasing WUE of groundnut. Our results clearly demonstrated that the improved methods viz. ridge and furrow and paired-row would increase yield by 13 and 17%, and irrigation water-saving by 27 and 42%, respectively, when compared with flat-bed method. We achieved enhanced WUE in improved planting methods. The variation in yield of this crops has been explained in terms of changes in root dry weight, intercepted PAR, chlorophyll fluorescence efficiency, leaf photosynthesis as well as mitigation of high day-time soil temperature through irrigation. Thus, our research findings would help growers to adopt improved planting method and saving of irrigation water.

The marginal analyses on the developed Y-ET regression relationships have revealed the dynamic relationship of Y, ET and WUE for this crop. The computed parameters viz. WUE$_m$, E$_{wp}$ and K$_y$ would help in making interpretation of yield variation in different water regimes. We have obtained K$_y$ values those are less than one, which implied that groundnut crop showed signs of reduction in pod yield with lower irrigation regimes. The E$_{wp}$ values are greater than zero and less than one, which reveals that there exists further scope of increasing pod yield and WUE of the crop. The results of our study would help in predicting yield of groundnut with respect to availability of water. The yield and WUE of the crop with respect to different irrigation regimes could be used as guidelines for irrigation formulation of strategies. The functional relationships would help substantially for management decisions on irrigation application. It has also indicated what would be the achievable pod yield with respect to the maximum ET. The improved method has been demonstrated to a large number of farmers through lecture, video-film etc. Moreover, farmers in the canal irrigated areas would get benefit out of this improved planting method. There is a huge scope of up-scaling of this technology for increasing yield and WUE of this crop. The study could be an important reference for water-saving of groundnut production in a hot sub-humid climate.

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