IRRIGATION MANAGEMENT IN DRIP IRRIGATED CASTOR (*Ricinus communis* L.)

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CERTIFICATE

Mr. B.RAVI KUMAR has satisfactorily prosecuted the course of research and that the thesis entitled **"IRRIGATION MANAGEMENT IN DRIP IRRIGATED CASTOR"** submitted is the result of original research work and is of sufficiently high standard to warrant its presentation to the examination. I also certify that the thesis or part thereof has not been previously submitted by him for a degree of any university.

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CERTIFICATE

This is to certify that the thesis **entitled "IRRIGATION MANAGEMENT IN DRIP IRRIGATED CASTOR"** submitted in partial fulfilment of the requirements for the degree of **MASTER OF SCIENCE IN AGRICULTURE** of the **Acharya N. G. Ranga Agricultural University, Hyderabad,** is a record of the bonafied research work carried out by **B.RAVI KUMAR** under my guidance and supervision. The subject of the thesis has been approved by the Student's Advisory Committee.

No part of the thesis has been submitted for any other degree or diploma. The published part has been fully acknowledged. All assistance and help received during the course of the investigation has been duly acknowledged by the author of the thesis.

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Ravi Kumar

DECLARATION

I, **B. RAVI KUMAR** hereby declare that the thesis entitled **"IRRIGATION MANAGEMENT IN DRIP IRRIGATED CASTOR"** submitted to the **Acharya N. G. Ranga Agricultural University** for the degree of **MASTER OF SCIENCE IN AGRICULTURE** is the result of original research work done by me. I also declare that any material contained in the thesis has not been published earlier in any manner.

Date: **(B.RAVI KUMAR)**

Place: Hyderabad

LIST OF ABBREVIATIONS

%	:	per cent
γ	:	Psychrometric constant (KPa/^{O}C)
Δ	:	Slope vapour pressure curve (KPa/^{O}C)
@	:	at the rate of
a	:	Y-axis intercept
ASM	:	Available soil moisture
b	:	Regression coefficient
B	:	Boron
BEP	:	Break Even Point
CD	:	Critical difference
CGR	:	Crop Growth Rate
Cl^-	:	Chloride
cm	:	Centimetre
cm^2	:	Centimetre square
CO_3	:	Carbonates
CPE	:	Cumulative pan evaporation
Ca	:	Calcium
DAS	:	Days after sowing
DOR	:	Directorate of Oil Seeds Research
dSm^{-1}	:	desi simen per metre
d	:	Irrigation Water depth in m
e_a	:	Actual vapour pressure(KPa)
e_s	:	Saturation vapour pressure (KPa)
EC_w	:	electrical conductivity of water
et al.	:	and others
ETa	:	Actual evaportranspiration
ETc	:	Crop evapotranspiration
ET_o	:	Reference crop evapotranspiration
F – test	:	fisher's test
FC	:	Field capacity
Fig.	:	Figure
g	:	Gram
g/cm^3	:	grams per cubic centimeter
g/g/day	:	Grams per gram per day
$g/m^2/day$	:	grams per square meter per day
ha^{-1}	:	per hectare
HCO_3	:	Bicarbonates

INCID	:	Indian National Committee on Irrigation and Drainage
IW	:	Irrigation water
Kc	:	Crop coefficient
km hr^{-1}	:	kilometer per hour
K	:	Potassium
LAD	:	Leaf area duration
LAI	:	leaf area index
LA	:	Leaf Area (m^2)
m	:	Metre
m^2	:	square metre(s)
meq l^{-1}	:	Milliequelent per litre
mm	:	millimeter
MPa	:	Mega pascal (s)
Mg	:	Magnesium
N	:	Nitrogen
NAR	:	Net assimilation rate
NPV	:	Net Present Value
NS	:	Non significant
Na	:	Sodium
^oC	:	Degree celcius
OC	:	Organic Carbon
P_2O_5	:	Phosphorous
PCH-III	:	Palem castor hybrid (111)
PET	:	Potential evapotranspiration
pH	:	Pussancea Hydrogen (potential hydrogen)
Q	:	Emitter flow rate (mm/hr)
RBD	:	Randomized block design
RGR	:	Relative growth rate
R_s	:	Rupees
RSC	:	Residual Sodium carbonate
SAR	:	Sodium Adsorption ratio
S_l	:	Spacing between laterals (m)
S_e	:	Spacing between emitters (m)
USWB	:	United State Weather Bureau
WUE	:	Water use efficiency
W	:	Water in liters per irrigation
Y	:	Crop yield (Kg/ha)
Y max	:	Maximum yield

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ABSTRACT

A field experiment was conducted on a sandy clay soil at Water Technology Centre Unit, College farm, College of Agriculture ,Rajendranagar, Hyderabad during *rabi* season, 2009–10 to investigate the " **Irrigation Management in Drip Irrigated Castor**".

The treatments consisted of seven irrigation treatments based on surface drip method of irrigation and irrigation scheduling levels in the form of pan evaporation replenishment. The evaporation replenishment factor *viz.,* 0.4, 0.6 and 0.8 was either kept constant throughout the crop life or was combinations of the above at vegetative, flowering and capsule development stages. Besides seven drip irrigated treatments a surface check basin system irrigated at an IW/CPE ratio of 0.8 with an irrigation water depth of 50 mm was included. The experiment was laid out in a randomized block design with three replications.

Higher castor bean yields were registered when irrigations were scheduled by drip at 0.6Epan up to flowering and 0.8Epan later on (I_6). However it was on par with 0.6Epan throughout the crop life (I_2) and 0.8Epan throughout the crop life (I_3) and was significantly superior over rest of the treatments. Similar trends were observed in growth and yield attributing characters. Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life was statistically inferior in comparison to drip irrigation treatments except 0.4Epan throughout the crop life (I_1). Drip irrigation treatments recorded highest water productivity ranging from 0.777 to 1.137 kg m^{-3} (I_1 to I_7) in comparison to conventional check basin irrigated crop (0.571 kg m^{-3}). Maintaining higher moisture regimes in drip irrigated treatments (I_2, I_3 and I_6) had resulted in higher oil content and oil yield over rest of the treatments. Lowest oil content and oil yield was registered in conventionally irrigated surface irrigation treatment (I_8).

The seasonal ET_c requirement of castor varied from 239.3 mm to 428.08 mm among different drip irrigated treatments. It was highest in 0.8Epan throughout the crop life (I_3) followed by 0.6Epan up to flowering and 0.8Epan later on (I_6) as compared to other irrigation treatments. The seasonal ET_c under surface check basin irrigated crop was the highest and amounted to 445.87 mm. The average daily ET_c rate varied from 1.58 mm to 2.87 mm under different treatments. It was highest in surface check basin irrigated crop when compared to rest of the treatments.

The quadratic water production function indicated that the predicted maximum castor bean yield (Y_{max}) of 3611 kg ha^{-1} was obtained at 383 mm of seasonal water (ET_c) requirement. The water production function did not emerge through the origin and the value of regression constant (a) was negative, indicating that some minimum amount of irrigation water i.e., crop ET_c (182.5 mm) was required to be expended to realize the economic yield (beans) in castor crop.

The economic analysis (farm income, NPV, net cash flow, BEP for price and water, and payback period) suggested that the drip irrigation in castor was economically viable even without a government subsidy.

It was concluded that castor grown in winter (*rabi*) season under Rajendranagar conditions irrigated with drip system at 0.6Epan up to flowering and 0.8Epan at later stages with an optimal seasonal water requirement of 383 mm gave maximum bean yield (3611 kg ha^{-1}) and was most remunerative under the prevailing prices of output and input.

CHAPTER I

INTRODUCTION

Castor (*Ricinus communis* L.), a tropical plant belonging to the Euphorbiaceae family, is cultivated around the world for its non-edible oil seed. India occupies an important place in the world's castor production, accounting for about 57.7% of the global castor area (1.52 million ha) and 71% (1.58 million tons) of the total castor production (FAO, 2010). In India three states *viz.,* Gujarat, Rajasthan and Andhra Pradesh account for 96% of the total castor seed production (0.88 million tons) in the country. Because of its unlimited industrial applications, castor oil enjoys tremendous demand worldwide, estimated at about 0.25 million tons per annum. The major importers of castor oil in the world market are European Union, the USA and Japan. The world demand for castor oil is estimated to be growing at the rate of about 3 to 5% per annum. India is a biggest exporter of castor oil holding about 70% share of world's castor oil & its derivatives requirement in the international trade. Thus the crop is a major Forex earner for the country, more than 300 million US$ annually (FAO, 2010).

Traditionally in India the castor is raised under *rainfed* conditions characterized by marginal soils, low in rainfall with erratic distribution, delayed sowings, little or no fertilizer application and use of poor quality seed resulting in low productivity. Raising castor during winter (*rabi*) season with assured irrigation using high yielding varieties and hybrids is a new dimension in castor production with promise that provides greater stability and higher productivity.

Depending on the location, castor water requirement may vary from 453 mm to 1178 mm ha^{-1} in the growing season (Patel *et.al.,* 1998; Wackchaure *et. al.,* 1999). The competition for water among various sectors of use is increasing and will undoubtedly continue to increase as a result of rising domestic demands owing to expanding population, industrial development and environmental restrictions. Therefore, farmers are switching over to alternative modern irrigation systems which will increase the efficiencies of irrigation system and help them realize increased crop yields per drop of water used.

Drip Irrigation is the frequent application of small quantities of water on (surface drip) or below the soil surface (subsurface drip) as drops by emitters placed along a water delivery integral dripperline (Bucks *et. al.,* 1982). It was found to be an efficient agronomic management tool that allows precise control of water over the root zone environment of crop (Bresler, 1977). This control often results in consistently high yields (Firake *et. al.,* 1998). In addition, better water and fertilizer management by drip through fertigation can help reduce fertilizer inputs, water needs, and runoff (Bucks et. al., 1982; Bar Yosuf, 1999). But till date no systematic work was attempted on drip irrigated castor grown in winter (*rabi*) season in India including Andhra Pradesh.

Due to the economic importance of castor and the need to increase irrigation efficiency, drip irrigation is being investigated as a possible alternative in terms of growth and yield response to water, water use and crop coefficients at various crop growth sub-periods, economic viability etc., when grown under water constrained situations during *rabi* season. For field application farmers need information on when to irrigate (optimum time) and how much to irrigate (depth of water) at various crop developmental phases and likely response of castor bean yields to drip irrigation scheduling to maximize water productivity and returns. On the other hand, irrigation scheme planners require information on castor water use and crop coefficients to estimate the likely demand for water and to carry out economic analyses of proposed new irrigation schemes.

Moreover since drip is a capital-intensive technology, the huge initial investment needed for installing the drip system remains the main deterrent to its wide spread adoption. The extent to which this discouragement effect is real and the extent to which this effect can be counterbalanced by government subsidy are important policy issues requiring empirical answers. Past studies (INCID, 1994; Sivanappan, 1994) on the subject for various drip irrigated crops have either conducted benefit cost analysis without a proper methodology or relied heavily on the experience of one or a few farmers adopting drip irrigation. Therefore, there is need to evaluate empirically the economic viability of drip irrigation impact on profitability of castor within a framework of systematic protocol.

Keeping the above in view, the present field experiment entitled **"Irrigation management in drip irrigated castor"** was conducted at Water Technology Centre Unit, College Farm, College of Agriculture, Rajendranagar, Hyderabad, during rabi season 2009 – 2010 with the following objectives:

1. To study the effect of variable water supply levels on growth, yield, oil content and water use efficiency of Palem Castor Hybrid – 111 (PCH – 111) under drip irrigation

2. To optimize the crop water requirement for castor under Rajendranagar agro-climatic conditions
3. To evaluate the economic viability of drip irrigation for hybrid castor

CHAPTER II

REVIEW OF LITERATURE

The research work done on irrigation management in castor and its effect on growth characters, yield attributes, bean yield, crop evapotranspiration and drip irrigation were briefly reviewed in this chapter under appropriate heads.

2.1 EFFECT OF IRRIGATION ON GROWTH

2.1.1 Plant height

Water deficits at vegetative period of castor reduces expansive growth of stems and results in reduced plant height (Bennett and Hammond, 1983). Sudhakar and Rao (1998) reported that the plant height of castor variety Aruna declined with decrease in IW/CPE ratio from 0.8 (110.3 cm) to 0.6 (93.7 cm), 0.4 (78.5cm) and to 0.2 (68.4cm) on sandy loam soils of Rajendranagar, Hyderabad. Likewise plant height was significantly higher with irrigations scheduled at 20% depletion of available soil moisture (DASM) in comparison to either 40% DASM and 60% DASM at Sardar Krishna Nagar, Gujarat (DOR, 1994). Whereas, at Junagadh taller castor plants were recorded when irrigations were scheduled at 40% DASM as compared to 20% DASM (DOR, 1995).

Sudha Rani (2001) observed 7% increase in plant height with irrigations at 0.75 IW/CPE ratio over rainfed castor during *kharif* season at ICRISAT, Hyderabad. Similarly Nagabhushanum and Raghavaiah (2005) reported that the castor crop in 0.8 IW/CPE irrigation schedule registered 32.7, 25.5 and 24.5 % more plant height than at 0.4, 0.6 IW/CPE ratio and irrigations scheduled at 15 days interval, respectively. Castor grown under field conditions with irrigations scheduled at 0.4, 0.6 and 0.8 IW/CPE ratio revealed that the plant height significantly higher throughout the crop growing season in treatment 0.8 IW/CPE than in 0.4 and 0.6 IW/CPE ratio (Kiran, 2003). However, several researchers on the contrary reported that the plant height was not significantly influenced by varied IW/CPE ratios at Raichur (DOR, !989), Sardar Krushi Nagar (DOR, 1995) and Hyderabad (DOR, 2001).

2.1.2 Leaf Area Index (LAI)

Water deficits have been shown to inhibit leaf expansion through its reduction of relative leaf turgidity (Slatyer, 1967). Development of adequate leaf area is important in castor and has been shown to be closely related to final bean yield (Sudhakar and Rao, 1998). Water stress reduces expansive growth of leaves and results in lower LAI (Bennett and Hammond, 1983). Leaf area expansion was dependent on leaf turgor potential (Boyer, 1970). There was a significant improvement in LAI with increase in IW/CPE ratio from 0.2 (stressed) to 0.8 (unstressed) with the severely stressed crop showing 30% reduction in LAI as compared to unstressed crop (LAI of 4.5) on sandy loams soils of Rajendranagar, Hyderabad (Sudhakar and Rao, 1998). Likewise irrigating the crop at 0.75 IW/CPE ratio recorded 5% higher LAI as compared to rainfed castor at 45 days after sowing during *kharif* season (Sudha Rani, 2001). On the other hand the LAI between 0.6 and 0.8 IW/CPE ratio was comparable and significantly superior to 0.4 IW/CPE ratio (DOR, 2001). Whereas, maintenance of higher soil water regime through adequate water supply at 0.8 IW/CPE ratio favoured optimum LAI (Nagabhushanam, 2002; Kiran, 2003).

2.1.3 Dry matter production

Dry matter accumulation in castor is a result of leaf and stem growth during vegetative phase and a combination of spike, capsules and bean growth with concurrent shifts in leaf and stem mass during reproductive phase.

Maintenance of favouarable soil water balance adopting 0.8 IW/CPE ratio irrigation schedule aided the castor plant in accumulating more dry matter (36.4 g plant $^{-1}$) as compared to 0.2 (26.6 g plant^{-1}), 0.4 (30 g plant $^{-1}$), and 0.6 (32.9 plant^{-1}) IW/CPE ratio (Sudhakar and Rao, 1998).

Castor grown under irrigated conditions at 0.75 IW/CPE ratio produced 6% and 11% higher over rainfed crop at 5 and 105 days after sowing, respectively (Sudha Rani, 2001). However, Rao and Venkaterwarulu (1988) observed that the dry matter production between rainfed crop and irrigated crop did not differ significantly. But Nagabhushanam (2002) on the other hand reported that dry matter production with irrigations scheduled at 0.8 IW/CPE ratio was higher when compared to 0.4 and 0.6 IW/CPE ratio and irrigations scheduled at 15 days interval during rabi season. Similar observations were made by Kiran (2003).

2.2 EFFECT OF IRRIGATION ON YIELD ATTRIBUTES AND YIELD

2.2.1 Length of Primary spike

The length of primary spike was maximum when irrigations were scheduled at 60% available soil moisture (ASM) and this was significantly superior over 40% ASM or 80% ASM (DOR, 1995). The length of the main spike increased with increase in IW/CPE ratio from 0.4 to 0.8 (DOR, 2001). Sudha Rani (2001) reported that irrigating the castor at 0.75 IW/CPE ratio increased the spike length by 7% over rainfed crop during *kharif* at ICRISAT, Hyderabad. On the other hand some researchers found that the length of the primary spike was not significantly influenced by different moisture regimes (DOR, 1996; Nagabhushanam, 2002).

2.2.2 Number of spikes per plant

Number of spikes per plant were more when irrigations were scheduled at 1.0 IW/CPE ratio when compared to 0.4 IW/CPE ratio (DOR, 1991). At Junagadh, number of spikes per plant increased with increase in water regime from 40% to 80% ASM (DOR, 1996). Likewise Firake *et al.* (1998) found that using drip irrigation for daily replenishment of water equivalent to 75% of USWB Class A pan evaporation resulted in significantly higher number of spikes per plant in comparison to 25%, 50% and 100% of daily replenishment of pan evaporation.

Number of spikes per plant was higher with 0.8 IW/CPE ratio and it was on par with the crop wherein irrigations were scheduled at 15-days interval and both were significantly superior over 0.4 and 0.6 IW/CPE ratio (Nagabhushanam, 2002). Similar results were reported by Kiran (2003) and Nagabhushanam and Raghavaiah (2005).

On the contrary, Vijay Kumar and Shiva Shankar (1992) observed non-significant difference in number of spikes per plant between rainfed and irrigated castor at 44 and 85 days after sowing on sandy loam soils of Palem during *kharif* season. Similarly, number of spikes per plant was statistically on par irrespective of irrigation regime viz., 0.75, 1.0 and 1.25 IW/CPE ratio at Sardar Krishna Nagar, Gujarat (DOR, 1994).

2.2.3 Number of capsules per plant

At Junagadh, number of capsules per spike significantly increased with increase in IW/CPE ratio from 0.75 to 1.25 (DOR, 1995). Likewise Sudhakar and Rao (1998) reported that scheduling irrigation at 0.8 IW/CPE ratio produced maximum number of capsules per plant over 0.2, 0.4 and 0.6 IW/CPE ratios. Application of water equivalent to 75% of daily evaporation from USWB Class A pan by drip system produced significantly higher number of capsules per spike over 25%, 50% and 100% replenishment (Firake et al., 1998).

Sudha Rani (2001) found that the number of capsules per plant were significantly higher at 0.75 IW/CPE ratio over rainfed castor during *kharif* season. Capsules per primary spike recorded in 0.8 IW/CPE ratio and irrigations at 15-days interval were on par and both the moisture regimes were significantly superior over 0.4 and 0.6 IW/CPE ratio (Nagabhushanam, 2002). Similar observations were made by Kiran (2003).

On the contrary to above findings, Vijay Kumar and Shiva Shankar (1992) reported that the number of capsules per plant did not vary significantly between castor crop raised under rainfed and under assured irrigation treatment. Number of capsules per plant were statistically comparable among differing irrigation schedules viz., 0.4, 0.6 0.8 and 1.0 IW/CPE ratio at Sardar Krishna Nagar, Gujarat (DOR, 1994). Irrigations scheduled at 20%, 40% and 60% DASM were not significant on number of capsules per main spike (DOR, 1994).

2.2.4 Test (100-seed) weight

The 100-seed weight was significantly higher when irrigations were scheduled at 1.0 IW/CPE ratio as compared to 0.4 IW/CPE ratio (DOR, 1991). Irrigations scheduled at 1.25 IW/CPE ratio had significantly higher 100-seed weight in comparison to either 0.75 or 1.0 IW/CPE ratio (DOR, 1994). At Junagadh, significantly higher 100-seed weight was registered when irrigations were scheduled at 80% ASM as compared to 40% ASM (DOR, 1995). Sudhakar and Rao (1998) and reported that the test weight increased linearly with increase in IW/CPE ratio from 0.2 to 0.8. Similar results were obtained by Kiran (2003). On the other hand the 100-seed weight between 0.6 and 0.8 IW/CPE ratio was statistically comparable and significantly superior over 0.4 IW/CPE ratio (DOR, 2001). Nagabhushanam (2002) stated that the 100-seed weight was higher with 0.8 IW/CPE ratio, which was on par with irrigations scheduled at 15-days interval.

Findings of Vijay Kumar and Shiva Shankar (1992), DOR (1994) and Sudha Rani (2001) suggested that irrigation regimes with varying IW/CPE ratios were not able to significantly influence the 100-seed weight of castor.

2.2.5 Seeds per capsule

Number of seeds per capsule increased with increase in IW/CPE ratio and significantly higher value (2.88) was recorded when irrigations were scheduled at 0.8 IW/CPE ratio. However, among the lower IW/CPE ratios the difference in the number od seeds per capsule between 0.6 and 0.4 IW/CPE ratio and that between 0.4 and 0.2 IW/CPE ratio were not significant.

2.2.6 Bean Yield

The duration and intensity of water deficits is dependent on environmental conditions, water holding capacity of the soil and crop growth stage during which water deficits occur (Loren *et al*., 1987). Thus castor bean yield was markedly decreased when plants were subjected to moisture stress from flowering to seed development stage (Kudinova, 1973). Joshi *et a*l. (1980) reported that the seed yield of castor hybrid (GAUCH 1) decreased linearly with decreasing moisture regime from 75% (2.8 tons ha^{-1}), to 60% (2.64 tons ha^{-1}), and to 25% ASM (2.37 t ha^{-1}), and finally no irrigation (1.8 t ha^{-1}) on sandy loam soils. Higher bean yield of 1836 kg ha^{-1} was obtained when irrigations were supplemented from 55 to 155 days after sowing compared to rainfed crop at Raichur (DOR, 1986). On the other hand at Dantewada and Sardar Krishna Nagar, Gujarat irrigations were required until 195 days after sowing to achieve a higher bean yield of 1558 to 2268 kg ha^{-1} (DOR, 1986).

Supplemental irrigation of castor contributed to 57% higher bean yield (2130 kg ha^{-1}) over rainfed castor (Wali *et al*., 1991). Similarly Sudha Rani (2001) reported 32.7% increase in bean yield with supplemental irrigation (1500 Kg ha^{-1}) over rainfed crop (1130 Kg ha^{-1}) in *kharif* season.

Three irrigations of 80 mm irrigation water depth applied each at 75, 95 and 115 days after sowing to castor produced significantly higher bean yield as compared to three irrigations of 80 mm irrigation water depth applied each at 55, 75 and 95 days after sowing indicating that irrigation at 115 days after sowing was critical for castor bean yield at Sumerpur, Rajasthan (Singh and Singh, 1992). On the other hand the work of Vijay Kumar and Shiva Shankar (1992) at Palem, Andhra Pradesh on sandy loam soils revealed that two irrigations of 50 mm depth each at 44 and 85 days after sowing resulted in 18.9% higher bean yield over rainfed crop.

At Sardar Krishna Nagar, irrigating castor at 0.8 IW/CPE ratio gave significantly higher castor bean yield over 0.4 and 0.6 IW/CPE ratio (DOR, 1994). On the same lines Nagabhushnam, (2002) observed significantly higher bean yield with 0.8 IW/CPE ratio as compared to scheduling of irrigation at 15 days interval and at IW/CPE ratio of 0.4 and 0.6. Kiran (2003) also reported that the bean yield obtained at 0.8 IW/CPE ratio was higher than irrigation scheduled 0.4 and 0.6 IW/CPE ratio at Rajendra Nagar, Hyderabad. Whereas, field trials conducted at Bhavanisagar revealed that irrigating TMV 5 castor at 0.6 IW/CPE was better than irrigating at 0.4 and 0.8 IW/CPE (Selvaraj *et al.,* 1992). On the other hand, scheduling irrigation at a higher IW/CPE ratio of 1.0 to 1.25 was required under high evaporative demand conditions to achieve higher bean yield (DOR, 1994 and DOR, 1995).

In the field trials conducted at Osimo, Italy revealed that castor crop when supplied with water equivalent to 33%, 66% and 100% of replenishment of evaporation from USWB Class A Pan, maximum bean yield was obtained with the highest level of evaporation replenishment factor which was higher by 2:1 times than the un-irrigated control (Laureti and Marras, 1995).

Reddy et al. (1999) stated that the vegetative stage, formation of primary and secondary spike stages were most sensitive for moisture stress in reducing the seed yield and providing protective irrigation of 50 mm each during the above crop growth stages recorded 42% additional bean yield over the rainfed crop.

Patel *et. al.* (1998) reported that scheduling of irrigations at 0.2Epan (fraction of evaporation from USWB Class A Pan) through drip after cessation of monsoon i.e., from October onwards was better to realize full potential of castor under Gujarat conditions as compared to 0.4Epan, 0.6Epan, 0.8Epan and surface irrigation when the CPE reached to 80 mm. Further, it was observed that the crop under drip irrigation (0.2, 0.4, 0.6 and 0.8Epan) was superior to surface irrigation method.

Sudhukar and Rao (1998) observed a linear increase in bean yield of castor with increasing IW/CPE ratio from 0.2 to 0.8 during *rabi* season. Koutroubas et al. (2000) reported that bean yield of irrigated castor was significantly higher than un-irrigated control (rainfed) crop and concluded that under Northern Greece agro-climatic conditions irrigation of castor with water equivalent to 75% of evaporatranspiration was adequate to realize higher bean yield.

A 3-year field study at Sardar Krishinagar, Gujarat with castor hybrid GCH 4 on sandy loam soil revealed that irrigation scheduling at 0.8Epan through drip after cessation of monsoon starting from October increased the bean yield by 23% to 36% in comparison to 0.4Epan, 0.6Epan and surface method of irrigation i.e., farmers practice at a fixed irrigation interval (Patel *et.al*. 2004). Similar observations were made by Patel et.al. (1998).

2.2.7 Harvest index

Each higher level of IW/CPE ratio significantly enhanced the harvest index over its lower level up to 0.8 (Sudhakar and Rao, 1998).

2.3 OIL CONTENT AND OIL YIELD

Most of the published reports pertaining to the effect of irrigation on oil content of castor were fairly consistent indicating that there was not significant effect of soil water availability on oil content. At Junagadh, oil content of castor was not significantly influenced by different moisture regimes of 40%, 60% and 80% ASM (available soil moisture) (DOR, 1995). Likewise oil content of GAUCH-1 castor hybrid was not affected by drip irrigation scheduled at 25%, 50%, 75% and 100% of evaporation from USWB Class A Pan. However, the oil productivity increased with increase in irrigation levels up to 75%Epan and thereafter decreased with further increase in irrigation level up to 100%Epan (Firake et al., 1998). Similar observations were made by Sudha Rani (2001), Nagabhushanam (2002) and Kiran (2003) on oil content in relation to varying irrigation regimes.

2.4 WATER USE STUDIES

2.4.1 Crop Evaporationspiration

The seasonal water use (ET_c) of castor crop is controlled by climatic, agronomic and varietal factors. A summary of the reported seasonal ET_c values of castor is given in Table 1.

The range of seasonal ET_c values reflects the variable agroclimatic conditions under which the crop is grown and varieties used.

Table 1. Summary of seasonal evapotranspiration requirements of castor

S.No.	Location	Soil type	Irrigation method	Seasonal ETc (mm)	Reference
1	Sumerpur, Rajasthan	Sandy loam	Surface check basin	560	Singh and Singh (1992)
2	Khandha, Gujarat	Sandy loam	Surface border strip	1178	Patel et.al. (1998)
			Surface drip	706 – 977	
3	Rahuri, Maharashtra	Sandy clay loam	Surface border strip	453	Wackchaure et.al. (1999)
			Surface drip	326 – 425	
4	Sardar Krushinagar, Gujarat	Sandy loam	Surface check basin	530	Patel et. al. (2004)
			Surface drip	200 – 300	
5	Rahuri, Maharashtra	Sandy loam	Surface border strip	635	Firake et. al. (1998)
			Surface drip	250 – 541	
6	Rajendranagar, Andhra Pradesh	Sandy loam	Surface check basin	466	Sudhakar & Rao (1998)

Sudhakar and Rao (1998) reported that the seasonal crop ET_c and ET_c rate increased with increase in IW/CPE ratio from 0.2 to 0.8. The seasonal ET_c and mean ET_c rate varied between 226 to466 mm and 1.46 to 3.01 mm day^{-1} in varying IW/CPE ratios. The peak ET_c rate was recorded at 120 days after sowing under 0.8 IW/CPE ratio.

Patel *et. al.* (1998) evaluated the feasibility of adoption of drip irrigation in castor under Gujarat conditions and reported that drip irrigation saved water to the tune of 31 to 73% under different treatments (replenishment of water equivalent to 0.2 to 0.8 evaporation from USWB Class A Pan) as compared to surface border irrigation (1178 mm). Likewise Patel *et. al.* (2004) observed 24.5 to 62.3% saving in water as compared to surface border irrigation at Sardar Krushinagar.

The work of Firake et. al. (1998) also revealed that drip irrigation in castor resulted in a water saving of 14.8 to 64.5% in comparison to surface border irrigation. Similar observations were made by Wackchaure et. al. (1999) and Anonymous (1995).

2.4.2 Water use efficiency

Water use efficiency defined as bean yield per hectare per unit depth of water consumed for crop evapotranspiration reflects whether irrigation schedule followed was successful in conserving water, but it does not define the point of greatest economic yield on total production curve. Highest water use efficiency will frequently occur on relatively dry treatments having less than highest economic bean yields. Thus several researchers (Patel et.al., 1998; Firake et.al., 1998; Sudhakar and Rao, 1998; Wackchaure et.al., 1999; Patel et.al., 2004; Seshasaila Sree and Reddy, 2005) reported that increased water supply (i.e., wet moisture regimes) tended to decrease the water use efficiency. Further all the studies on castor consistently revealed that adoption of drip irrigation at all the levels of evaporation replenishment was found to be significantly superior in terms of water use efficiency as compared to surface methods of irrigation in different agro-climatic zones.

Wackchaure et. al. (1999) studied the feasibility of drip irrigation in castor at Rahuri and observed that adoption of drip doubled the water use efficiency (5.86 kg ha-mm^{-1}) as compared to conventional surface method of irrigation. This they attributed to higher bean yield with minimum quantity of water used by the crop under drip irrigation.

2.4.3 Crop coefficient

The crop coefficient values increased with increase in IW/CPE ratio at all the crop growth sub-periods of castor (Sudhakar and Rao, 1998). They further reported that the K_c value was initially low, increased with crop age attained peak value of 1.2 between 110 – 120 days after sowing and gradually decreased towards maturity.

2.4.4 Water production function

The functional relationship between crop yield and water use is defined as crop water production function (Vaux and Pruitt, 1983). Knowledge of the relationship between crop production and water use would greatly contribute in water supply strategies at farm and project level, evaluation of alternative cropping patterns in relation to water availability and utilization, economic analysis and allocation of water among crops under limited water situations.

A linear relationship between bean yield and crop evapotranspiration was obtained by Sudhakar and Rao (1998) experimenting with castor in Hyderabad, India. Studies by other workers under Andhra Pradesh agro-climatic conditions lend support to this linear relationship for a wide range of crops viz., sesame (Rao et.al., 1991), sunflower (Chamundeshwari et. al., 1996; Kumar and Rao, 2000; Kumar and Rao, 2003), groundnut (Devi and Rao, 2001a), mustard (Manjula and Rao, 1998a and 1998b; Kumar et. al., 2002; Kumar et. al., 2004), soybean (Sudhakar and Rao, 1998), corn (Devi and Rao, 2001b) and turmeric (Rao et. al., 1992).

On the other hand evaluated various forms of crop water production functions viz., linear, quadratic, cubic and power and found that the best fit between bean yield and crop evapotranspiration was obtained with quadratic function under Rahuri agro-climatic conditions (Wackchaure et. al., 1999).

CHAPTER III

MATERIAL AND METHODS

In this chapter, the details of material used and methodologies adopted during the course of present investigation are elucidated under appropriate heads.

3.1 LOCATION OF THE EXPERIMENTAL SITE

The experiment entitled **"Irrigation management in drip irrigated castor"** was carried out at Water Technology Center, College Farm, College of Agriculture, Rajendranagar, Hyderabad (Latitude 17°19' N, Longitude 78°23' E and altitude of 542.6 m above mean sea level) during 2009-10 winter (*rabi*) season.

3.2 CHARACTERISTICS OF THE EXPERIMENTAL SITE

3.2.1 Physical and chemical properties of soil

The soil samples were drawn at random from 0 to 30 cm soil depth in the experimental field and were analysed for their physical and chemical properties by adopting standard procedures and the results are summarized in Table 2.

A perusal of the data in Table 2 revealed that the soil was sandy clay in texture, alkaline in reaction and non-saline. The fertility status of the experimental soil indicated that it is low in available nitrogen, medium in available phosphorus and high in available potassium. The infiltration rate was 2.3 mm hour^{-1} and hydraulic conductivity was 2.5 mm hour^{-1}.

Table 2. Physical and chemical properties of soil in the experimental field

S.No.	Particulars	Value	Method adopted
I	**Physical properties**		
1.	Mechanical analysis		
	a) Sand (%)	53.6	Bouyoucos hydrometer method (Piper, 1996)
	b) Silt (%)	12.0	
	c) Clay (%)	34.4	
	Textural class	Sandy clay	
2.	Infiltration rate (cm $hour^{-1}$)	2.30	Double ring infiltrometer
3.	Hydraulic conductivity (cm $hour^{-1}$)	2.50	Constant pressure head method
II	**Chemical properties**		
1.	pH (1:2.5 soil : water)	8.03	Glass electrode pH meter (Jackson, 1967)
2	Electrical conductivity (dS m^{-1}) (1: 2.5 soil:water)	0.20	Solubridge method (Jackson,1967)
3	Organic carbon (%)	0.38	Walkley and Black's modified method (Jackson, 1967)
4	Available nitrogen (kg ha^{-1})	220.1	Alkaline permanganate method (Subbaiah and Asija, 1956)
5	Available P_2O_5 (kg ha^{-1})	32.4	Olsen's method using Colorimeter (Olsen *et. al.*, 1954)
6	Available K_2O (kg ha^{-1})	327.0	Neutral ammonium acetate method using Flame Photometer (Jackson, 1967)

3.2.2. Moisture holding properties

The soil moisture retention capacity at –0.1MPa and –1.5 MPa and bulk density of the experimental soil were estimated for each 25 cm soil depth increments up to 100 cm of effective crop root zone depth by following standard procedures (Dastane *et al*., 1970) and the resultant data are presented in Table 3. The total plant available water i.e., the difference between –0.1MPa and –1.5 MPa in 0-100 cm soil depth amounted to 124.61 mm. During the course of investigation the groundwater table remained well below the 6 m soil depth (as evident from the nearby open well) and it was assumed that it did not contribute to the crop water use.

Table 3. Moisture retention characteristics of the experimental soil

Soil depth increment(cm)	Moisture percentage at		Bulk density (g cm^{-3})	Available soil moisture (mm)
	Field capacity (–0.1 MPa)	Permanent wilting point (–1.50 MPa)		
0 – 25	18.90	9.95	1.36	30.43
25 – 50	18.09	9.79	1.37	28.39
50 – 75	17.50	8.74	1.51	33.06
75 – 100	16.60	7.87	1.50	32.73
0 – 100	17.77	9.08	1.43	124.61

3.2.3 Irrigation water analysis

The source of water for irrigation of crop was from an open well (No. 6) of College Farm, Rajendranagr. To ascertain the water quality the water was analyzed

Table 4. Irrigation water quality analysis data

S.No.	Parameter	Value	Method
1	pH	7.6	Digital pH meter
2	EC_w (dSm^{-1})	2.20	Digital conductivity Bridge
3	CO_3 (mg L^{-1})	Nil	Titration with 0.02 NH_2SO_4 using Phenolphthalein indicator
4	HCO_3 (mg L^{-1})	378.2	Titration with 0.02 NH_2SO_4 using methyl orange indicator
5	Cl (mg L^{-1})	623.9	Titration with standard $AgNO_3$ using K_2CrO_4 as indicator
6	Na (mg L^{-1})	119.4	Flame Photo meter
7	K (mg L^{-1})	64.7	Flame Photo meter
8	Ca (mg L^{-1})	200.0	Titration with standard EDTA using EBT indicator and ammonium buffer
9	Mg (mg L^{-1})	116.2	Titration with standard EDTA using EBT indicator and ammonium buffer
10	B (mg L^{-1})	0.39	Spectrophotometer method
11	SAR	1.66	$SAR = \frac{Na^{+}}{\sqrt{Ca^{2+} + Mg^{2+}/2}}$
12	RSC (meq L^{-1})	Nil	$RSC = (CO_3^{--} + HCO_3^{-}) - (Ca^{++} + Mg^{++})$

using standard methods (Dhyan Singh *et. al.*, 2007) and the resultant data are presented in Table 4.

Perusal of the data indicated that the irrigation water was marginally alkaline (pH = 7.6) and comes under Class II (C_3S_1) suggesting that it is suitable for irrigation by following good management practices. Medium in chloride and low in sodium levels suggested that irrigation water is safe for irrigation of high, medium and low tolerant crops and do not pose any sodicity problem. Further the non-presence of RSC indicated no residual alkalinity problem as was also evident from low CO_3 and HCO_3 levels in comparison to Ca and Mg.

3.3 PERVIOUS CROP HISTROY

The cropping history of the experimental site for the preceding three years is summarized in Table 5.

Table 5. Previous Cropping history of the experimental field

S.No.	Year	Season	Cropping pattern
1	2007 – 08	*Kharif*	Cotton
		Rabi	Fallow
		Summer	Fallow
2	2008 – 09	*Kharif*	Cotton
		Rabi	Fallow
		Summer	Fallow
3	2009 – 10	*Kharif*	Fallow
		Rabi	Present investigation

3.4 WEATHER CONDITIONS DURING THE CROP GROWTH PERIOD

To characterize the weather conditions during the crop growing season, the meteorological parameters recorded from a B – Class meteorological observatory located at nearby experimental site were used and illustrated in Fig. 1.

The mean weekly maximum temperature during the castor crop period (07 – 11 – 2009 to 5 – 04 – 2010) ranged from 28.1°C to 36.2°C with an average of 31.12°C (Fig. 1). The mean weekly minimum temperature for the corresponding period varied between 11.9°C and 17.2°C with an average of 15.08°C. The mean temperature at germination & establishment, vegetative, flowering, capsule initiation, capsule development, and seed filling periods was 22.7°C, 20.8°C, 21.4°C, 23.7°C, 26.4°C and 27.5°C, respectively.

The mean relative humidity during the crop growing period varied from 47.6% to 67.35% with an average of 57.41% (Fig. 1). The atmospheric pressure at Rajendranagar has been estimated to be 1.016 bars.

The mean weekly bright sunshine hours per day varied from 7.9 to 9.1 hours with an average of 8.65 hours. Likewise the mean weekly wind velocity ranged from 2.0 to 3.6 km/hour with an average of 2.8 km/hour (Fig. 1).

The mean pan evaporation from USWB Class A pan evaporimeter during the cropping period ranged from 3.4 to 6.6 mm/day with an average of 4.55 mm/day. The seasonal pan evaporation was 679.8 mm. While the total precipitation received during the cropping period was only 46.8 mm. Thus it can be deduced that the moisture environment was insufficient for active plant growth

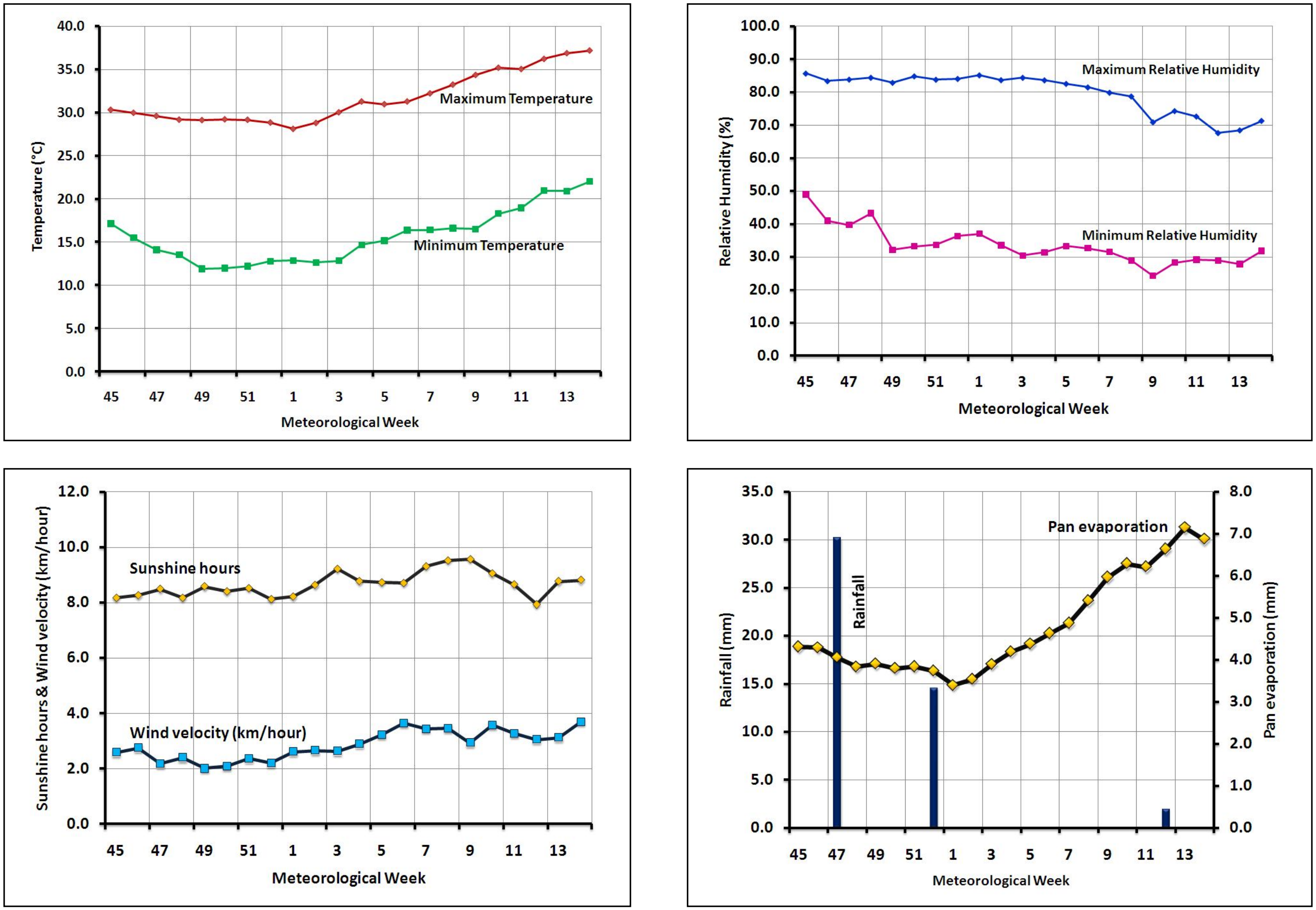

Fig. 1. Weekly meteorological data during crop growing period of castor

reflecting the need for the irrigation water application (Fig. 1). The moisture index (Thornthwaite and Mather, 1955) revealed that the climate was semi-arid.

3.5 EXPERIMENTAL DETAILS

3.5.1 Details of treatments

The details of the treatments are summarized in Table 6. There were seven irrigation treatments based on surface drip method of irrigation and irrigation scheduling levels in the form of pan evaporation replenishment. The evaporation replenishment factor viz., 0.4, 0.6 and 0.8 was either kept constant throughout the crop life or was combinations of the above at vegetative, flowering and capsule development stages (treatments I_1 to I_7).

Table 6. Details of irrigation treatments

Treatment designation	Treatment details
I_1	Drip irrigation at 0.4Epan throughout the crop life
I_2	Drip irrigation at 0.6Epan throughout the crop life
I_3	Drip irrigation at 0.8Epan throughout the crop life
I_4	Drip irrigation at 0.4Epan up to flowering and 0.6Epan later on
I_5	Drip irrigation at 0.4Epan up to flowering and 0.8Epan later on
I_6	Drip irrigation at 0.6Epan up to flowering and 0.8Epan later on
I_7	Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity
I_8	Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life

Besides the seven drip irrigation scheduling treatments one treatment consisted of a surface check basin irrigation (I_8) as check for comparison. The irrigation scheduling in surface irrigated plot was based on IW/CPE ratio of 0.8. The irrigation water depth was 50 mm. The pan evaporation data used in the irrigation scheduling was measured from USWB Class A Pan evaporimeter located in a B-Class meteorological observatory at the nearby experimental plot.

3.5.2 Calculation of depth of irrigation water in surface irrigation treatment (I_8)

The irrigation water equivalent to 50 mm depth in I_8 treatment at each irrigation event was calculated as follows:

$$W = A \times d \times 1000$$

Wherein,

W **=** Water in liters per irrigation

A **=** Plot area in m^2

d **=** Irrigation water depth in m

Thus calculated irrigation water was delivered in surface irrigation treatment plot directly using a water meter and flexible pipe.

3.5.3 Irrigation scheduling in drip irrigation treatments (I_1 to I_7)

Irrigation schedules in drip irrigated treatments were based on some fraction of daily pan evaporation rates from USWB Class A Pan evaporimeter, which are expressed in mm of water evaporated over a given time period, usually a day. Based on pan evaporation rates the irrigation set time was calculated by the following relationship:

$$Irrigation\ set\ time\ (in\ hours) = \frac{Pan\ evaporation\ rate\ (mm/day)}{Application\ rate\ (mm/hour)}$$

$$Application\ rate\ \left(\frac{mm}{hour}\right) = \frac{Q}{S_l \times S_e}$$

Wherein,

Q **=** Emitter flow rate (mm/hour)

S_l **=** Spacing between laterals (m)

S_e **=** Spacing between emitters (m)

The calendar of irrigation water application, incident rainfall & field water supply under different treatments and pan evaporation from USWB class A pan evaporimeter are given in Table 7.

3.5.4 Design and layout of experiment

The experiment was laid out in a Randomized Block Design with three replications as shown in Fig. 2. Buffer channels of 1.0 m width were laid out on either side of the surface check basin irrigation plot (I_8) to avoid the seepage into the adjoining drip irrigated plots.

3.5.5 Details of drip irrigation system

Drip Irrigation is defined as the frequent application of small quantities of water on (surface drip) or below the soil surface (subsurface drip) as drops by

Table 7. Field water supply (mm) to castor at different crop growth sub-periods under different irrigation treatments

Crop growth sub-periods	Irrigation Treatment								Epan
	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	
Establishment (0 – 15 DAS)	25.72	38.58	51.44	25.72	25.72	38.58	25.72	50.00	63.9
Vegetative (16 – 50 DAS)	49.20	73.80	98.40	49.20	49.20	73.80	49.20	100.00	134.6
Flowering (51 to 81 DAS)	50.88	76.32	101.76	50.88	50.88	76.32	76.32	100.00	110.9
Capsule development (82 – 106 DAS)	49.72	74.58	99.44	74.58	99.44	99.44	86.84	100.00	104.5
Seed filling (107 – 135 DAS)	51.16	76.74	102.32	76.74	102.32	102.32	102.32	100.00	170.9
Maturity (136 – 150 DAS)	--	--	--	--	--	--	--	--	95.0
Season Total (mm)	226.68	340.02	453.36	277.12	327.56	390.46	340.40	450.00	679.8
Rainfall (mm)	46.80	46.80	46.80	46.80	46.80	46.80	46.80	46.80	--
Field water supply (mm)	273.48	386.82	500.16	323.92	374.36	437.26	387.20	496.80	--

emitters placed along a water delivery integral dripperline. In the present field experiment surface drip irrigation system was used for irrigating castor.

The drip system consisted of Head control unit (including non return valve, air release valve, vacuum breaker, filtration unit viz., primary sand filter and secondary screen filter, fertigation unit, throttle valve, pressure gauge and water meter); Water carrier system (including uPVC main pipeline, uPVC submain pipeline, control valve, flush valve and other fittings) and Water distribution system (including 16 mm dripperline with molded emitters, grommet, start connecter, nipple and end cap).

The water source for drip irrigation was from an open well. Initially water was pumped from open well to a reservoir tank. The tank in turn supplied water to surface drip irrigation plots. The water from the reservoir tank was supplied with a pressurized submersible water pump to a sand filter system and then to screen filtration system to remove both organic and inorganic impurities from irrigation water. Filtered water then flowed to an irrigation manifold that supplied water to specific plots (Fig. 2). As an example, water scheduling plan for I_1 treatment is shown in Fig. 2. Simultaneously water supply to different plots of a given drip irrigated treatment were controlled in all the three replications.

Flow meters were used to measure flow rates to each individual treatment according to designated pan evaporation replenishment factor. Irrigation water from manifolds flowed in to 16-mm dripperlines laid out on the ground surface along the crop rows with emitters spaced 50 cm apart delivering 4 L/hour. Surface drip irrigation application rate was 6.66 mm/hour.

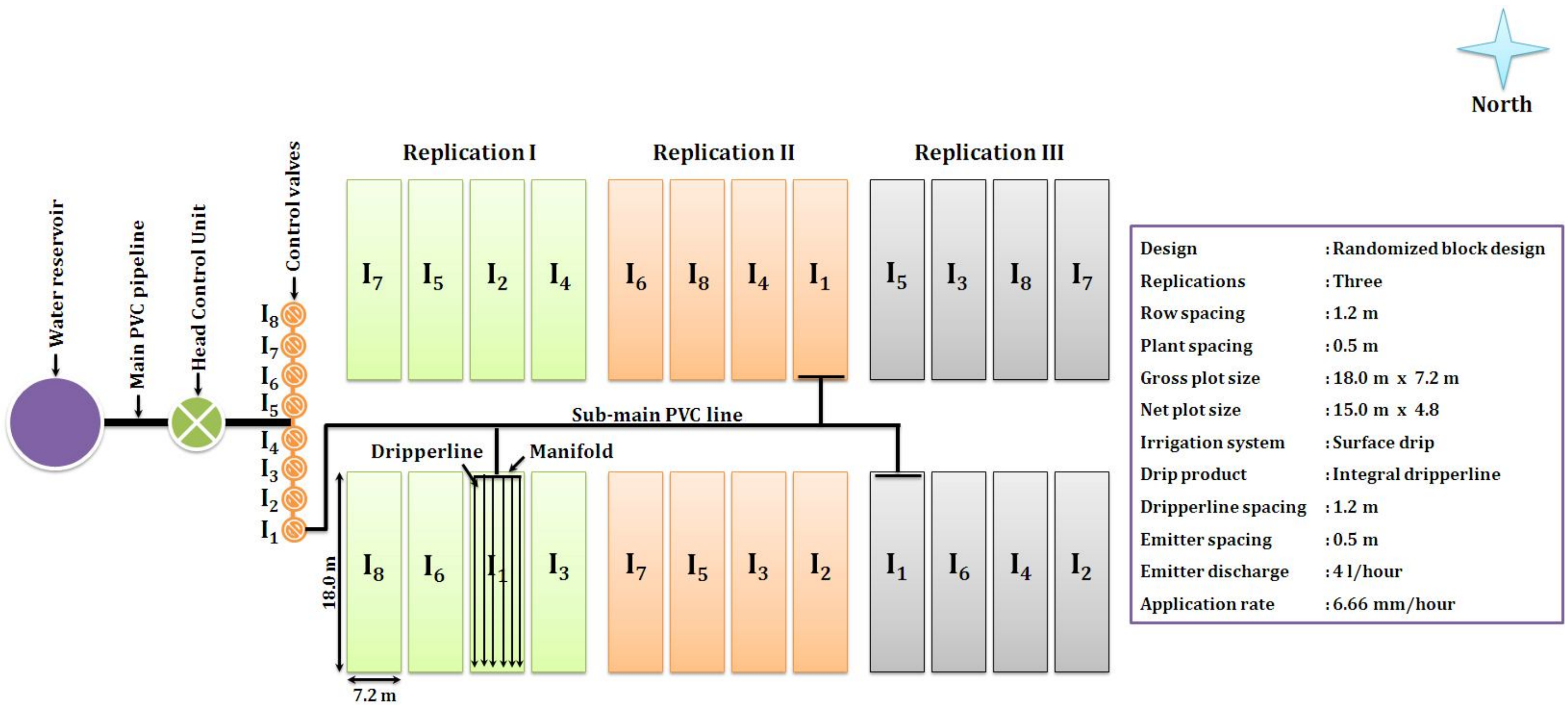

Fig. 2. Drip irrigation field experiment layout plan for castor crop

3.6 CULTIVATION DETAILS

3.6.1 Preparatory tillage

The experimental field was prepared thoroughly by working with tractor mounted disc plough once followed by tractor drawn cultivator and disc harrow twice to achieve optimum tilth.

3.6.2 Seeds

Palem Castor Hybrid – 111 (PCH - 111) released by the Regional Agricultural Research Station, Palem, Mahaboobnagar, Acharya N.G. Ranga Agricultural University was used as test variety. The duration of the hybrid is 180 days and is recommended for both *kharif* and *rabi* seasons under rainfed and irrigated tracts of Andhra Pradesh. The hybrid is highly resistant to *Fusarium spp.* wilt. The hybrid is distinguished by green stem, single bloom, with divergent branching, attractive spikes and spiny capsules with a potential yield of 4 – 5 tons/ha under irrigated conditions.

3.6.3 Sowing

Castor crop was sown on 7th November 2009. Bold seeds of test variety Palem Castor Hybrid – 111 were hand dibbled @2 seeds/hill at a depth of 5 cm by adopting an inter-row spacing of 1.2 m and plant to plant distance of 0.50 m to achieve a desired plant population of 16667 plants ha^{-1}. Before sowing the seeds were treated with Thiram @ 3g kg^{-1} seed as a prophylactic measure against seed borne diseases like Alternaria leaf blight, seedling blight and wilt.

3.6.4 Fertilizer application

The crop was fertilized with the recommended dose of fertilizer @ 60 kg N, 40 kg P_2O_5 and 30 kg K_2O ha^{-1}. A uniform dose of 40 kg P_2O_5 ha^{-1} was applied as basal in all the treatments. The source of NPK fertilizers were single super phosphate, urea and muriate of potash (white crystalline form), respectively. The nitrogen and potassium was fertigated as given in Table 8.

Table 8. Fertigation schedule for castor

Date	Nutrient Dose (kg/ha)	
	Nitrogen	Potassium
25 – 11 – 09	5.5	6.0
04 – 12 – 09	5.5	--
12 – 12 – 09	5.5	--
22 – 12 – 09	5.5	6.0
30 – 12 – 09	5.5	--
08 – 01 – 10	5.5	6.0
17 – 01 – 10	5.5	--
26 – 01 – 10	5.5	6.0
06 – 02 – 10	5.5	--
15 – 02 – 10	5.5	6.0
Total	**55.0**	**30.0**

3.6.5 After care

Gap filling was done 10 days after sowing (DAS) and plots were thinned 15 DAS keeping one healthy plant per each hill.

Pendimethaline @ 3.0 L ha^{-1} was applied as pre-emergence application to minimize the weed competition. Further hand weeding was carried out at 30 DAS to keep the crop free from weed competition.

The crop was kept free from pests and diseases by taking up need based plant protection measures viz., Monocrotophos @ 1.0 L ha^{-1}, Endosulphon @ 1.0 L ha^{-1} and Carbendazim @ 0.5 kg ha^{-1}.

3.6.6 Harvesting and Threshing

The crop was harvested on 5th April 2010. One row on both sides of the plot and three plants on either end of each row were harvested as border rows. Besides this, one crop row was earmarked for periodical destructive sampling to estimates leaf area and dry matter production. The plants in the remaining crop rows were harvested as net plot. The crop was harvested in three pickings based on the physiological maturity of the primary, secondary and tertiary spikes .The harvested spikes were heaped, sun dried and threshed manually by beating with sticks. The threshed produce was winnowed and beans were cleaned. The bean yield was recorded separately for primary, secondary and tertiary spikes and finally summed up to get total bean yield. The stalks were harvested by cutting at the base of the plant. The plants from each plot were sun dried thoroughly and weighed to estimate the stalk yield.

3.7 INITIAL EMERGENCE COUNT AND FINAL PLANT STAND

In each net plot the initial emergence count at 10 DAS and final plant stand at harvest was recorded and the percent stand was worked out as follows:

$$Plant\ stand\ (\%) = \frac{Observed\ plant\ stand}{Theoretical\ plant\ stand} \times 100$$

These values were then transformed to arcsine values (degrees) and then subjected to F – test.

3.8 GROWTH OBSERVATIONS

Five representative plants in each net plot treatment were randomly selected and tagged. All the successive biometric observations during the crop growth were recorded periodically on the selected plants. The same plants were harvested separately for generating the data on post-harvest yield attributes and also for assessing the individual plant yields. Growth characteristics such as plant height (cm), leaf area index (LAI) and dry matter per plant were recorded at 10, 30, 60, 90 & 120 DAS and at harvest.

3.8.1 Plant height

Plant height (cm) was measured from the base of the plant to the tip of the plant (whorl) before spike emergence, whereas after the emergence of spike, the height was recorded from the base of the plant to the base of the spike.

3.8.2 Leaf area index

Since leaves are the primary photosynthetic organs of the plant, it is desirable to express plant growth on leaf area (one side only) basis. Hence, five plants were harvested from the area earmarked for destructive sampling in each net plot for leaf area determination and leaf area was measured by using leaf area meter (Li-COR, Lincoln, Nebraska, USA) and it was expressed as leaf area index (LAI) by dividing the leaf area with ground area occupied by it.

3.8.3 Dry matter accumulation

The weight of dry matter is an index of productive capacity of the plant. The five plants harvested from each net plot for estimating leaf area were utilized for measuring dry matter accumulation. The roots were clipped off from each selected plant, the reminder was cleaned, transferred to properly labeled brown paper bags and then partially dried in the sun. Later on they were subjected to oven drying at 65 $\pm$ 2°C until constant weights were recorded and expressed as dry matter accumulation (g) per plant.

3.9 GROWTH ANALYSIS

In recent years the techniques of physiological analysis of plant growth have been extensively used for understanding the yield influencing factors, which in turn are influenced by an array of environmental and cultural variables. Hence, the following growth functions based on leaf area and dry matter accumulation were determined in the present investigation.

3.9.1 Relative growth rate

The relative growth rate (RGR) of plant at time instant (t) is defined as " the increase of plant material per unit of material initially present per unit of time " and is mathematically expressed as (Hunt, 1978).

$$RGR = \frac{(lnW_2 - lnW_1)}{(t_2 - t_1)}$$

Where, W_2 and W_1 are dry weights (g) at times t_2 and t_1 in days, respectively, In is natural logarithm, and RGR is the mean relative growth rate or increase in dry weight expressed in g g^{-1} day^{-1}.

3.9.2 Crop growth rate

The growth rate of a plant or crop growth rate (CGR) of a unit area of canopy cover at any instant time(t) is defined as " the increase of plant material per unit of time" and is mathematically given as:

$$CGR = \frac{(W_2 - W_1)}{(t_2 - t_1)} \times \frac{1}{P}$$

Where, W_2 and W_1 are the values of dry weight of plant (g) harvested from equal but separate areas of ground, (P) at times t_2 and t_1 in days, respectively; and CGR is the mean crop growth rate expressed in g/0.6m^{-2} day^{-1}.

3.9.3 Net assimilation rate

Since leaf surfaces are the primary photosynthetic organs, the productive efficiency (growth) expressed on leaf area basis provides a more meaningful measure of growth. Thus, Gregory (1918) suggested the concept of net assimilation rate (NAR) or average asimilation rate defined as "the net increase in plant dry weight (photosynthesis minus respiration) per unit of assimilatory surface per unit time". Williams (1946) provided a convenient formula for the estimation of mean net assimilation rate (NAR) over a period of times as given below:

$$NAR = \frac{(W_2 - W_1)}{(t_2 - t_1)} \times \frac{(lnLA_2 - lnLA_1}{(LA_2 - LA_1)}$$

Where, W_2 and W_1 are dry weights (g) at times t_2 and t_1 in days, respectively. Likewise LA_2 and LA_1 are leaf area values in m^2 measured at time t_2 and t_1, respectively and NAR represents the mean net assimilation rate expressed in g m^{-2} day^{-1}; In is natural logarithm.

3.9.4 Leaf area duration

Leaf area duration (LAD) expresses the magnitude and persistence of leaf area or leafiness during the period of crop growth. If leaf area is plotted against time, it produces a function that indicates the assimilatory capacity of a crop during the period in question (Watson, 1947). LAD based on leaf area of individual plants from successive harvests was calculated as given by Hunt (1980).

$$LAD = \frac{(LA_2 + LA_1)(t_2 - t_1)}{2}$$

Where, LA_2 and LA_1 are leaf areas in m^2 obtained at times t_2 and t_1 respectively. LAD represents mean LAD expressed in m^2 days.

3.10 YIELD ATTRIBUTES AND YIELD

3.10.1 Number of spikes per plant

The number of spikes on each five tagged plants was counted, totaled and the average was worked out and expressed as number of spikes per plant.

3.10.2 Spike length (cm)

The length of primary, secondary and tertiary spikes was measured separately on each five tagged plants in each plot and average length of spike was expressed in cm.

3.10.3 Number of capsules per plant

The number of capsules in each primary, secondary and tertiary spikes of five tagged plants was counted in each plot and average number of capsules per spike was worked out.

3.10.4 Capsule weight (g)

Total weight of ten capsules obtained from spikes of labeled plants was weighed and the mean value was worked out to obtain the average capsule weight (g).

3.10.5 Number of seeds per capsule

The total number of seeds produced in each capsule of the five sampled plants were counted and the average number of seeds per capsule was computed.

3.10.6 Test (100-seed) weight (g)

A random sample of 100 seeds treatment-wise from each net plot were collected, weighed and expressed as test (100-seed) weight (g).

3.10.7 Bean yield per plant (g)

The seed yield of five tagged plants in each treatment was weighed and the mean value was worked out to obtain the seed yield per plant (g).

3.10.8 Bean yield (kg ha^{-1})

The bean yield from each net plot treatmentwise including the yield of five labeled plants was weighed and expressed in kg ha^{-1}.

3.10.9 Total dry matter (Kg ha^{-1})

The total above ground dry matter from each net plot treatment-wise including the dry matter yield of five labeled plants was weighed and expressed in kg ha^{-1}.

3.10.10 Harvest index

Harvest index was calculated using the following formula:

$$Harvest\ index = \frac{Yield\ (kg\ ha^{-1})}{Total\ dry\ matter\ (kg\ ha^{-1})} \times 100$$

3.10.11 Oil content (%)

Oil content of castor beans was estimated by Nuclear Magnetic Resonance (NMR) analyser (Jambunathan et.al., 1985) and was expressed as percentage.

3.10.12 Oil yield (Kg ha^{-1})

Oil yield was calculated by multiplying the oil content (%) in each treatment with corresponding bean yield as given below:

$$Oil\ yield\ (kg\ ha^{-1}) = \frac{Oil\ content\ (\%)\ \times Bean\ yield\ (kg\ ha^{-1})}{100}$$

3.11 WATER USE STUDIES

3.11.1 Reference crop evapotranspiration (ET_o)

The evapotranspiration rate from an extensive surface of green grass of uniform height (0.12m), actively growing, completely shading the ground with an albedo of 0.23 and not short of soil water is called reference crop evapotranspiration and is denoted by ET_o. The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available at the reference evapotranspiring surface, soil factors do not affect ET. Relating ET to a specific surface provides a reference to which ET from other surfaces can be related. It obviates the need to define a separate ET level for each crop and stage of growth. ET_o values measured or calculated at different locations or in different seasons are comparable as they refer to the ET from the same reference surface. The only factors affecting ET_o are climatic parameters. Consequently, ET_o is a climatic parameter and can be computed from weather data (Fig. 3).

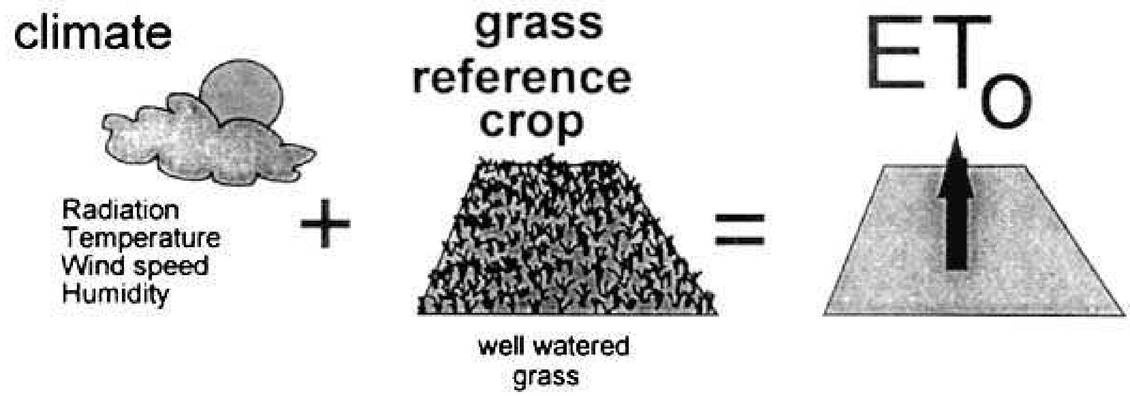

Fig. 3. Reference crop evapotranspiration

ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. Thus, in the present study the FAO Penman-Monteith method (Allen et.al., 1998), Modified Penman method and Adjusted Pan evaporation method (Doorenbos and Pruitt, 1977) were used to determine ET_o as follows

3.11.1.1 Penman-Monteith equation

Allen *et. al.* (1998) proposed the Penman – Monteith equation. The mathematical relationship is as follows:

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 - 0.34U_2)}$$

Where:

ET_o	= Reference crop evapotranspiration (mm/day)
R_n	= Net radiation at the crop surface (MJ/m^2/day)
G	= Soil heat flux density (MJ/m^2/day)
T	= Air temperature at 2 m height (°C)

U_2 = Wind speed at 2 m height (m/s)

e_s = Saturation vapour pressure (kPa)

e_a = Actual vapour pressure (kPa)

$(e_s - e_a)$ = Saturation vapour pressure deficit (kPa)

Δ = Slope vapour pressure curve (kPa/°C)

γ = Psychrometric constant (kPa/°C)

3.11.1.2 Modified Penman method

The relationship is expressed as:

$$ET_0\ (mm/day) = c[\underbrace{W.R_n}_{Radiation} + \underbrace{(1-W).f(u).(ea-ed)}_{Aerodynamic}]$$

Where:

ET_o = Reference crop evapotranspiration in mm/day

W = Temperature related weighing factor

R_n = Net radiation in equivalent evaporation in mm/day

f(u) = Wind related function

(ea – ed) = Difference between the saturation vapour pressure at Tmean and the mean actual vapour pressure of the air both in mbar

c = Adjustment factor to compensate for the effect of day and night weather conditions

3.11.1.3 Adjusted pan evaporation method

The relationship is expressed by:

$$ET_o\ (mm/day) = K_{pan} . E_{pan}$$

Where:

ET_o = Reference crop evapotranspiration in mm/day for the period considered

E_{pan} = Pan evaporation in mm/day and represents the mean daily value of the period

considered

K_{pan} = Pan coefficient

3.11.2 Crop evapotranspiration under standard conditions (ET_c)

The crop evapotranspiration under standard conditions, denoted as ET_c, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. The "amount of water required to compensate the evapotranspiration loss from the cropped field" is defined as crop water requirement. Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration. The irrigation water requirement basically represents the difference between the crop water requirement and effective precipitation.

In the present study the crop evapotranspiration was estimated by using the general water balance equation between time intervals of t_1 and t_2 as follows:

$$ET_c = \int_{t_1}^{t_2} (I + \Delta SW \mp Vz + RO + EP$$

Where,

I = is the depth of irrigation (mm),

ΔSW = the change in profile soil water storage (mm),

±Vz = includes the vertical flux (mm d^{-1}) across the lower boundary (1.0 m). The water table was below 6 m from the ground surface all through the crop season, hence the possibility of ground water contribution by capillary rise to ETc was assumed to be zero

RO = the surface runoff (mm), which was eliminated by adjusting the height measured in providing 50 mm irrigation I_8 treatment and there was not any runoff in drip irrigated plots (I_1 to I_7).

EP = is the effective rainfall (mm) calculated 24 h after rainfall, following the Balance sheet method (Misra and Ahmed, 1987; Bandyopadhyay and Mallick, 2003). The effective rainfall received from time to time was deducted from the pan evaporation in in drip irrigated plots (I_1 to I_7) and CPE value in I_8 treatment for arriving at the desired IW:CPE ratios for irrigation.

The sum of periodical ET_c of castor gives the seasonal crop water use. By plotting ET_c of different irrigation treatments versus time, the average daily ET_c rates were estimated. Soil water content was measured at sowing, the day before and after each irrigation, 24 h after rainfall, every 7-day interval and at the time of harvesting using Gopher soil moisture profiling system (Dataflow Systems Pty Ltd, Christchurch, New Zealand). Gravimetric soil samples were also collected at 0.25 ±0.02-m depth increments by soil auger to measure the profile soil water content from soil surface to 1.0±0.02 m.

3.11.3 Water productivity

Water productive efficiency is the ratio between bean yield to the amount of water used in evapotranspiration. It was calculated by the following relationship:

$$Water\ productivity\ (kg/m^3) = \frac{Bean\ yield\ (kg/ha)}{ET_c\ (m^3)}$$

3.11.4 Crop coefficient

Allen *et.al*. (1998) defined crop coefficient (K_c) as “ratio between crop evapotranspiration under standard conditions (ET_c) and the reference crop evapotranspiration (ET_o)”. Most of the effects of the various weather conditions are incorporated into the ET_o estimate. Therefore, as ET_o represents an index of climatic demand, K_c varies predominately with the specific crop characteristics and only to a limited extent with climate. This enables the transfer of standard values for K_c between locations and between climates. This has been a primary reason for the global acceptance and usefulness of the crop coefficient approach and the K_c factors developed in past studies for several crops.

Crop coefficients developed for various crop growth sub-periods enable construction of crop coefficient curve. For estimation of crop coefficients in the present experiment the crop growing season was divided in to germination & establishment phase, vegetative phase, flowering & capsule initiation, capsule development and seed filling stages. The ETo was estimated by different empirical methods viz., Penman-Monteith equation, Modified Penman method and adjusted pan evaporation methods as outlined in section (3.11.1), while the crop evapotranspiration was estimated as per the procedure outlined in section (3.11.2) and the Kc values for different crop growth sub-periods were calculated by the following relationship:

$$Kc = \frac{ET_c}{ET_o}$$

Where in,

K_c = Crop coefficient

ET_c = Crop evapotranspiration (mm/day) under standard conditions

ET_o = Reference crop evapotranspiration (mm/day)

3.12 CORRELATION AND REGRESSION STUDIES

3.12.1 Regression of bean yield on growth and yield components

Crop yield (dependent variable) was assumed as a function of various growth and yield components (independent variables) and the following straight line model was established by least square technique (Gomez and Gomez, 1984) as follows:

$$Y = a + bx$$

Where,

Y = Castor bean yield plant^{-1}

a = Y – axis intercept

b = Regression coefficient

x = Growth and yield components

Similarly seasonal crop evapotranspiration was related to leaf area index and leaf area duration adopting the above linear model. Further the periodical crop evapotranspiration under I_2 treatment was related to reference crop evapotranspiration estimated by Penman Monteith method, Modified Penman method, Adjusted pan evaporation method and evaporation from USWB Class A pan evaporation.

3.12.2 Correlations between bean yield and growth & yield components

Correlation matrix between bean yield plant^{-1} and growth viz., plant height & leaf area index and various yield components viz., number of spikes plant^{-1}, primary and secondary spike length, number of capsules plant^{-1}, capsule weight, number of seeds per capsule and test weight was established by least square technique.

3.13 WATER PRODUCTION FUNCTIONS

The functional relationship between crop yield and water use is defined as crop water production function. The seasonal water production functions evaluated in the present study for castor are as follows:

a) Linear water production function

$$Y = a + b(ET_c)$$

Where in:

Y = Crop yield (kg/ha)

ET_c = Crop evapotranspiration (mm)

a = Y-axis intercept

b = Regression coefficients reflecting the yield variation per unit change in crop ET_c

b) Quadratic water production function

$$Y = a + b(ET_c) + c(ET_c^2)$$

Where in:

Y = Crop yield (kg ha^{-1})

ET_c = Crop evapotranspiration (mm)

a = Y – axis intercept

b & c = Regression coefficients reflecting the yield variation per unit change in ET_c

3.14 ECONOMIC ANALYSIS

To find out the economic viability of the drip investment in the context of castor crop, the net cash flow, net present value (NPV), breakeven point for price, breakeven point for yield and pay-back period were computed by adopting discounted cash flow technique. Since the NPV is the difference between the sum of the present value of benefits and that of costs for a given life period of the drip system, it collates the total benefits with the total costs covering items like capital and depreciation costs of the drip system. In terms of the NPV criterion, the investment on drip system can be treated as economically viable if the present value of benefits is greater than the present value of costs. The NPV can be defined as follows:

$$NPV = \sum_{t=1}^{t=n} \frac{B_t - C_t}{(1 + I)^t}$$

Wherein

B_t = Benefit in year t,

C_t = Cost in year t,

t = 123….n

n = Project life in years i.e., assumed as 10 years

i = rate of interest i.e. in the present case it was assumed as 12%

3.15 STATISTICAL ANALYSIS

The data on yield, growth and yield attributes were analysed by following randomized block design technique (Panse and Sukhatme, 1978).

CHAPTER IV

RESULTS

The results of a field experiment entitled **"Irrigation management in drip irrigated castor"** conducted during *rabi* season of 2009–10 at College Farm, Rajendranagar, Hyderabad are presented here under. Experimental data are furnished in tables and illustrated through figures wherever found necessary.

4.1 INITIAL AND FINAL PLANT STAND

The data on initial and final plant stand of castor (Table 9) was not significantly influenced by different irrigation treatments. The mean initial and final plant stand was 96.6% and 94.2%, respectively.

4.2 GROWTH CHARACTERS

4.2.1 Plant height

Increase in average plant height was rather slow up to 30 DAS, thereafter it increased linearly up to 90 DAS, and after that although it continued to increase until maturity it occurred at a diminishing rate (Table 10 and Fig. 4).

Plant height of castor was significantly influenced by different irrigation treatments at all the growth stages (30 DAS, 60 DAS, 90 DAS, 120 DAS and at harvest) except at 10 DAS.

At 30 DAS, 60 DAS and 90 DAS the plant height recorded under I_2 (0.6Epan throughout the crop life), I_3 (0.8Epan throughout the crop life) and I_6 (0.6Epan up to flowering and 0.8Epan later on) was statistically on par and significantly

Table 9. Initial and final plant stand of castor as influenced by different irrigation treatments

Treatment details	Initial plant stand		Final plant stand	
	%	Arcsine	%	Arcsine
I_1 – Drip irrigation at 0.4Epan throughout the crop life	96.8	79.85	94.5	76.43
I_2 – Drip irrigation at 0.6Epan throughout the crop life	96.6	79.56	94.3	76.24
I_3 – Drip irrigation at 0.8Epan throughout the crop life	97.0	80.17	94.4	76.36
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	96.0	78.67	93.6	75.49
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	97.4	80.93	95.3	77.63
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	96.7	79.61	94.0	75.48
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8 Epan 96 – maturity	96.6	79.48	95.0	77.30
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	95.8	78.22	92.5	74.11
SEm±		0.82		0.66
CD (P=0.05)		NS		NS
General mean	**96.6**	**79.56**	**94.2**	**76.13**

Table 10. Plant height (cm) of castor at different growth stages as influenced by different irrigation treatments

Treatment details	Days After Sowing					
	10	**30**	**60**	**90**	**120**	**At harvest**
I_1 – Drip irrigation at 0.4Epan throughout the crop life	10.9	26.5	57.8	85.7	95.2	105.0
I_2 – Drip irrigation at 0.6Epan throughout the crop life	10.1	32.1	73.7	132.3	142.5	146.5
I_3 – Drip irrigation at 0.8Epan throughout the crop life	11.1	34.7	71.5	135.5	145.5	155.5
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	10.0	26.7	61.5	105.0	118.5	122.0
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	11.4	27.0	60.7	109.1	123.5	127.1
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	10.6	35.5	73.2	133.6	146.4	153.9
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	10.2	25.8	60.5	104.7	120.1	125.1
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	10.2	27.5	61.5	95.4	105.5	112.7
SEm±	0.64	1.47	3.10	4.76	4.91	5.73
CD (P=0.05)	NS	4.51	9.52	14.58	15.10	17.55
General mean	**10.56**	**29.5**	**65.05**	**112.66**	**124.65**	**130.97**

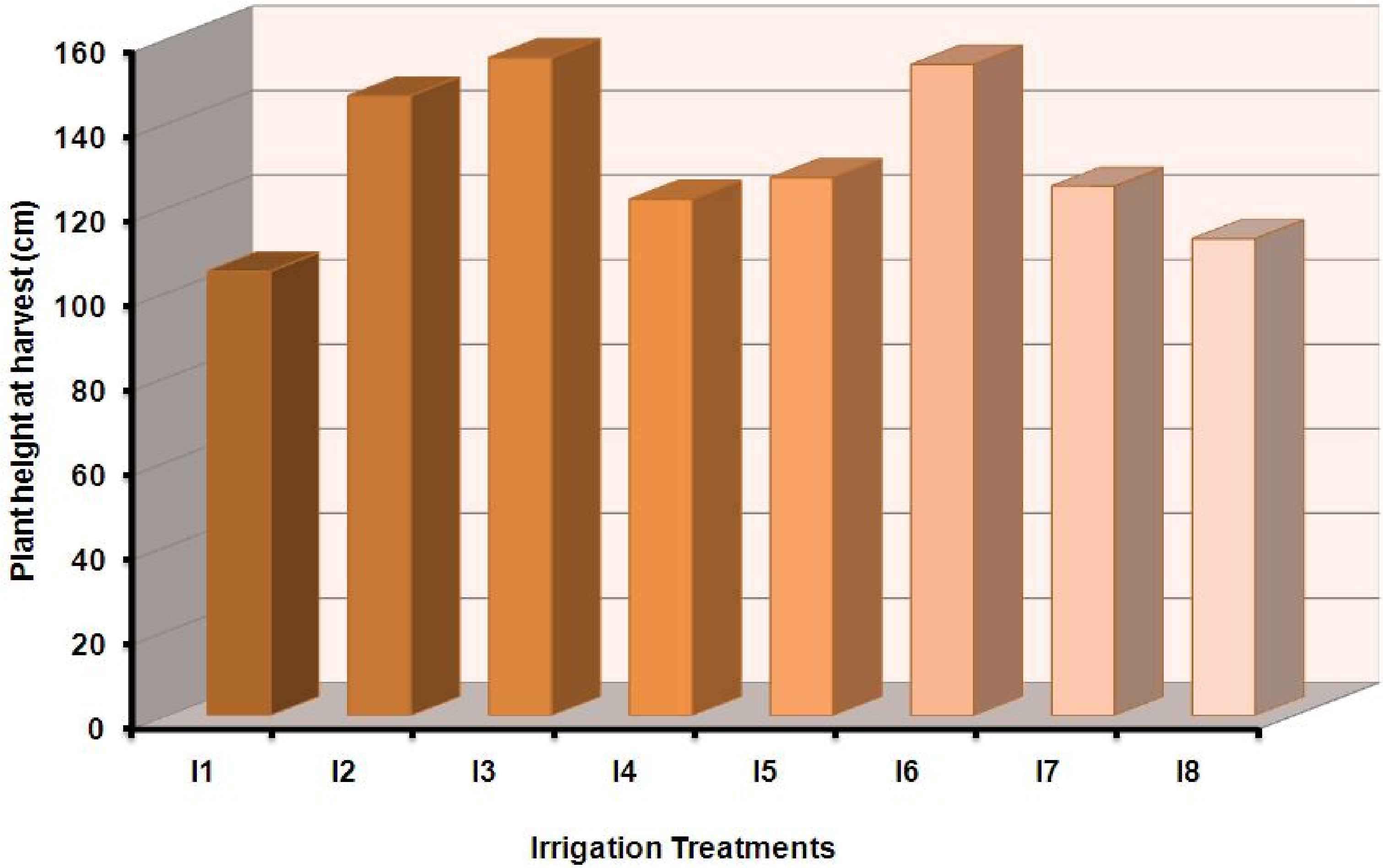

Fig. 4. Plant height at harvest of castor as influenced by different irrigation treatments

superior over other irrigation treatments *viz.,* I_1, I_4, I_5, I_7 and I_8. The plant height in later treatments was not statistically significant except that at 90 DAS lowest plant height was recorded under I_1 treatment (drip irrigation at 0.4Epan throughout the crop life) and it was on par with I_8.

At 120 DAS higher scheduling of irrigations with drip at 0.6Epan up to flowering and 0.8Epan later on (I_6) recorded higher plant height but it was on par with I_2 (0.6Epan throughout the crop life) and I_3 (0.8Epan throughout the crop life) and significantly superior over other irrigation treatments I_1, I_4, I_5, I_7 and I_8. Likewise the plant height in I_5 was statistically on par with I_4 and I_7 but significantly higher than I_8 and I_1. Lowest plant height was registered under I_1 but it was on par with I_8.

At harvest the results were similar to that at 120 DAS except that the difference in plant height between I_4, I_8 and I_1 were not significant.

4.2.2 Leaf area index

The average leaf area index (LAI) increased at a slower rate up to 10 DAS and thereafter it increased linearly with the ontogeny of the plant reaching a peak value at 120 DAS but thereafter it decreased precipitously towards maturity due to senescence of leaves (Table 11 and Fig. 5). The development of LAI reflected a sigmoid pattern of growth.

The LAI was not significantly influenced by different irrigation treatments at 10 DAS and at harvest but at 30, 60, 90, and 120 DAS the irrigation treatments had significant effect on LAI.

Table 11. Leaf area index of castor at different growth stages as influenced by different irrigation treatments

Treatment details	Days After Sowing					
	10	30	60	90	120	At harvest
I_1 – Drip irrigation at 0.4Epan throughout the crop life	0.056	1.09	1.25	1.78	1.91	1.73
I_2 – Drip irrigation at 0.6Epan throughout the crop life	0.067	1.21	1.65	2.05	2.65	2.15
I_3 – Drip irrigation at 0.8Epan throughout the crop life	0.071	1.33	1.76	2.15	2.75	2.10
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	0.065	1.10	1.25	1.85	2.06	1.77
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	0.077	1.14	1.31	1.98	2.25	2.04
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	0.058	1.25	1.70	2.10	2.60	2.05
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	0.071	1.15	1.31	1.83	2.11	1.82
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	0.077	1.13	1.38	1.91	2.32	1.96
SEm±	0.01	0.04	0.05	0.06	0.08	0.13
CD (P=0.05)	NS	0.13	0.15	0.20	0.26	NS
General mean	**0.068**	**1.17**	**1.45**	**1.95**	**2.33**	**1.95**

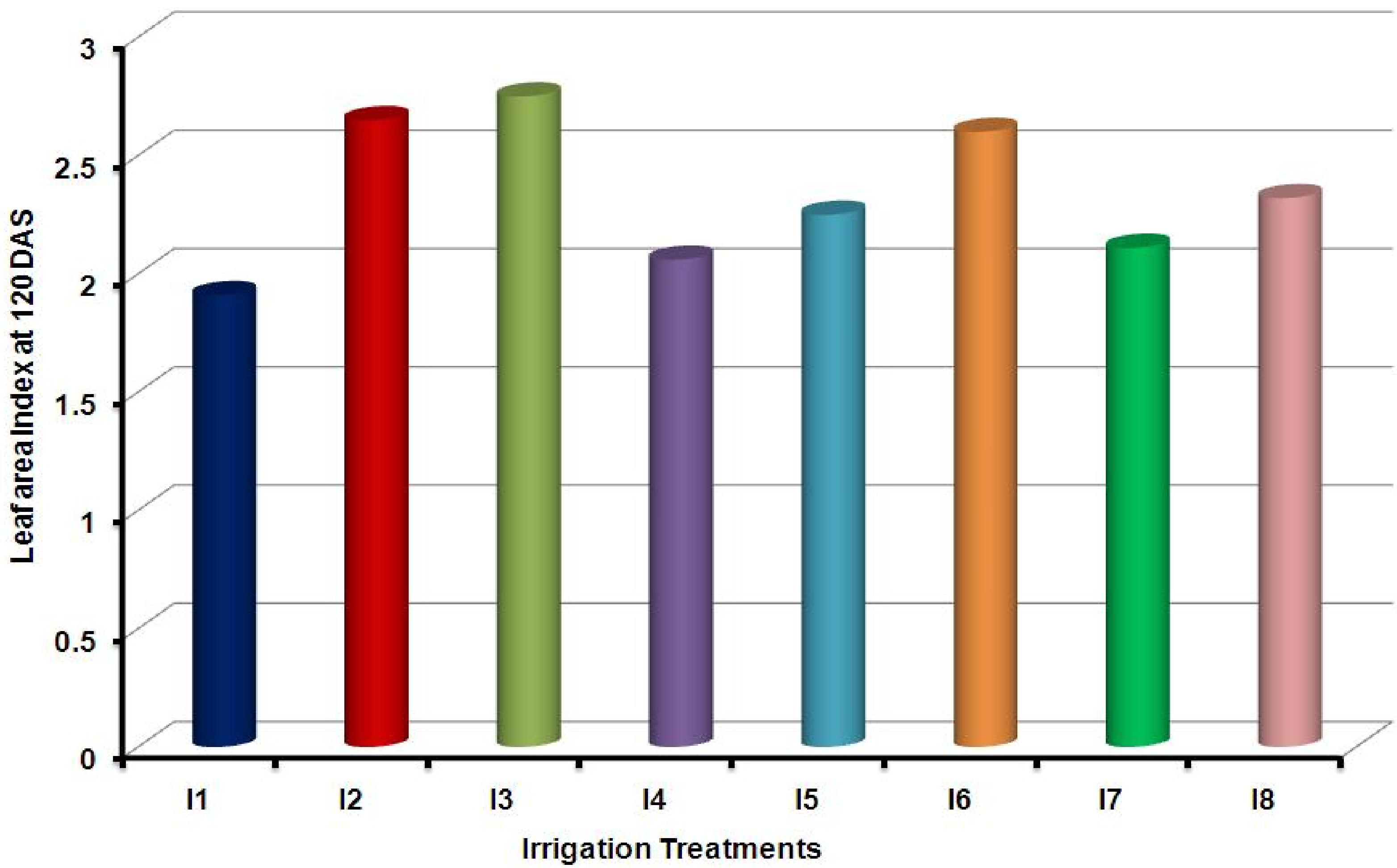

Fig. 5. Leaf area index at 120 DAS of castor as influenced by different irrigation treatments

At 30 DAS scheduling irrigations to castor with drip at 0.8Epan (I_3) throughout the crop life resulted in higher LAI but it was on par with I_2 (0.6Epan throughout the crop life) and I_6 (0.6Epan up to flowering and 0.8Epan later on) and significantly superior over I_1, I_4, I_5, I_7 and I_8 treatments.

Further the data indicated that the difference between I_2, I_5, I_6, I_7 and I_8. Lowest LAI was recorded when irrigations were scheduled at 0.4Epan throughout the crop life (I_1), however it was on par with I_2, I_4, I_5, I_7 and I_8.

At 60 DAS the LAI trend was similar to 30 DAS except that the difference in LAI between I_1, I_4, I_5, I_7 and I_8 were not significant.

At 90 DAS the significantly higher LAI was recorded under I3 (0.8Epan throughout the crop life) but it was on par with I_2, I_5, I_6 and I_8 treatments. Likewise the difference in LAI between I_2, I_4, I_5, and I_8 and that between I_1, I_4, I_5, I_7 and I_8 were not significant.

At 120 DAS scheduling irrigations with drip at 0.8Epan (I_3) throughout the crop life resulted in higher LAI but it was on par with I_2 (0.6Epan throughout the crop life) and I_6 (0.6Epan up to flowering and 0.8Epan later on) and significantly superior over I_1, I_4, I_5, I_7 and I_8 treatments. Further the data indicated that the difference between I_4, I_5, I_7 and I_8 was not significant. Lowest LAI was recorded when irrigations were scheduled at 0.4Epan throughout the crop life (I_1), however it was on par with I_4, and I_7.

4.2.3 Dry matter per plant

Average dry matter per plant increased gradually up to 10 DAS and thereafter it increased sharply and linearly between 10 and 60 DAS, and after that although it continued to increase markedly until harvest it occurred at a decreasing rate (Table 12 and Fig. 6).

The dry matter/plant was not significantly influenced by different irrigation treatments at 10 DAS but at 30, 60, 90, 120 DAS and at harvest irrigation treatments had significant effect on dry matter/plant.

At 30 DAS drip irrigation of castor at 0.8Epan throughout the crop life (I_3) accumulated significantly higher dry matter/plant as compared to other irrigation treatments. Further the data indicated that the I_2, I_4, I_6 and I_7 had statistically similar dry matter/plant but significantly superior over I_1, I_5 an I_8, which were on par.

At 60 DAS higher dry matter/plant was recorded under I_6 (drip irrigation at 0.6Epan up to flowering and 0.8Epan later on) but it was on par with I_3 (drip irrigation at 0.8Epan throughout the crop life) and significantly superior over other irrigation treatments. Further the crop performance under I_2 (drip irrigation at 0.6Epan throughout the crop life) in terms of dry matter/plant was statistically similar to I_3. Likewise the difference in dry matter/plant between I_7 and I_4 and that between I_4, I_5 and I_8 was not significant. Significantly lower dry matter/plant was produced by the crop in I_1 wherein the irrigations were scheduled at 0.4Epan throughout the crop life but it was on par with I_5 and I_8.

Table 12. Dry matter (g/plant) of castor at different growth stages as influenced by different irrigation treatments

Treatment details	Days After Sowing					
	10	30	60	90	120	At harvest
I_1 – Drip irrigation at 0.4Epan throughout the crop life	1.10	78.0	160.0	245.0	330.0	355.0
I_2 – Drip irrigation at 0.6Epan throughout the crop life	1.08	88.1	215.9	400.9	575.0	647.0
I_3 – Drip irrigation at 0.8Epan throughout the crop life	1.15	95.8	223.0	405.0	580.7	655.0
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	1.11	85.0	175.0	325.3	435.0	488.0
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	0.91	77.0	169.0	338.7	425.4	470.5
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	1.07	86.5	228.1	410.3	590.5	660.0
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	0.95	88.0	181.0	333.0	427.9	481.0
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	1.13	76.7	167.0	205.6	385.0	425.0
SEm±	0.09	1.8	3.5	7.8	11.7	17.4
CD (P=0.05)	NS	5.6	10.8	24.1	35.8	53.2
General mean	**1.06**	**84.4**	**189.9**	**333.0**	**468.7**	**522.7**

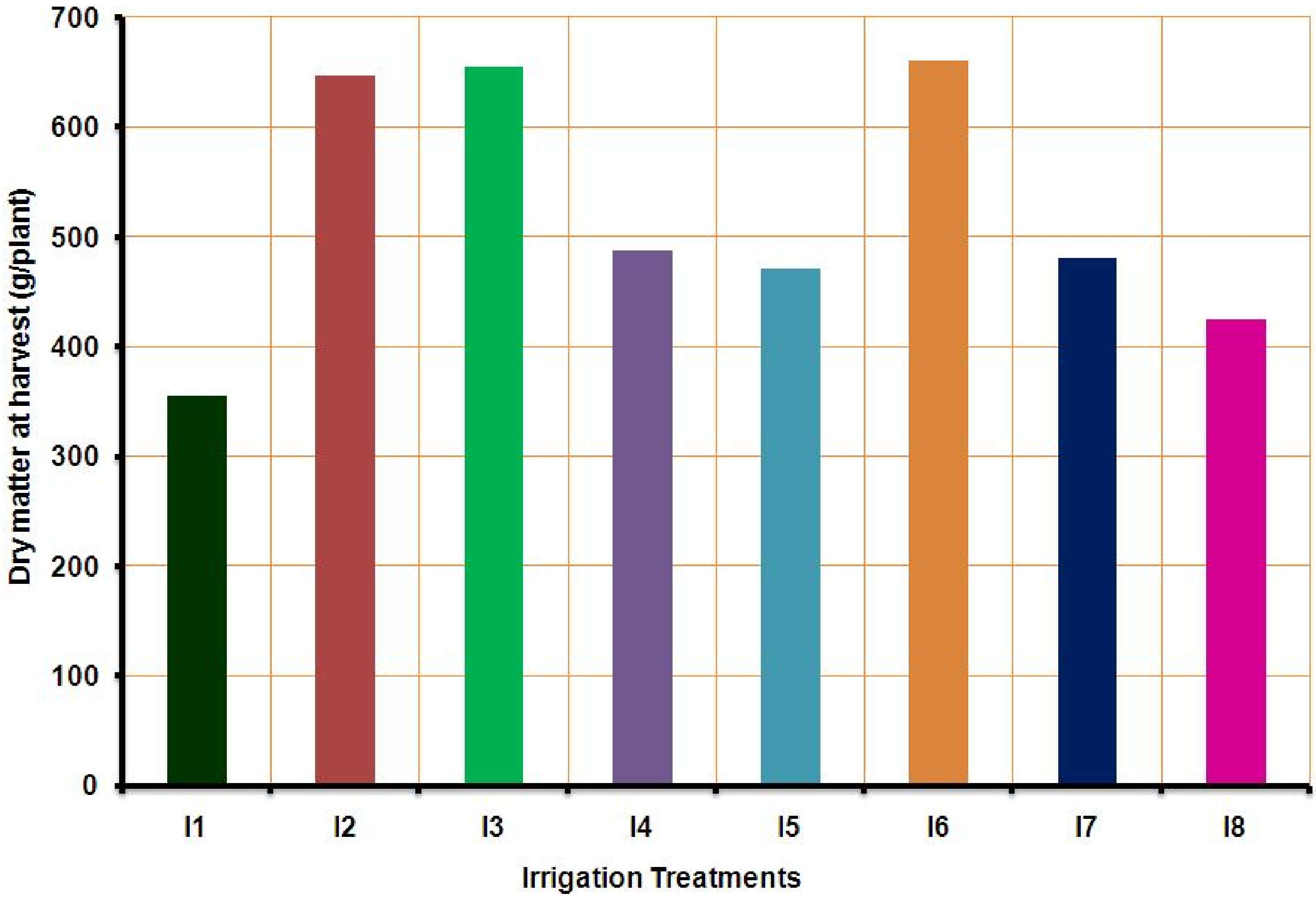

Fig. 6. Dry matter per plant of castor at harvest as influenced by different irrigation treatment

At 90 and 120 DAS and at harvest scheduling of irrigations with drip at 0.6Epan up to flowering and 0.8Epan later on (I_6) registered higher dry matter/plant which was on par with I_2 (0.6Epan throughout the crop life) and I_3 (0.8Epan throughout the crop life) and significantly superior over other treatments. Further, the data indicated that the difference in dry matter between I_4 (0.4Epan up to flowering and 0.6Epan later on), I_5 (0.4Epan up to flowering and 0.8Epan later on) and I_7 (0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity) was statistically not significant at 90 and 120 DAS and at harvest but superior over I_1 (0.4Epan throughout the crop life) and I_8 (surface check basin irrigation at 0.8 IW/CPE ratio throughout the crop life), which were on par.

4.2.4 Days to flowering

The number of days to flowering was early (48 days) in case of I_8 treatment as compared to other treatments (Table 13). Whereas the number of days to flowering in I_1 to I_7 treatments varied from 57 to 67 days.

4.2.5 Days to capsule initiation

The number of days taken for capsule initiation was lowest (64 days) under I_8 treatment in comparison to other irrigation treatments (Table 13). Further it was observed that the number of days to capsule initiation under I_1 to I_7 treatments varied from 71 to 82 days.

Table 13. Days to flowering and capsule initiation of castor as influenced by different irrigation treatments

Treatment details	Days to flowering	Days to capsule initiation
I_1 – Drip irrigation at 0.4Epan throughout the crop life	60	78
I_2 – Drip irrigation at 0.6Epan throughout the crop life	57	74
I_3 – Drip irrigation at 0.8Epan throughout the crop life	65	80
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	67	74
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	57	68
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	61	82
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6 Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	59	71
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	48	64
General mean	**59.25**	**73.9**

4.3 GROWTH ANALYSIS

4.3.1 Relative growth rate

The greatest relative growth rates were found early in the crop growing season (10 – 30 DAS) (Table 14). Thereafter they declined with crop ontogeny in all the treatments. Mean RGR value was highest in I3 treatment at 0 – 10 DAS. Whereas at 10 – 30 DAS the RGR values in I_2, I_3, I_4, I_5, I_6, I_7 and I_8 were markedly different but superior over I_1 treatment. Similar trend was observed at 30 – 60 DAS and 60 – 90 DAS except that at 60 – 90 DAS the RGR values registered under

Table 14. Relative growth rate (g/g/day) of castor at different growth stages as influenced by different irrigation treatments

Treatment details	Days After Sowing					
	0 – 10	**10 – 30**	**30 – 60**	**60 – 90**	**90 – 120**	**120 to harvest**
I_1 – Drip irrigation at 0.4Epan throughout the crop life	0.0041	0.041	0.0100	0.0061	0.0043	0.0010
I_2 – Drip irrigation at 0.6Epan throughout the crop life	0.0033	0.095	0.0108	0.0096	0.0048	0.0011
I_3 – Drip irrigation at 0.8Epan throughout the crop life	0.0060	0.096	0.0101	0.0092	0.0045	0.0014
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	0.0045	0.094	0.0104	0.0089	0.0042	0.0016
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	–0.0040	0.096	0.0113	0.0100	0.0032	0.0014
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	0.0029	0.095	0.0119	0.0090	0.0046	0.0013
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	–0.0020	0.098	0.0104	0.0088	0.0036	0.0013
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	0.0053	0.091	0.0112	0.0030	0.0090	0.0014
General mean	**0.002**	**0.088**	**0.0107**	**0.0080**	**0.0047**	**0.0013**

Table 15. Crop growth rate (g/0.6m^2/day) of castor at different growth stages as influenced by different irrigation treatments

Treatment details	Days After Sowing					
	0 – 10	**10 – 30**	**30 – 60**	**60 – 90**	**90 – 120**	**120 to harvest**
I_1 – Drip irrigation at 0.4Epan throughout the crop life	0.110	3.84	2.73	2.83	2.83	0.83
I_2 – Drip irrigation at 0.6Epan throughout the crop life	0.100	4.07	3.26	5.83	4.80	1.4
I_3 – Drip irrigation at 0.8Epan throughout the crop life	0.115	4.16	3.24	5.73	4.52	1.81
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	0.110	4.19	3.0	5.01	3.65	1.76
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	0.091	3.80	3.06	5.65	2.89	1.50
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	0.100	4.27	3.72	5.74	4.67	1.65
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	0.090	4.35	3.10	5.06	3.16	1.77
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	0.110	3.77	3.01	1.28	5.68	1.33
General mean	**0.103**	**4.05**	**3.14**	**4.64**	**4.02**	**1.50**

I_1 and I_8 were not markedly different. At 90 – 120 DAS and 120 – harvest the difference in RGR values under different treatments was not appreciable.

4.3.2 Crop growth rate

The mean CGR values in general showed two peaks during the crop growing season (Table 15). The CGR values were low between 0 – 10 DAS, increased between 10 – 30 DAS, declined marginally between 30 – 60 DAS and again attained peak values between 60 – 90 DAS. After that, CGR gradually declined towards maturity in all the treatments.

The differences in CGR were not appreciable between 0 – 10 DAS. Between 10 – 30 DAS the treatments I_2, I_3, I_4, I_6 and I_7 had higher mean CGR values as compared to I_1, I_5 & I_8.

Between, 30 – 60 DAS I_6 treatment registered highest CGR, whereas I_2, I_3, I_4, I_5, I_7 and I_8 had intermediate values and lowest in I_1 treatment. Whereas between 60 – 90 DAS treatments I_2, I_3, I_4, I_5, I_6 and I_7 registered higher and comparable values but superior to I_1 and I_8. At later stages i.e., between 90 – 120 DAS and 120 – harvest no consistent trend was observed.

4.3.3 Net assimilation rate

The NAR values were negative between 0 – 10 DAS. Whereas between 10 – 30 DAS the NAR values were high in comparison to other growth periods but declined abruptly during 30 – 60 DAS and thereafter continued to decrease gradually towards maturity (Table 16).

Table 16. Net assimilation rate (g/m²/day) of castor at different growth stages as influenced by different irrigation treatments

Treatment details	Days After Sowing					
	0 – 10	10 – 30	30 – 60	60 – 90	90 – 120	120 to harvest
I_1 – Drip irrigation at 0.4Epan throughout the crop life	–4.93	7.98	1.66	1.35	1.10	0.33
I_2 – Drip irrigation at 0.6Epan throughout the crop life	–3.49	7.44	1.66	2.15	1.44	0.42
I_3 – Drip irrigation at 0.8Epan throughout the crop life	–3.76	7.03	1.52	2.13	1.31	0.54
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	–3.97	8.25	1.83	2.35	1.35	0.65
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	–2.64	6.98	1.80	2.48	0.98	0.49
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	–4.31	7.98	1.82	2.18	1.40	0.51
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	–2.94	8.15	1.82	2.32	1.16	0.65
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	–3.91	6.96	1.71	0.56	1.97	0.43
General mean	**–3.74**	**7.59**	**1.72**	**1.94**	**1.34**	**0.50**

Table 17. Leaf area duration (m^2 days) of castor at different growth stages as influenced by different irrigation treatments

Treatment details	Days After Sowing					
	0 – 10	10 – 30	30 – 60	60 – 90	90 – 120	120 to harvest
I_1 – Drip irrigation at 0.4Epan throughout the crop life	0.16	6.87	21.06	27.11	33.00	32.10
I_2 – Drip irrigation at 0.6Epan throughout the crop life	0.20	7.66	25.74	33.30	42.30	43.20
I_3 – Drip irrigation at 0.8Epan throughout the crop life	0.21	8.40	27.72	35.10	44.10	43.50
I_4 – Drip irrigation at 0.4 Epan up to flowering (81 DAS) and 0.6Epan later on	0.19	6.99	21.15	27.90	35.10	34.50
I_5 – Drip irrigation at 0.4 Epan up to flowering (81 DAS) and 0.8 Epan later on	0.23	7.30	22.08	29.49	37.90	38.50
I_6 – Drip irrigation at 0.6 Epan up to flowering (81 DAS) and 0.8 Epan later on	0.17	7.84	26.55	34.20	42.30	41.80
I_7 – Drip irrigation at 0.4 Epan up to 50 DAS, 0.6 Epan from 51 – 95 DAS and 0.8 Epan 96 – maturity	0.21	7.32	22.05	28.05	35.20	35.20
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	0.23	7.24	22.59	29.52	38.80	39.30
General mean	**0.20**	**7.45**	**23.62**	**30.58**	**38.58**	**38.50**

The differences in NAR values among different irrigation treatments were not appreciable between 0 – 10 DAS, 10 – 30 DAS and 30 – 60 DAS. But during 60 – 90 DAS the treatments viz., I_2, I_3, I_4, I_5, I_6 and I_7 had higher NAR values in comparison to I_1 and I_8. At later stages between 90 – 120 DAS no consistent trend was observed. Between 120 DAS – harvest the difference in NAR values among different treatments was not appreciable.

4.3.4 Leaf area duration

The mean leaf area duration (LAD) increased gradually up to 30 DAS, showed steep increase between 30 – 60 DAS, and thereafter it continued to increase but at a decreasing rate up to 120 DAS and attained asymptotic form towards harvest (Table 17).

The difference in LAD among different treatments was not discernible until 30 DAS. Whereas between 30 – 60 DAS, 60 – 90 DAS, 90 – 120 DAS and 120 DAS – harvest treatments I_2 (0.6Epan throughout the crop life), I_3 (0.8Epan throughout the crop life) and I_6 (0.6Epan up to flowering and 0.8 later on) registered markedly higher mean LAD as compared to other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Among the latter treatments at all the growth stages I_1 treatment (0.4Epan throughout the crop life) recorded markedly lower mean LAD.

4.4 YIELD ATTRIBUTES

4.4.1 Number of spikes per plant

The number of spikes/plant was significantly influenced by different irrigation treatments (Table 18). The mean number of spikes/plant was 4.79.

Table 18. Number of spikes plant^{-1} and capsules plant^{-1} of castor as influenced by different irrigation treatments

Treatment details	No. of spikes/ plant	No. of capsules/plant		
		Primary	Secondary & tertiary	Total
I_1 – Drip irrigation at 0.4Epan throughout the crop life	3.81	105.8	144.6	250.4
I_2 – Drip irrigation at 0.6Epan throughout the crop life	5.20	129.2	161.3	290.5
I_3 – Drip irrigation at 0.8Epan throughout the crop life	5.52	127.0	158.8	285.8
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	4.63	120.0	145.8	265.8
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	4.53	117.0	150.5	267.5
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	5.32	136.0	159.0	295.0
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan from 96 – maturity	4.81	117.8	154.2	272.0
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	4.54	112.0	148.5	260.5
SEm±	0.16	--	--	3.45
CD (P=0.05)	0.50	--	--	10.6
General mean	**4.79**	**120.6**	**152.8**	**273.4**

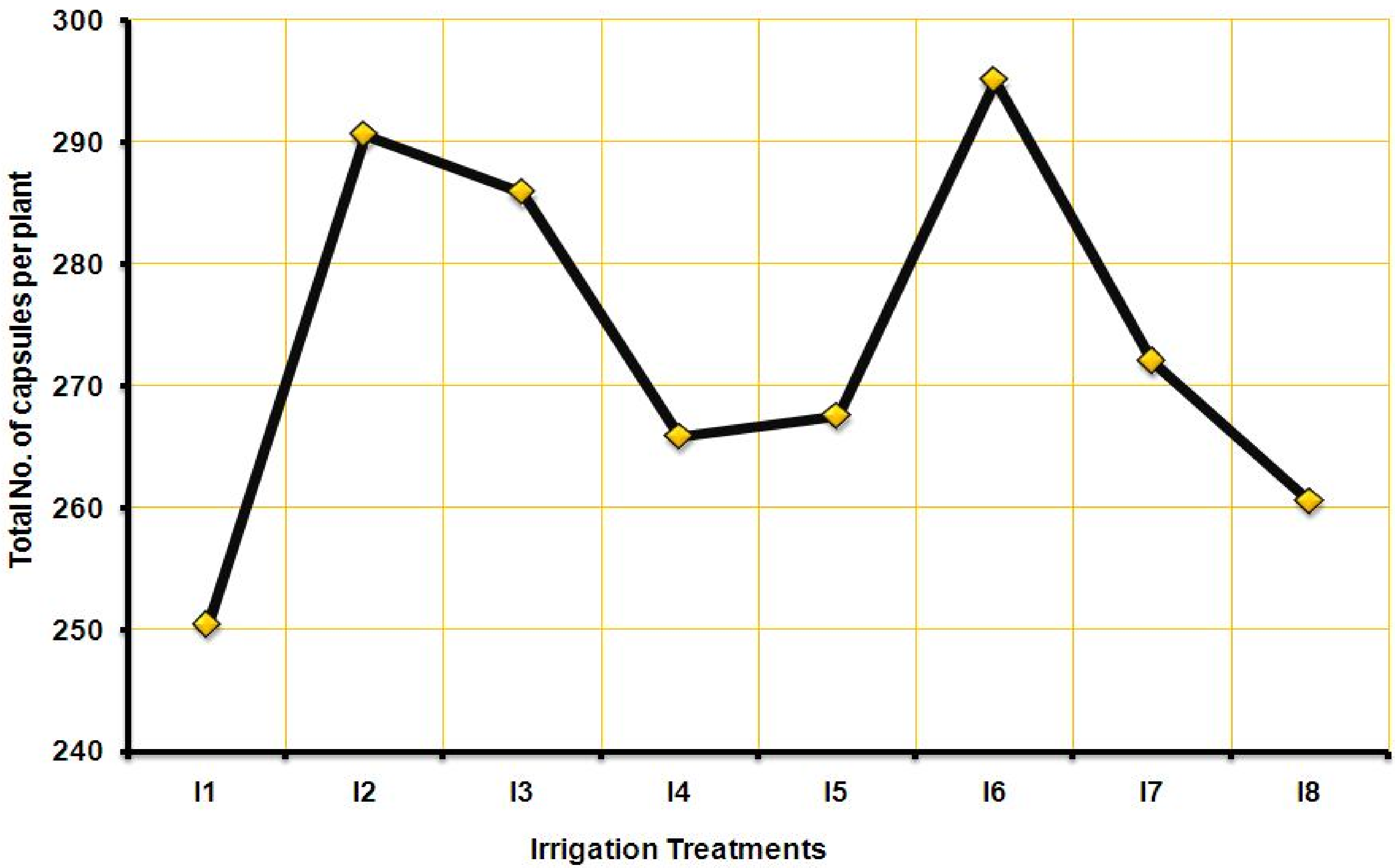

Fig. 7. Total number of capsules per plant of castor as influenced by different irrigation treatments

Scheduling of irrigations with drip at 0.6Epan (I_2) and 0.8Epan (I_3) throughout the crop life, and drip irrigation at 0.6Epan up to flowering and 0.8Epan later on (I_6) recorded significantly higher number of spikes/plant as compared to other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8 except that the difference between I_2 and I_7 was not significant. Likewise the number of spikes/plant recorded under I_4, I_5, I_7 and I_8 were statistically on par. Significantly lower number of spikes per plant was produced by the crop when irrigated by drip at 0.4Epan throughout the crop life (I_1).

4.4.2 Capsules per plant

Capsules/plant was significantly influenced by different irrigation treatments (Table 18 and Fig. 7). The mean total number of capsules/plant were 273.4.

Drip irrigation of castor at 0.6Epan up to flowering + 0.8Epan later on (I_6) resulted in higher number of capsules/plant, but it was on par with I_2 (0.6Epan throughout crop life) and I_3 (0.8Epan throughout the crop life) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Among the later treatments I_7 (drip irrigation at 0.4 Epan up to 50 DAS, 0.6 Epan from 51 – 95 DAS and 0.8 Epan from 96 – maturity) had significantly higher capsules/plant as compared to I_1 and I_8 but statistically on par with I_4 and I_5. Lowest number of capsules/plant was produced by the crop in I_1 treatment (drip irrigation at 0.4Epan throughout the crop life) but it was on par with the crop in I_8 treatment (surface irrigation at 0.8 IW/CPE ratio throughout the crop life).

4.4.3 Spike length

Both primary and secondary spike length was significantly influenced by different irrigation treatments (Table 19). The mean primary and secondary spike length was 54.1 cm and 32.3 cm, respectively.

Scheduling of irrigations with drip at 0.6Epan throughout the crop life (I_2) recorded significantly higher primary spike length but it was on par with I_3 (0.8Epan throughout the crop life) and I_6 (drip irrigation at 0.6Epan up to flowering and 0.8Epan later on) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. However, the difference in primary spike length between I_1, I_4, I_5, I_7 and I_8 was statically not significant. Significantly lower spike length was recorded by the crop irrigated by drip at 0.4Epan throughout the crop life (I_1) but it was on par with the crop in I_8 treatment (surface irrigation at 0.8 IW/CPE ratio throughout the crop life).

Secondary spike length recorded under treatments I_2 (drip at 0.6Epan throughout the crop life), I_3 (0.8Epan throughout the crop life) and I_6 (drip irrigation at 0.6Epan up to flowering and 0.8Epan later on) was statically on par and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Among the later treatments the I_5 (Drip irrigation at 0.4 Epan up to flowering and 0.8 Epan later on) the highest secondary spike length but the differences between I_4, I_5 and I_7 and that between I_1, I_4, I_7 and I_8 were not significant.

Table 19. Spike length (cm) of castor as influenced by different irrigation treatments

Treatment details	Spike length (cm)	
	Primary	Secondary & tertiary
I_1 – Drip irrigation at 0.4Epan throughout the crop life	45.0	29.0
I_2 – Drip irrigation at 0.6Epan throughout the crop life	60.4	35.5
I_3 – Drip irrigation at 0.8Epan throughout the crop life	59.8	34.5
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	52.5	31.3
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8 Epan later on	54.0	32.0
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8 Epan later on	58.7	35.7
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	53.6	30.9
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	49.1	29.5
SEm±	1.7	0.8
CD (P=0.05)	5.4	2.4
General mean	**54.1**	**32.3**

4.4.4 Capsule weight

The capsule weight was not significantly influenced by different irrigation treatments (Table 20). The mean capsule weight was 15.5g.

4.4.5 Seeds per capsule

However, the seeds/capsule was not significantly influenced by different irrigation treatments (Table 20). The mean number of seeds/capsule was 3.73.

4.4.6 Test (100-seed) weight

The test (100-seed) weight was significantly influenced by different irrigation treatments (Table 20 and Fig. 8). The mean test (100-seed) weight was 37.8g.

Drip irrigation scheduling at 0.6Epan up to flowering and 0.8Epan later on (I_6) had higher test (100-seed) weight but it was on par with I_2 (drip irrigation scheduling at 0.6Epan throughout the crop life) and I_3 (drip irrigation scheduling at 0.8Epan throughout the crop life) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Further it was noticed that the difference in test weight (100-seed) between I_2, I_3 and I_5 and that between I_1, I_4, I_5, I_7 and I_8 were not significant.

4.4.7 Bean yield per plant

The seed yield/plant was significantly influenced by different irrigation treatments (Table 20 and Fig. 9). The mean seed yield/plant was 311.6g.

Table 20. Yield attributes of castor as influenced by different irrigation treatments

Treatment details	Capsule weight (g)	Seeds/ capsule	Test (100-Seed) weight (g)	Bean yield/ plant (g)
I_1 – Drip irrigation at 0.4Epan throughout the crop life	1.45	3.7	36.5	251.6
I_2 – Drip irrigation at 0.6Epan throughout the crop life	1.63	3.8	39.0	345.6
I_3 – Drip irrigation at 0.8Epan throughout the crop life	1.64	3.8	39.0	347.8
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	1.49	3.7	36.5	298.9
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	1.51	3.7	37.9	305.1
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	1.62	3.7	39.5	351.5
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6 Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	1.53	3.7	37.5	310.8
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	1.51	3.8	37.0	281.1
SEm± CD (P=0.05)	0.07 NS	0.1 NS	0.46 1.41	9.3 28.5
General mean	**1.55**	**3.73**	**37.8**	**311.6**

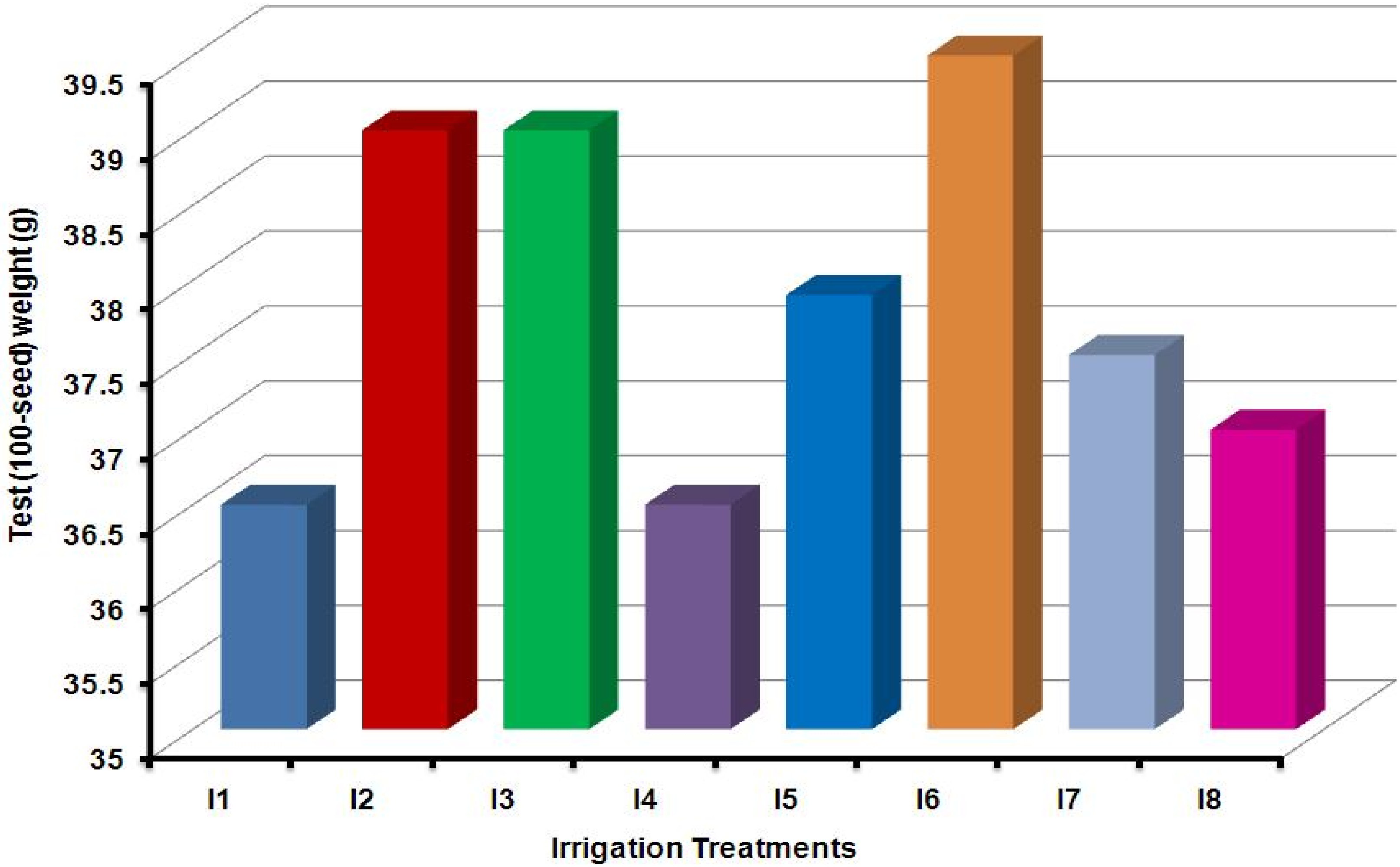

Fig. 8. Test (100-seed) weight of castor as influenced by different irrigation treatments

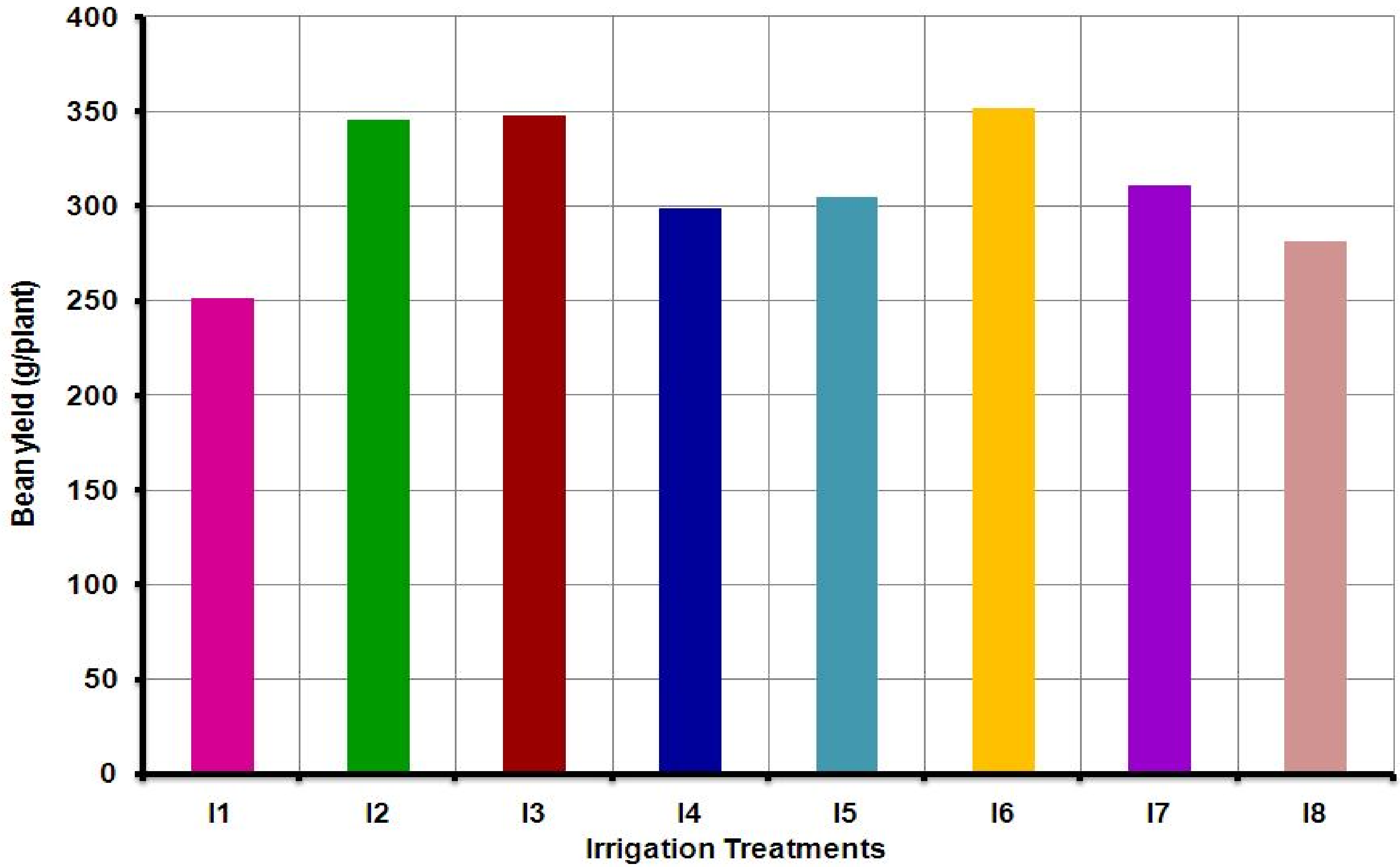

Fig. 9. Bean yield per plant of castor as influenced by different irrigation treatments

Scheduling of irrigations with drip at 0.6Epan up to flowering and 0.8Epan later on (I_6) registered higher seed yield/plant but it was on par with I_2 (drip irrigation scheduling at 0.6Epan throughout the crop life) and I_3 (drip irrigation scheduling at 0.8Epan throughout the crop life) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Among the later treatments the difference in bean yield/plant between I_4 (drip irrigation at 0.4Epan up to flowering and 0.6Epan later on) I_5 (drip irrigation at 0.4Epan up to flowering and 0.8Epan later on) and I_7 (drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan from 96 – maturity) was statistically not significant. Likewise the difference in bean yield/plant between I_4, I_5 and I_8 and that between I_1 and I_8 were not significant.

4.5 YIELD

4.5.1 Bean yield

Data on castor bean yield as influenced by different irrigation treatments is presented in Table 21 and Fig. 10. The mean bean yield was 3122.5 kg/ha.

Drip irrigation scheduling at 0.6Epan up to flowering and 0.8Epan later on (I_6) registered higher bean yield but it was statistically on par with I_2 (drip irrigation scheduling at 0.6Epan throughout the crop life) and I_3 (drip irrigation scheduling at 0.8Epan throughout the crop life) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Among the later treatments the difference in bean yield/ha between I_4 (drip irrigation at 0.4Epan up to flowering and 0.6Epan later on), I_5 (drip irrigation at 0.4Epan up to flowering and 0.8Epan

Table 21. Castor bean yield, total dry matter production and harvest index as influenced by different irrigation treatments

Treatment details	Bean yield (Kg/ha)	Total dry matter (Kg/ha)	Harvest index (%)
I_1 – Drip irrigation at 0.4Epan throughout the crop life	1859	5024	37.0
I_2 – Drip irrigation at 0.6Epan throughout the crop life	3805	9280	41.0
I_3 – Drip irrigation at 0.8Epan throughout the crop life	3950	9518	41.5
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	2850	7402	38.5
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	2775	7115	39.0
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	4280	10191	42.0
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	2910	7462	39.0
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	2550	6623	38.5
SEm±	161	383	0.8
CD (P=0.05)	495	1175	2.5
General mean	**3122**	**7827**	**39.5**

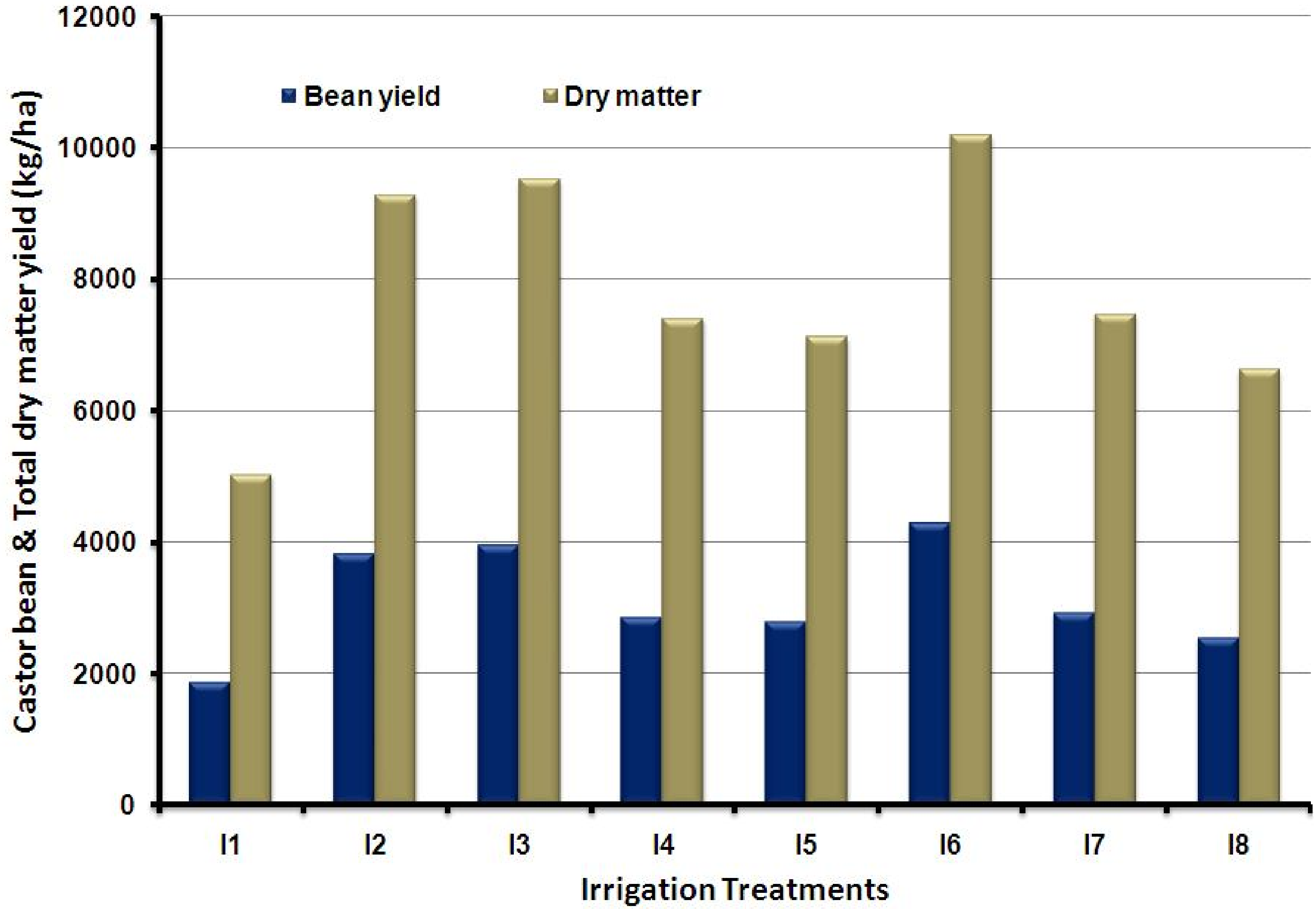

Fig .10. Castor bean yield and total dry matter production as influenced by different irrigation treatments

later on), I_7 (drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity) and I_8 (surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life) was statistically not significant. Lowest bean yield/ha was recorded under I_1, wherein irrigations were scheduled with drip at 0.4Epan throughout the crop life.

4.5.2 Total dry matter

Total dry matter production was significantly influenced by different irrigation treatments (Table 21 and Fig. 10). The mean total dry matter was 7827.4 kg/ha.

Scheduling of irrigations with drip adopting 0.6Epan up to flowering and 0.8Epan later on (I_6) registered higher total dry matter but it was statistically on par with (drip irrigation scheduling at 0.6Epan throughout the crop life) and I_3 (drip irrigation scheduling at 0.8Epan throughout the crop life) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Among the later treatments the difference in total dry matter/ha between I_4 (drip irrigation at 0.4Epan up to flowering and 0.6Epan later on), I_5 (drip irrigation at 0.4Epan up to flowering and 0.8Epan later on), I_7 (drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity) and I_8 (surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life) was statistically not significant. Lowest total dry matter yield/ha was recorded under I_1, wherein irrigations were scheduled with drip at 0.4Epan throughout the crop life.

4.5.3 Harvest index

The harvest index was significantly influenced by different irrigation treatments (Table 21). The mean harvest index was 39.5%.

Drip irrigation scheduling at 0.6Epan up to flowering and 0.8Epan later on (I_6) registered higher harvest index but it was statistically on par with I_2 (drip irrigation scheduling at 0.6Epan throughout the crop life) and I_3 (drip irrigation scheduling at 0.8Epan throughout the crop life) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Further it was observed that the difference in harvest index between I_2, I_3, I_5 and I_7; that between I_4, I_5, I_7 and I_8 and that between I_1, I_4, I_5, I_7 and I_8 were statistically not significant.

4.5.4 Oil content

The oil content was significantly influenced by different irrigation treatments (Table 22). The mean oil content was 39.5%.

Irrigating castor with drip at 0.6Epan up to flowering and 0.8Epan later on (I_6) registered higher oil content but it was on par with I_2 (drip irrigation scheduling at 0.6Epan throughout the crop life) and I_3 (drip irrigation scheduling at 0.8Epan throughout the crop life) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. However, the difference in oil content among the later treatments viz., I_1, I_4, I_5, I_7 and I_8 was statistically not significant.

Table 22. Oil content and oil yield of castor as influenced by different irrigation treatments

Treatment details	Oil (%)	Oil yield (kg/ha)
I_1 – Drip irrigation at 0.4Epan throughout the crop life	45.6	847
I_2 – Drip irrigation at 0.6Epan throughout the crop life	47.2	1796
I_3 – Drip irrigation at 0.8Epan throughout the crop life	47.0	1856
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	45.3	1291
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	45.5	1262
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	48.8	2088
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	45.0	1309
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	44.9	1144
SEm±	0.39	92
CD (P=0.05)	1.20	285
General mean	**46.1**	**1449**

4.5.5 Oil yield

Data on castor oil yield as influenced by different irrigation treatments is presented in Table 22. The mean oil yield was 1449.7 kg/ha.

Drip irrigation scheduling at 0.6Epan up to flowering and 0.8 Epan later on (I_6) registered higher oil yield but it was statistically on par with I_2 (drip irrigation scheduling at 0.6Epan throughout the crop life) and I_3 (drip irrigation scheduling at 0.8Epan throughout the crop life) and significantly superior over other irrigation treatments viz., I_1, I_4, I_5, I_7 and I_8. Among the later treatments the difference in oil yield/ha between I_4 (drip irrigation at 0.4Epan up to flowering and 0.6Epan later on), I_5 (drip irrigation at 0.4Epan up to flowering and 0.8Epan later on), I_7 (drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity) and I_8 (surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life) was statistically not significant. Significantly lower oil yield/ha was recorded under I_1, wherein irrigations were scheduled with drip at 0.4Epan throughout the crop life.

4.6 WATER USE STUDIES

4.6.1 Water productivity

Water productivity was significantly influenced by different irrigation treatments (Table 23). The mean water productivity was 0.895 kg m^{-3} of water.

In general water productive efficiency decreased with increase in water supply. The highest water productive efficiency was recorded where irrigations were scheduled with drip at 0.6Epan throughout the crop life (I_2) but it was on par

Table 23. Water productivity of castor as influenced by different irrigation treatments

Treatment details	Water Productivity (Kg m^{-3})
I_1 – Drip irrigation at 0.4Epan throughout the crop life	0.777
I_2 – Drip irrigation at 0.6Epan throughout the crop life	1.137
I_3 – Drip irrigation at 0.8Epan throughout the crop life	0.923
I_4 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.6Epan later on	0.998
I_5 – Drip irrigation at 0.4Epan up to flowering (81 DAS) and 0.8Epan later on	0.840
I_6 – Drip irrigation at 0.6Epan up to flowering (81 DAS) and 0.8Epan later on	1.070
I_7 – Drip irrigation at 0.4Epan up to 50 DAS, 0.6Epan from 51 – 95 DAS and 0.8Epan 96 – maturity	0.848
I_8 – Surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life	0.571
SEm±	0.033
CD (P=0.05)	0.101
General mean	**0.895**

with I_6 and significantly superior over other irrigation treatments viz., I_1, I_3, I_4, I_5, I_7 and I_8. On the other hand the difference in water productivity values between I_6 and I_4; I_4 and I_3 and that between I_1, I_5 and I_7 were not significant but significantly higher in comparison to I_1 and I_8. Among the later two treatments I_1 (scheduling irrigations with drip at 0.4Epan throughout the crop life) had significantly higher water productivity than I_8 treatment.

4.6.2 Crop evapotranspiration at various growth sub-periods

During germination & establishment period the variation in crop evapotranspiration (ET_c) was not marked and it varied from 19.58 mm to 24.2 mm in different irrigation treatments (Table 24). At vegetative period the crop ET_c in I_2, I_3, I_6 and I_8 was comparable and varied between 71.35 mm to 83.12 mm but markedly higher than I_1, I_4, I_5 and I_7. Similar trend was observed at flowering period. Whereas at capsule development period I_3, I_6 and I_8 recorded comparable and higher crop ET_c values (98.05 mm to 107.95 mm), I_2, I_5 and I_7 intermediate values (72.00 mm to 83.5 mm) and I1 and I_4 lower values (50.67 mm to 67.05 mm). At seed filling period I_3, I_5, I_6, I_7 and I_8 were comparable and had higher crop ETc values; I_2 and I_4 intermediate crop ET_c values and lowest was recorded in I_1 treatment. Finally at maturity there was not marked variation in crop ET_c under different treatments.

The mean seasonal crop evapotranspiration (ET_c) was 350.78 mm (Table. 24). Maximum seasonal ET_c (445.87 mm) was recorded when irrigations were scheduled at an IW/CPE = 0.8 adopting surface check basin irrigation (I_8) as compared to drip irrigation treatments (239.3 mm to 428.08 mm). Among the drip irrigation treatments the seasonal crop ET_c increased with increase in irrigation water supply i.e., evaporation replenishment factor. Thus scheduling irrigations either at 0.8Epan throughout the crop life (I_3) or its combination treatment viz., I_6 (0.6 Epan up to flowering and 0.8 Epan later on) had higher seasonal crop ET_c values over other drip irrigation treatments. Reduction in pan evaporation replenishment factor in I_7, I_2 and I_5 caused reduction in seasonal crop ET_c.

Table 24. Crop evapotranspiration of castor at different crop growth subperiods under different treatments

Crop growth sub-periods	Irrigation Treatment							
	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8
	Crop Evapotranspiration (mm)							
Establishment (0 – 15 DAS)	20.55	21.25	24.20	19.58	20.10	22.00	21.25	22.52
Vegetative (16 – 50 DAS)	47.20	71.41	83.12	47.27	48.25	71.35	47.95	77.83
Flowering (51 to 81 DAS)	50.35	73.15	94.20	49.70	50.12	75.65	69.50	100.17
Capsule development (82 – 106 DAS)	50.67	72.00	99.25	67.05	83.25	98.05	80.55	107.95
Seed filling (107 – 135 DAS)	50.28	72.75	99.00	76.60	101.05	104.90	99.25	102.40
Maturity (136 – 150 DAS)	20.25	24.00	28.25	25.42	27.65	28.00	24.00	35.00
Seasonal Crop ET_c (mm)	**239.30**	**334.56**	**428.08**	**285.62**	**330.42**	**399.95**	**342.50**	**445.87**

Table 25. Reference crop evapotranspiration (ET_o) at different crop growth subperiods at Rajendranagar

Crop growth sub-periods	Reference crop ET (ET_o) (mm) by different methods			
	Penman Monteith	Modified Penman	Adjusted Pan evaporation	Evaporation from USWB Class A Pan
Establishment (0 – 15 DAS)	47.6	51.6	50.4	63.9
Vegetative (16 – 50 DAS)	98.5	105.1	106.2	134.6
Flowering (51 to 81 DAS)	91.2	96.2	87.9	110.9
Capsule development (82 – 106 DAS)	87.5	89.5	82.3	104.5
Seed filling (107 – 135 DAS)	130.2	140.4	135.0	170.9
Maturity (136 – 150 DAS)	69.5	75.0	76.1	95.0
Seasonal ET_o (mm)	**524.5**	**557.8**	**537.9**	**679.8**

Table 26. Crop evapotranspiration rate of castor at different crop growth subperiods under different treatments

Crop growth sub-periods	Irrigation Treatment							
	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8
	Crop Evapotranspiration (mm day^{-1})							
Establishment (0 – 15 DAS)	1.37	1.41	1.61	1.30	1.34	1.46	1.41	1.50
Vegetative (16 – 50 DAS)	1.34	2.04	2.37	1.35	1.37	2.04	1.37	2.22
Flowering (51 to 81 DAS)	1.67	2.44	3.14	1.65	1.67	2.52	2.31	3.33
Capsule development (82 – 106 DAS)	2.02	2.88	3.97	2.68	3.33	3.92	3.22	4.31
Seed filling (107 – 135 DAS)	1.73	2.50	3.41	2.64	3.48	3.61	3.42	3.53
Maturity (136 – 150 DAS)	1.35	1.60	1.88	1.69	1.84	1.86	1.60	2.33
Average ET_c rate (mm day^{-1})	**1.58**	**2.14**	**2.73**	**1.88**	**2.17**	**2.57**	**2.22**	**2.87**

Lowest seasonal crop ETc was exhibited by the crop in treatment I_1 wherein irrigations were scheduled at 0.4Epan throughout the crop life.

The cumulative value of crop ETc for different treatments increased with time (Fig. 11) and remained higher in surface irrigated crop at 0.8 IW/CPE ratio throughout the crop life (I_8) as compared to other irrigation treatments. Low pan evaporation replenishment at a given crop growth sub-period caused low cumulative crop ET_c. The crop in I_1 treatment (drip irrigation at 0.4Epan throughout the crop life) exhibited the maximum reduction in crop ET_c.

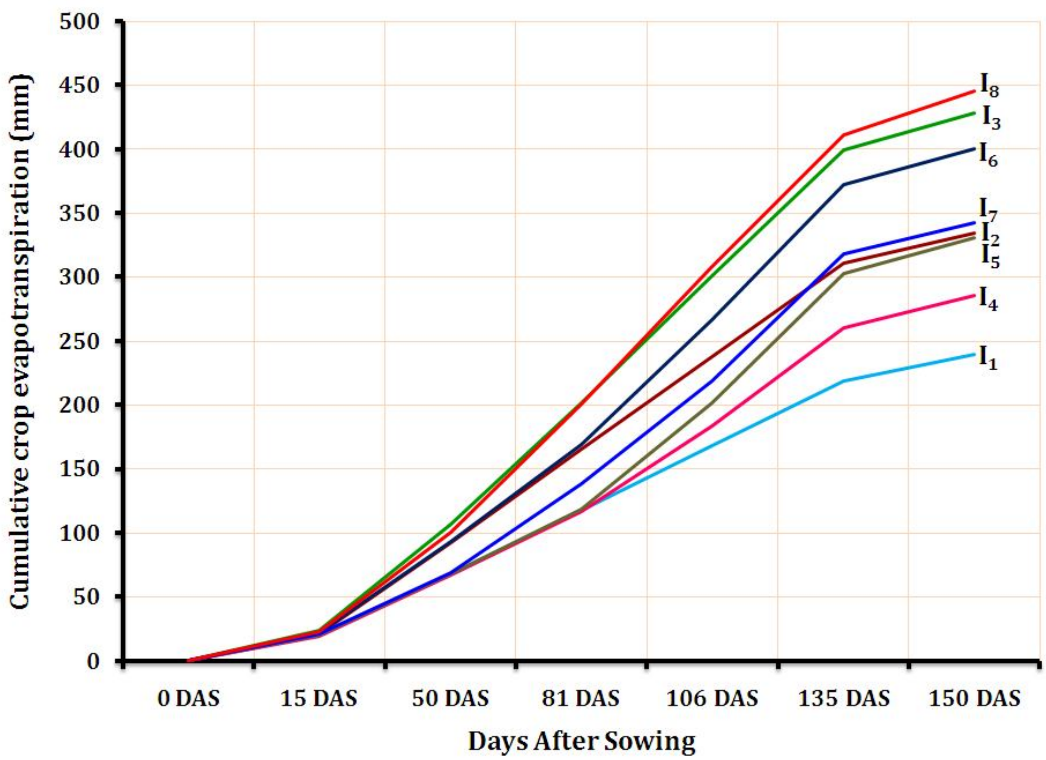

Fig. 11. Cumulative crop evapotranspiration of castor under different treatments

The reference crop evapotranspiration (ET_o) (Table 25) estimated by different methods viz., Penman Monteith, Modified Penman, Adjusted Pan evaporation methods showed trend similar to I_8 treatment except that the ETo values were slightly higher than crop ETc at all the crop growth sub-periods. Comparison of ETo estimates between different methods, it was observed that the estimates from Modified Penamn were higher followed by Adjusted pan evaporation and Penman Monteith methods.

Perusal of the data in Table 26 indicated that the variation in crop evapotranspiration rate was similar to periodical crop ETc at different crop growth sub-periods.

4.6.3 Crop coefficient

Data on crop coefficients (K_c) calculated based on castor crop ET_c and ET_o derived from Penman Monteith, Modified Penman and Adjusted Pan evaporation methods, and evaporation from USWB Class A Pan are presented in Table 27 to 28.

Perusal of the K_c values derived based on different ET_o methods and pan evaporation in different treatments revealed that they were low in the germination & establishment period, increased through vegetative and flowering period, attained peak values during capsule development period and thereafter gradually decreased towards maturity. The K_c values were primarily a function of evaporation replenishment factor during a given crop growth sub-period in different irrigation treatments. Higher the replenishment factor i.e., higher the water application level, higher were the K_c values. For example peak K_c values were registered under I_8 treatment in all the methods *viz.,* Penman Monteith (1.233), Modified Penman (1.206) and Adjusted Pan evaporation (1.311) methods,

Table27. Crop coefficients of castor in relation to ETo by Penman Monteith and FAO Modified Penman method as influenced by different irrigation treatments

Irrigation Treatment	Crop growth sub-periods						Total season
	Germination & Establishment	Vegetative	Flowering	Capsule development	Seed filling	Maturity	
Based on Penman Monteith Method							
I_1	0.431	0.479	0.552	0.579	0.386	0.291	0.456
I_2	0.446	0.724	0.802	0.822	0.558	0.345	0.637
I_3	0.508	0.843	1.032	1.134	0.760	0.406	0.816
I_4	0.411	0.479	0.544	0.766	0.588	0.365	0.544
I_5	0.422	0.489	0.549	0.951	0.776	0.397	0.629
I_6	0.462	0.724	0.829	1.120	0.805	0.402	0.762
I_7	0.446	0.486	0.762	0.920	0.762	0.345	0.653
I_8	0.473	0.790	1.098	1.233	0.786	0.503	0.850
Average	**0.449**	**0.626**	**0.771**	**0.940**	**0.677**	**0.381**	**0.668**
Based on FAO Modified Penman Method							
I_1	0.398	0.449	0.523	0.566	0.358	0.270	0.429
I_2	0.411	0.679	0.760	0.804	0.518	0.320	0.599
I_3	0.468	0.790	0.979	1.108	0.705	0.376	0.767
I_4	0.379	0.449	0.516	0.749	0.545	0.338	0.512
I_5	0.389	0.459	0.520	0.930	0.719	0.368	0.592
I_6	0.426	0.678	0.786	1.095	0.747	0.373	0.717
I_7	0.411	0.456	0.722	0.90	0.706	0.320	0.614
I_8	0.436	0.740	1.041	1.206	0.729	0.466	0.799
Average	**0.414**	**0.587**	**0.730**	**0.919**	**0.628**	**0.353**	**0.628**

Table 28. Crop coefficients of castor in relation to ETo by FAO Adjusted Pan evaporation method and free water evaporation from USWB Class a pan evaporimeter as influenced by different irrigation treatments

Irrigation Treatment	Crop growth sub-periods						Total season
	Germination & Establishment	Vegetative	Flowering	Capsule development	Seed filling	Maturity	
Adjusted Pan evaporation method							
I_1	0.401	0.444	0.572	0.615	0.372	0.266	0.444
I_2	0.421	0.672	0.832	0.874	0.538	0.315	0.621
I_3	0.480	0.782	1.071	1.201	0.733	0.371	0.795
I_4	0.388	0.445	0.565	0.814	0.567	0.334	0.530
I_5	0.398	0.454	0.570	1.011	0.748	0.363	0.614
I_6	0.436	0.671	0.860	1.191	0.777	0.367	0.743
I_7	0.421	0.451	0.790	0.978	0.735	0.315	0.636
I_8	0.446	0.732	1.139	1.311	0.758	0.459	0.828
Average	**0.423**	**0.581**	**0.799**	**0.999**	**0.653**	**0.348**	**0.651**
USWB Class A Pan evaporation							
I_1	0.321	0.350	0.454	0.484	0.294	0.213	0.352
I_2	0.332	0.530	0.659	0.688	0.425	0.252	0.492
I_3	0.378	0.617	0.849	0.949	0.579	0.297	0.629
I_4	0.306	0.351	0.448	0.641	0.448	0.267	0.420
I_5	0.314	0.358	0.451	0.796	0.591	0.291	0.486
I_6	0.344	0.530	0.682	0.938	0.613	0.294	0.588
I_7	0.332	0.356	0.626	0.770	0.580	0.252	0.503
I_8	0.352	0.578	0.903	1.033	0.599	0.368	0.655
Average	**0.334**	**0.458**	**0.634**	**0.787**	**0.516**	**0.279**	**0.515**

and evaporation from USWB Class A Pan (1.033). This was followed by I_3 (0.8Epan throughout the crop life) and I_2 (0.6Epan throughout the crop life) treatments. Lowest K_c values in all the methods were registered under I_1 treatment (Penman Monteith – 0.579; Modified Penman – 0.566; Adjusted Pan evaporation – 0.615; and evaporation from USWB Class A Pan – 0.484) wherein irrigations were scheduled at 0.4Epan throughout the crop life.

The K_c values derived from different methods viz., Penman Monteith, Modified Penman and Adjusted Pan evaporation methods, and evaporation from USWB Class A Pan under I_2 treatment were used (in view of higher yield with maximum water productivity) to construct the crop coefficient curve (Fig. 12) for predicting castor crop ET_c and practical irrigation scheduling.

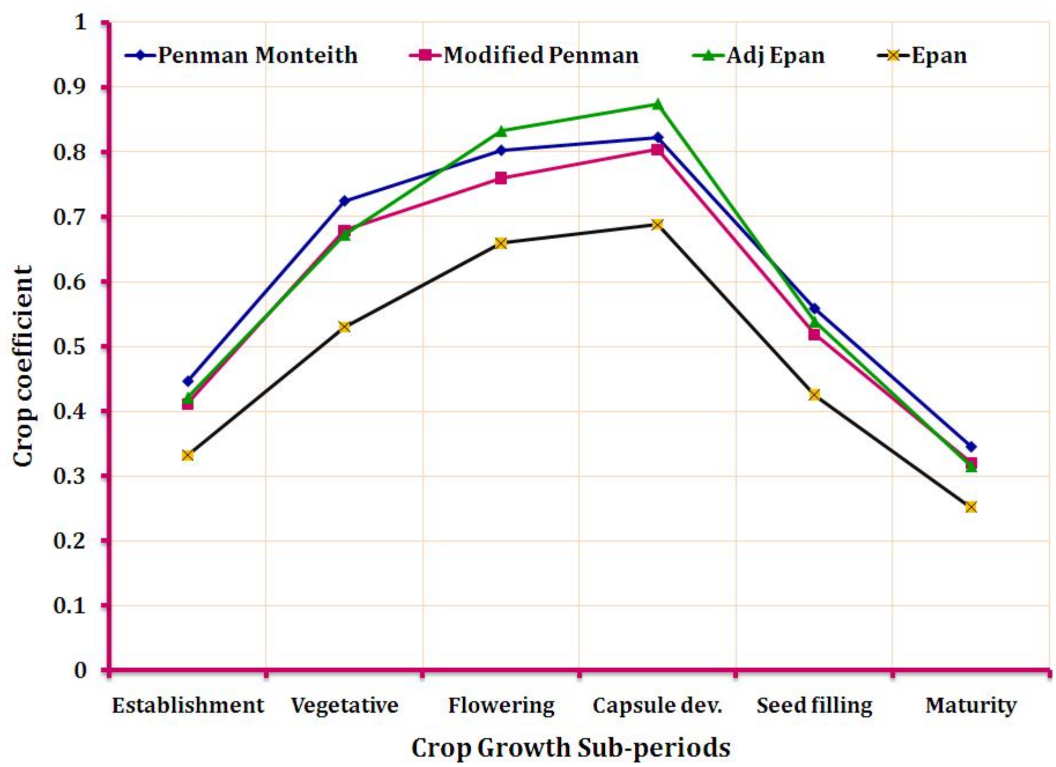

Fig. 12. Crop coefficient curves for castor

The curves in Fig. 12 revealed that the K_c values were low in the initial stage owing to incomplete canopy cover (i.e., LAI); with the advancement of the crop age, the K_c value increased due to increase in LAI and reached peak values during capsule development period. Over the penultimate crop growth sub-period of seed filling the K_c marginally decreased and at maturity period it precipitously reached to a relatively low value in all the methods.

4.6.4 Water production function

The relationship between castor bean yield (Y) and seasonal crop evapotranspiration (ET_c) was established following both linear and quadratic water production functions. The resultant functions and test statistics are as follows

Linear:

$$Y = 880.36 + 63926\, ET_c$$

$$R^2 = 0.306 \quad F\ value = 2.645$$

Quadratic:

$$Y = -9535 + 68.603 ET_c - 0.0895\, ET_c^2$$

$$R^2 = 0.99 \quad F\ value = 35.7$$

The test statistics (R^2 and F – value) of linear production function indicated that it was statistically not significant. The explained total variation (R^2) in bean yield was very low i.e., 30.6% (Fig. 13). On the other hand the test statistics and R^2 were significant for quadratic production function. The explained total variation in bean yield was 99.0%, suggesting that in the present study the best fit for the data

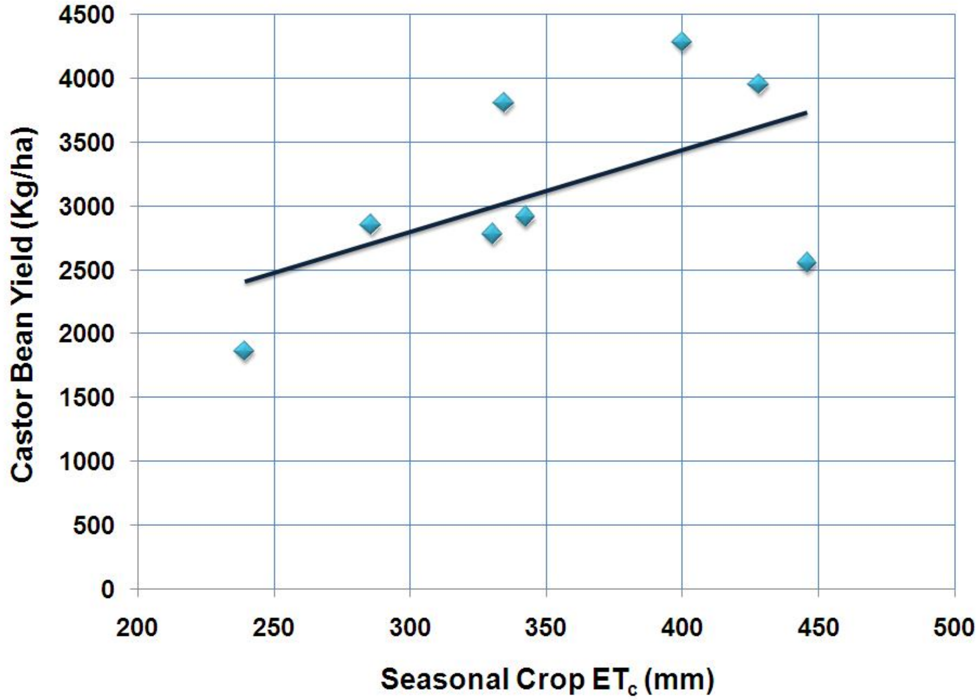

Fig. 13. Linear crop water production function for castor

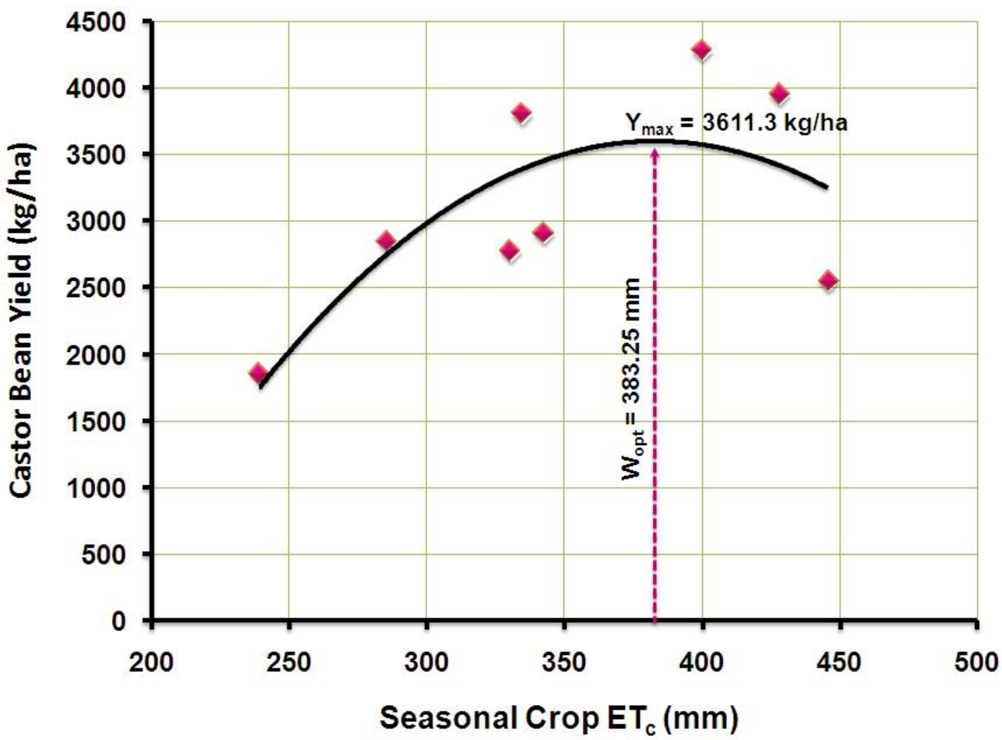

Fig. 14. Quadratic crop water production function for castor

was obtained with quadratic form as water production function i.e., the castor bean yield increased with increase in crop evapotranspiration, but the increase in bean yield was not proportional to the crop evapotranspiration (Fig. 14). The maximum yield (Y_{max}) was bracketed within the administered water levels. The predicted maximum castor bean yield (Y_{max}) of 3611.3 kg ha^{-1} was obtained with 383.25 mm of water. The water production function did not emerge through the origin and the value of regression constant (a) was negative, indicating that some minimum amount of crop ET_c (182.5 mm) was required to be expended to realize the economic yield in castor grown in *rabi* season.

The optimum quantity of water (ET_c) level that will maximize the net return under prevailing prices considered (Rs. 10.0 ha-mm and Rs. 30.0 kg^{-1} of castor bean yield), worked out to be 381.4 ha mm with the resultant bean yield of 3611 kg ha^{-1}. This optimum level represents one point on the derived demand curve (Fig. 14). Thus economic optimum levels of water under different appraised prices of output and input showed that the optimum level of irrigation water was inversely related to increase in the price of water (P_w), whereas it (ET_{opt}) had a direct positive relationship with the price of castor bean yield (Table 29). The increase in price of water from Rs. 7.5 mm^{-1} to Rs. 15.0 mm^{-1} under a given price of bean yield, say Rs. 20 kg^{-1}, is associated with only 2.1 mm decrease in the demand of water. Similar trends were noted with net returns and net return per rupee invested. The gross returns, net returns and net return per rupee invested varied from Rs. 72194.2 to 144447.6 ha^{-1}, Rs. 46708.3 to 121781.1 ha^{-1} and 1.832 to 5.732, respectively.

Table 29. Economic returns of castor at optimum levels of water under spectrum of appraised prices

Price of water (P_w) (Rs. mm^{-1})	Price of yield (P_y) (Rs. Kg^{-1})	Price ratio ($P_r=P_w/P_y$)	Optimum water (mm)	Optimum yield (kg ha^{-1})	Gross returns (Rs. ha^{-1})	Cost of water (Rs. ha^{-1})	Cost of cultivation (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	Net returns/rupee invested
7.5	**20**	0.3750	381.16	3610.90	72218.0	2858.7	19800.0	49559.3	2.187
	30	0.2500	381.86	3611.12	108333.6	2863.9	19800.0	85669.7	3.780
	40	0.1875	382.21	3611.19	144447.6	2866.5	19800.0	121781.1	5.732
10.0	**20**	0.5000	380.46	3610.59	72211.8	3804.6	19800.0	48607.2	2.059
	30	0.3333	381.39	3611.00	108330.0	3813.9	19800.0	84716.1	3.587
	40	0.2500	381.86	3611.12	144444.8	3818.6	19800.0	120826.2	5.115
12.5	**20**	0.6250	379.76	3610.19	72203.8	4747.0	19800.0	47656.8	1.941
	30	0.4166	380.92	3610.80	108324.0	4761.5	19800.0	83762.5	3.410
	40	0.3125	381.51	3611.02	144440.8	4768.8	19800.0	119871.2	4.879
15.0	**20**	0.7500	379.06	3609.71	72194.2	5685.9	19800.0	46708.3	1.832
	30	0.5000	380.46	3610.59	108317.7	5706.9	19800.0	82810.8	3.246
	40	0.3750	381.16	3610.90	144436.0	5717.4	19800.0	118918.6	4.660

4.6.5 Economic viability of drip irrigation in castor

Data on detailed cash flow and various economic indices worked out by discounted cash flow technique between check basin and surface drip irrigated castor are presented in Table 30.

Perusal of the data in Table 30 indicated that total investments on irrigation infrastructure spread over 10-year life period were markedly higher by 88.4% under drip irrigated castor as compared to surface check basin method of irrigation. However, the production expenses were less in case of drip irrigated castor by 8.8% as compared to castor crop irrigated by conventional check basin method.

The farm income registered under drip irrigated castor was markedly higher (1.28 lakh ha^{-1}) than furrow method of irrigation (0.76 lakh ha^{-1}). The economic indices (Table 30) suggested that the net present value (NPV) registered under both the methods of irrigation was positive. However, NPV obtained under drip irrigated castor was significantly higher (Rs. 76,323 ha^{-1}) than that realized with surface check basin irrigated castor crop (Rs. 45,568 ha^{-1}) owing to enhanced bean yields.

The breakeven point (BEP) for price indicated that the profitability of both under conventional check basin and surface drip irrigated castor was achieved above Rs. 9.98 kg^{-1} and Rs. 10.02 kg^{-1} price, respectively. Similarly BEP for yield suggested that profitability was achieved above 33.21% and 33.43% of castor bean yield data plugged each year under conventional check basin and surface drip irrigated castor, respectively. Further it was noticed that the investments &

expenses incurred by farmers under both the methods of irrigation were fully recovered from the income of very first year itself.

Table 30. Detailed cash flow and economic indices for check basin and surface drip irrigated castor

Particulars	Check basin	Surface drip
Yield (Tons/ha)	2550	4280
Price (Rs./kg)	30	30
TOTAL INCOME (Rs./ha)	**76,500**	**1,28,400**
Subsurface Drip system (Rs./ha)	--	19,468
Pumping unit & Electrical work (Rs./ha)	2,550	2,550
TOTAL INVESTMENTS	**–2,550**	**–22,018**
Land preparation (Rs./ha)	–2,500	–2,500
Seed material (Rs./ha)	–1,350	–1,350
Sowing (Rs./ha)	–1,000	–1,000
Weed control (Rs./ha)	–2,500	–1,000
Manures + Fertilizers (Rs./ha)	–4,000	–4,000
Irrigation scheduling (Rs./ha)	–3,814	–2,000
Electricity charges (Rs./ha)	–500	–300
Plant protection (Rs./ha)	–2,500	–2,000
Harvesting (Rs./ha)	–2,250	–3,000
Threshing & cleaning	–1,750	–2,500
Transportation (Rs./ha)	–750	–1,250
TOTAL EXPENSES (Rs./ha)	**–22,914**	**–20,900**
NET CASH FLOW (Rs./ha)	**51,036**	**85,482**
NET PRESENT VALUE (at 12%)	**45,568**	**76,323**
PAYBACK PERIOD	**1 year**	**1 year**
BEP PRICE	**9.98**	**10.02**
BEP Yield (%)	**–66.71**	**–66.57**

4.6.5 Relationship between crop evapotranspiration (ET_c) and reference crop ET (ET_o)

A perusal of the empirical regression constants and coefficients in Table 31 revealed that the castor crop ET_c was significantly and positively correlated with reference crop evapotranspiration estimated by different empirical methods.

The explained total variation as indicated by coefficient of determination (R^2) was 66.2% by Penman Monteith derived ET_o, 61% by Modified Penman derived ET_o, 52.3% by Adjusted Pan evaporation derived ET_o and 52.3% by USWB Class A Pan evaporation. The variance ratio for testing R^2 were significant (P=0.05) in all the cases. Likewise the linear significant (P=0.05) linear regression coefficients (b) in all the cases suggested the predictive capability of the functions is high (Fig. 15, 16, 17 and 18). This can be interpreted to mean that ET_o estimates derived by any of the empirical methods viz., Penman Monteith, Modified Penman and Adjusted Pan evaporation methods and evaporation from USWB Class A pan evaporimeter could be used for reliable prediction of castor crop ET_c.

4.7 REGRESSION OF BEAN YIELD ON GROWTH & YIELD ATTRIBUTES

Empirical equations pertaining to the regression of bean yield on a given growth and yield component of castor are presented in Table 32 and illustrated in Fig. 19 to 26.

Table 31. Regression of crop evapotranspiration (ET_c) of castor (from I_2 treatment) on reference crop evapotranspiration (ET_o) derived by different methods

S.No.	Relationship	Regression constants, coefficients and test statistics				
		a	b	t-value for b	R^2	F – Value for testing R^2
1	Crop ET_c versus ET_o derived by Penman Monteith method	–9.9183	0.7513*	3.80	0.662*	7.86
2	Crop ET_c versus ET_o derived by Modified Penman method	–6.7358	0.6722*	3.50	0.610*	6.25
3	Crop ET_c versus ET_o derived by Adjusted Pan evaporation method	–2.3363	0.6480*	3.09	0.523*	4.39
4	Crop ET_c versus Evaporation from USWB Class A Pan evaporimeter	–2.5711	0.5148*	3.13	0.532*	4.55

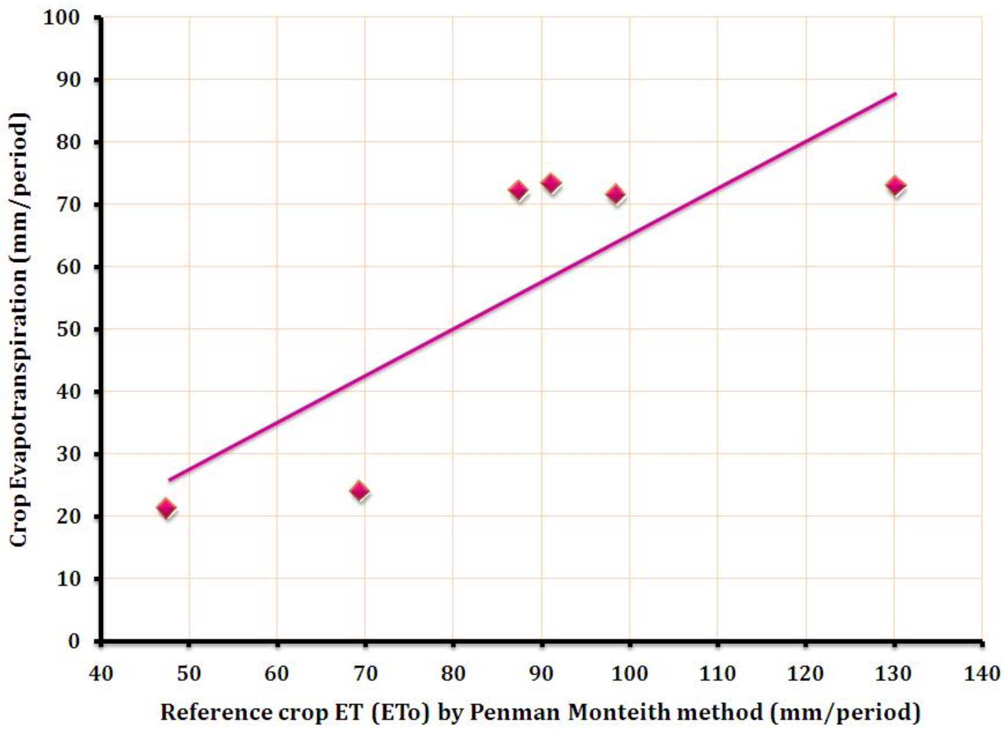

Fig. 15. Regression of crop ET_c on ET_o derived by Penman Monteith method

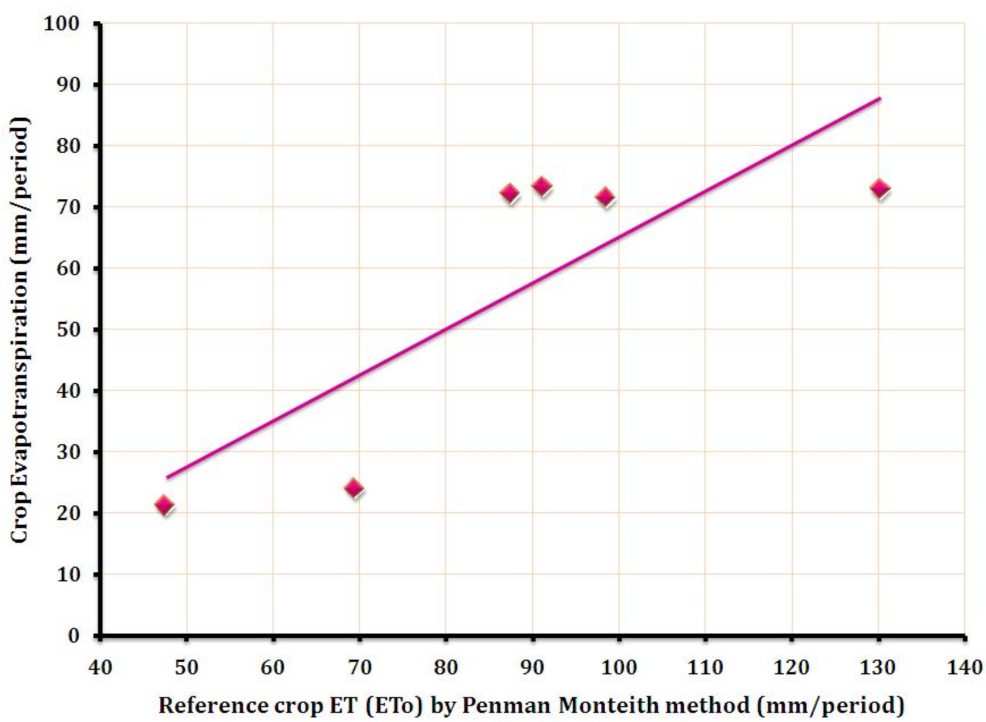

Fig. 16. Regression of crop ET_c on ET_o derived by Modified Penman method

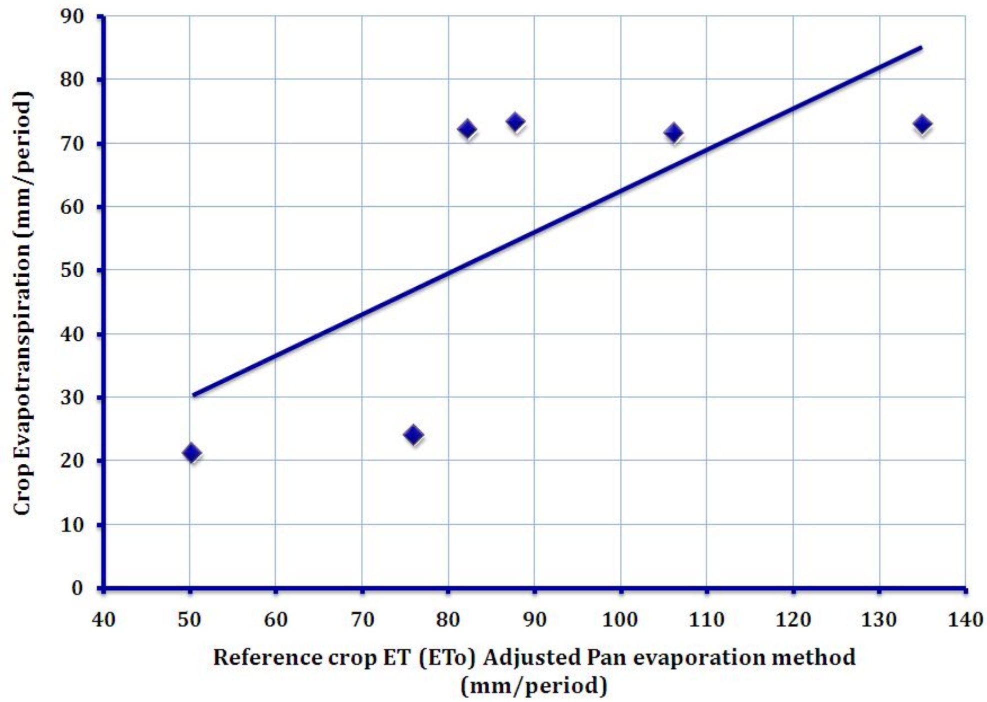

Fig. 17. Regression of crop ET_c on ET_o derived by Adjusted Pan evaporation method

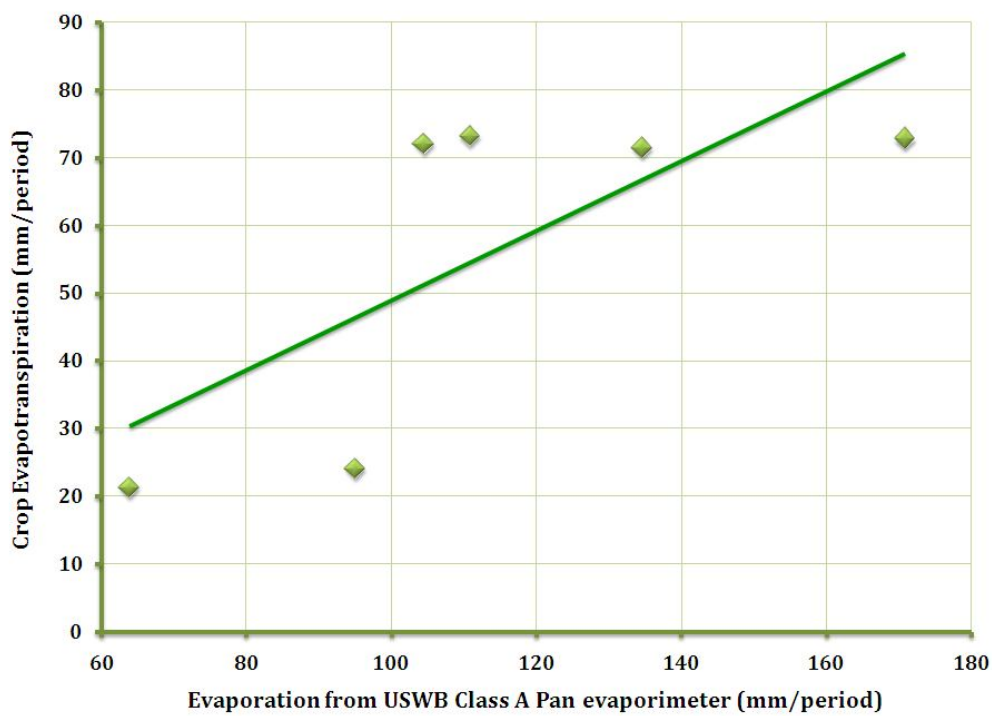

Fig. 18. Regression of crop ET_c on USWB Class A Pan evaporation

Perusal of the empirical data in Table 32 revealed that the independent variables significantly explained the variation in bean yield in all the functions as evident from the high coefficient of determination (R^2) values which varied from 0.639 to 0.977. The variance ratio (F-Value) for testing R^2 was significant at P=0.01 in all the cases. All the growth (plant height and leaf area index) and yield components (capsules/plant, primary spike length, secondary spike length, capsules per plant, seeds per capsule, capsule weight and test weight) had positive regression coefficients and statistically significant at (P=0.05) except secondary spike length suggesting that the bean yield increased linearly with increase in a given growth and yield component. However, the magnitude of reinforcement in bean yield varied with the magnitude of 'b" coefficient, which in turn was a function of independent variable (growth and yield component) and their unit of measurement (Fig. 19 to 26).

Further, the correlation studies (Table 33) between various growth and yield components indicated significant and positive correlation among themselves except between seeds per capsule versus plant height, spikes per plant, primary spike length, secondary spike length, capsules per plant, test weight and bean yield per plant.

4.8 RELATION BETWEEN SEASONAL CROP ETc VERSUS LEAF AREA INDEX AND LEAF AREA DURATION

The crop evapotranspiration (ET_c) showed a positive and significant (P=0.01) correlation with leaf area index and leaf area duration (Fig. 27 and 28).

Table 32. Empirical estimates for the relationship between Castor bean yield and growth and yield components

S.No.	Relationship	Regression constants, coefficients and test statistics				
		a	b	t-value for b	R^2	F – Value for testing R^2
1	Castor Bean yield (g) – Plant height (cm)	71.72	1.831*	11.39	0.955	12.9**
2	Castor Bean yield (g) – Leaf area index	88.68	95.140*	3.63	0.687	13.2**
3	Castor Bean yield (g) – Spikes per plant	10.70	68.274*	9.64	0.939	92.9**
4	Castor Bean yield (g) – Primary spike length (cm)	–298.96	2.231*	12.92	0.965	166.9**
5	Castor Bean yield (g) – Secondary spike length (cm)	–482.79	212.532**ns**	0.79	0.639	9.6**
6	Castor Bean yield (g) – Capsules per plant	–409.40	465.880*	7.44	0.902	55.3**
7	Castor Bean yield (g) – Seeds per capsule	–727.26	27.442*	5.71	0.844	32.6**
8	Castor Bean yield (g) – Capsule weight (g)	–39.87	6.491*	16.11	0.977	259.7**
9	Castor Bean yield (g) – Test (100-seed) weight (g)	–104.22	12.873*	7.90	0.912	62.5**

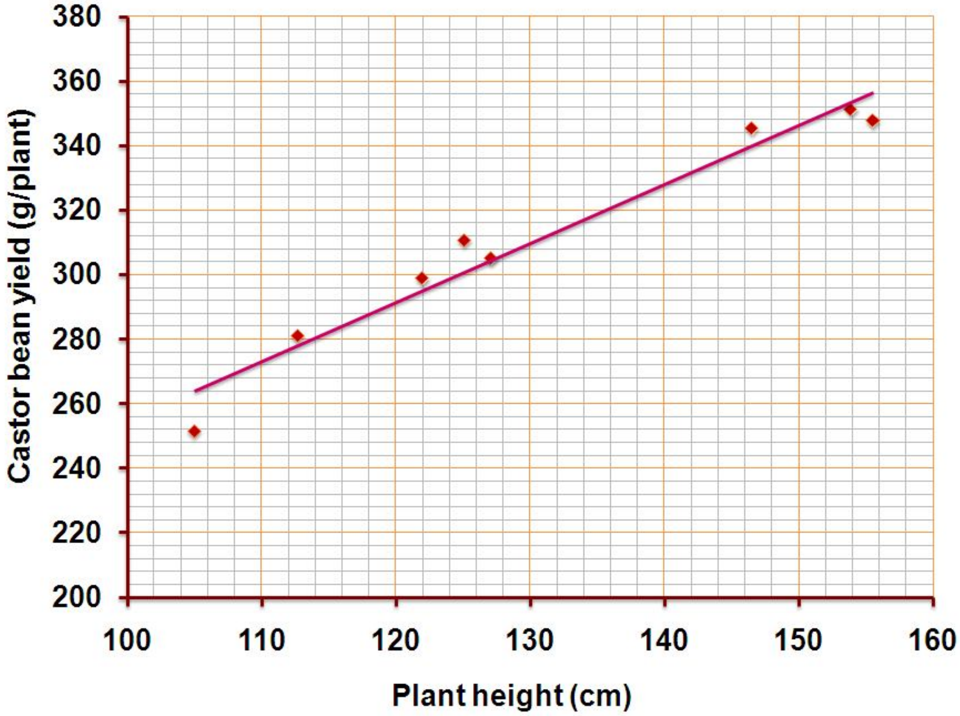

Fig. 19. Regression of bean yield on plant height

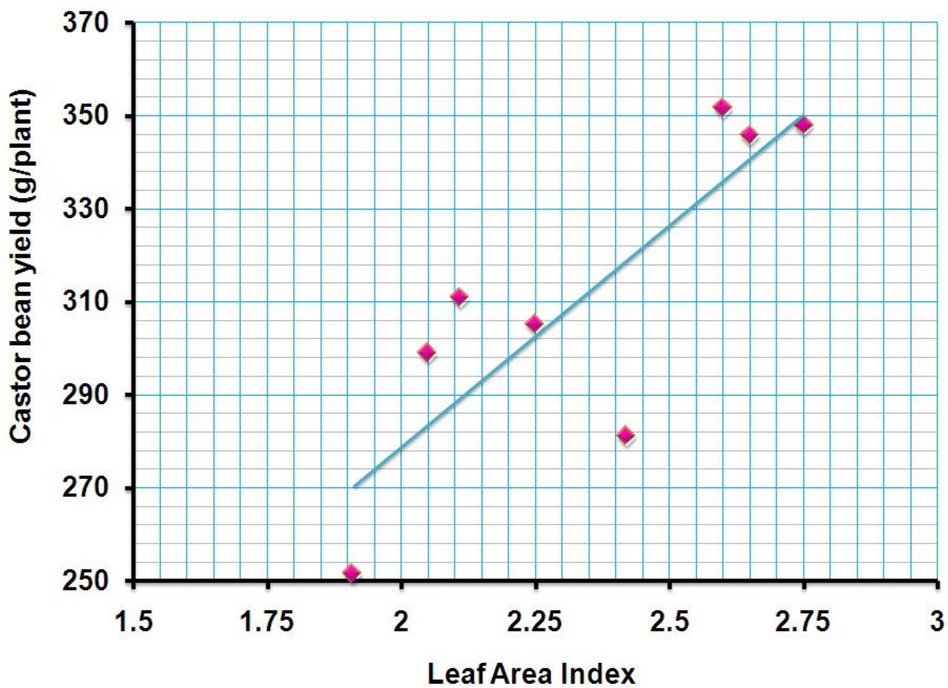

Fig. 20. Regression of bean yield on leaf area index

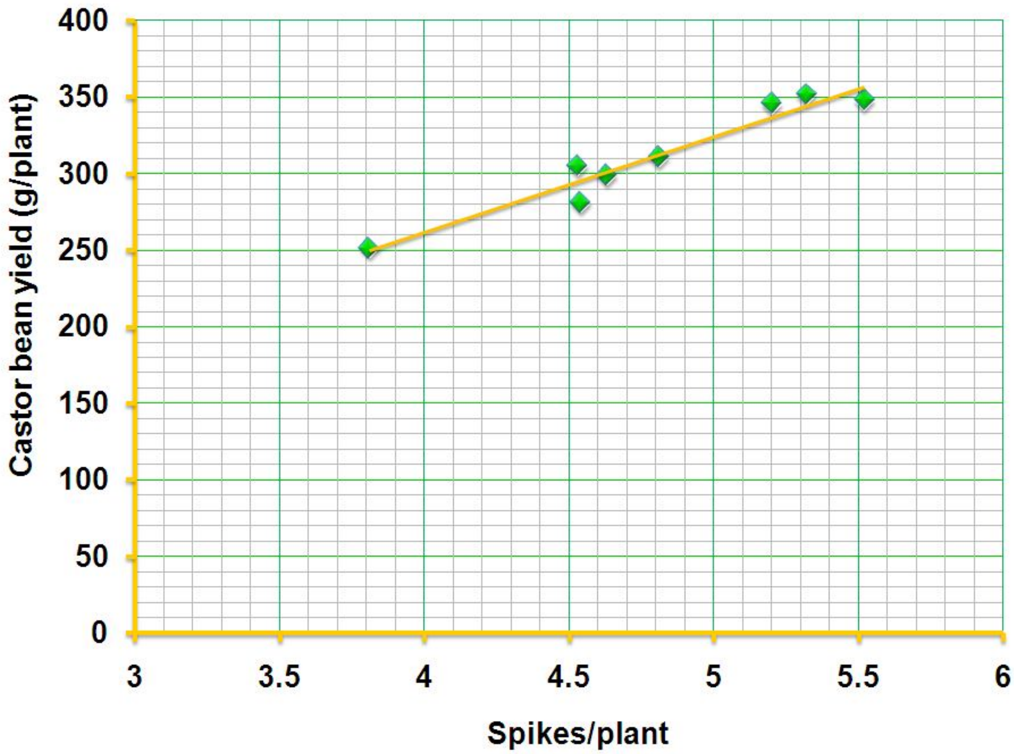

Fig. 21. Regression of bean yield on spikes/plant

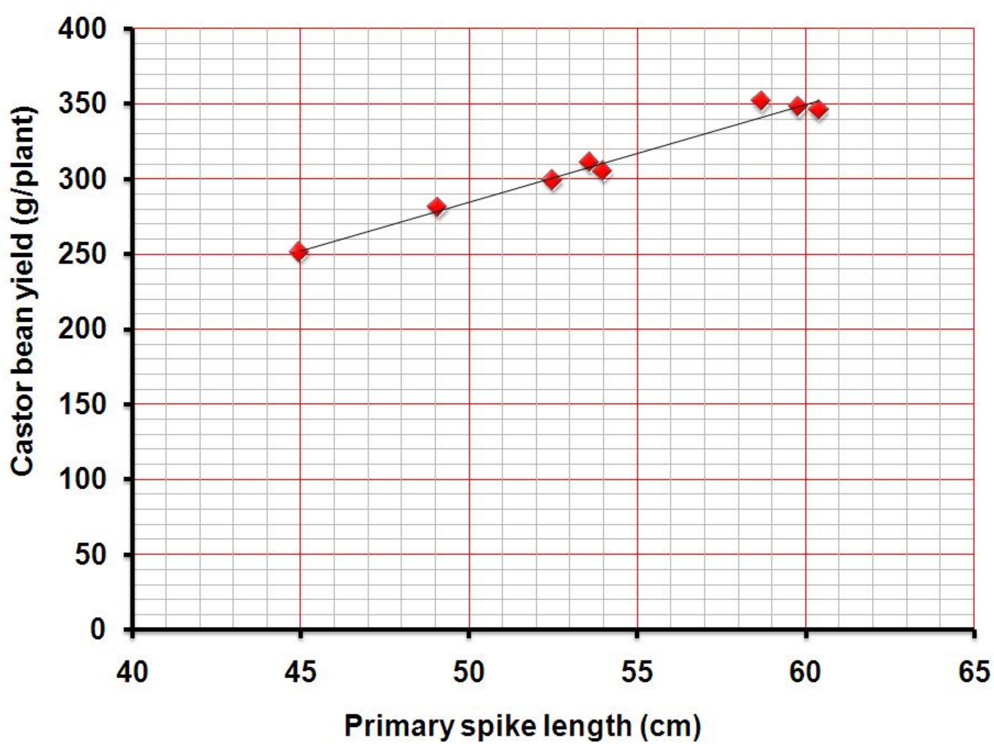

Fig. 22. Regression of bean yield on primary spikelength

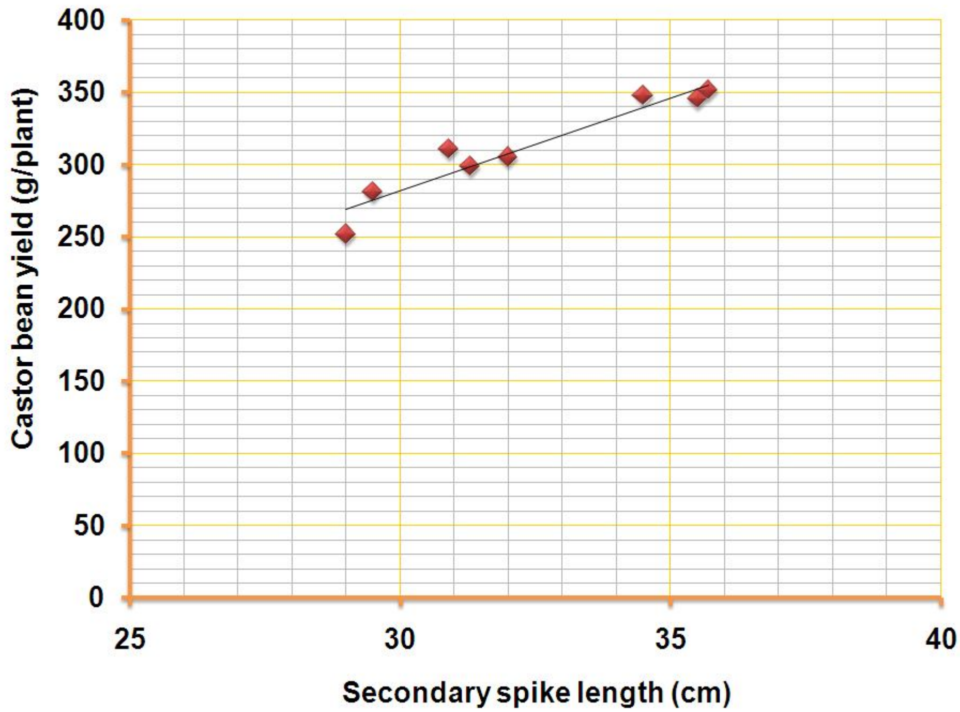

Fig. 23. Regression of bean yield on secondary spike length

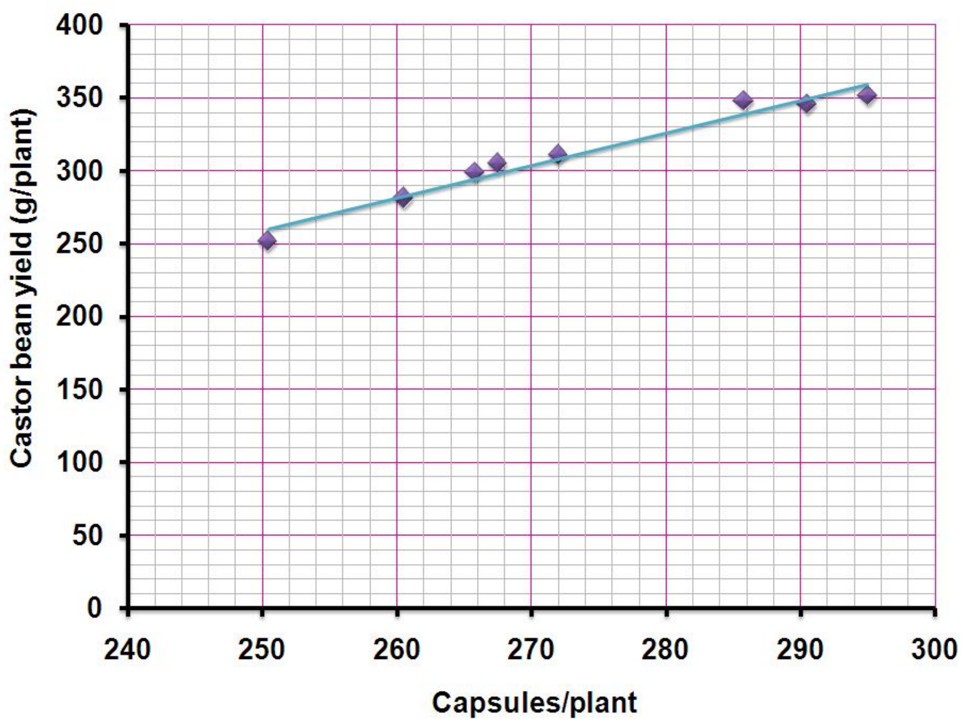

Fig. 24. Regression of bean yield on capsules/plant

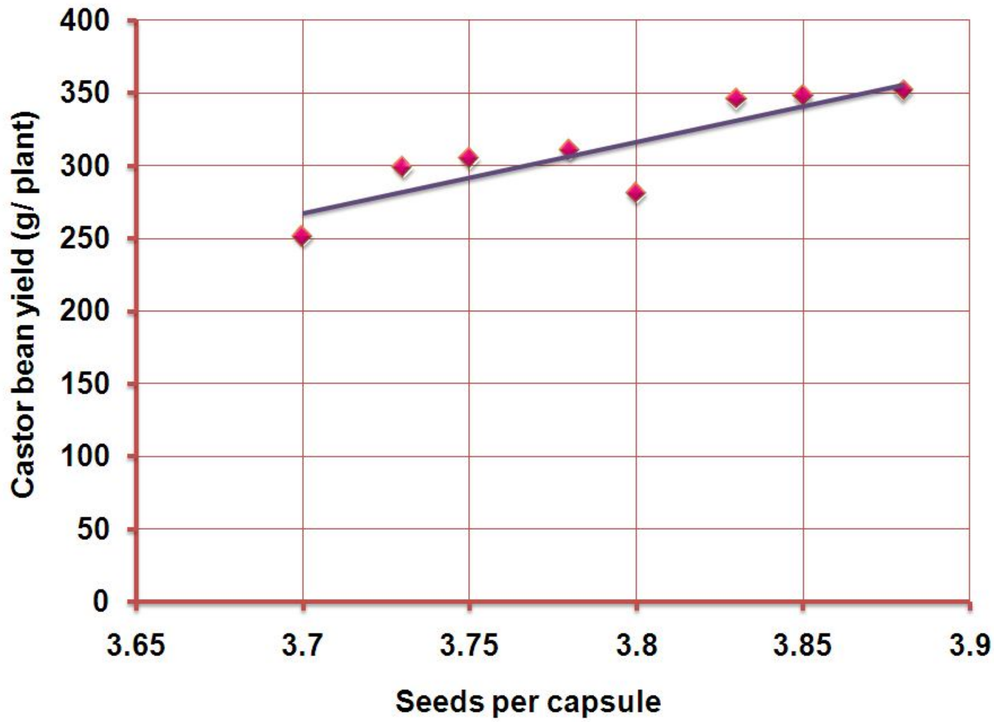

Fig. 25. Regression of bean yield on seeds/capsule

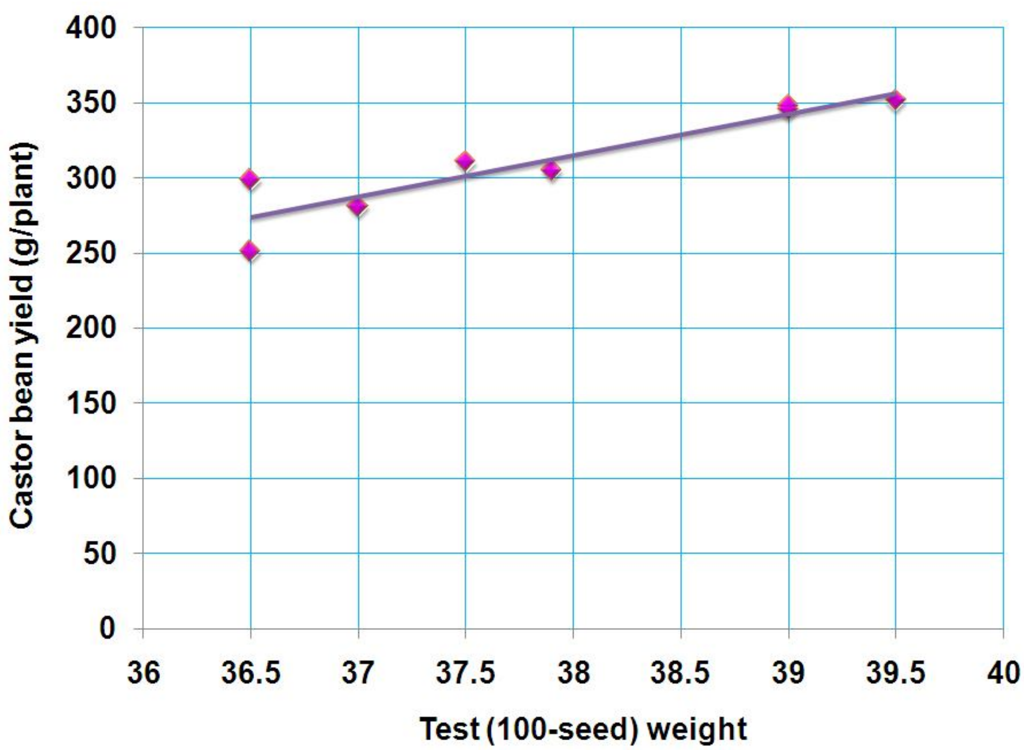

Fig. 26. Regression of bean yield on test (100-seed) weight

Table 33. Correlation matrix between Castor bean yield/plant, growth and yield attributes of castor

Parameter	Plant height	LAI	Dry matter	Spikes/ plant	Primary spike length	Secondary spike length	Capsules /plant	Seeds/ capsule	Capsule weight	Test weight	Bean yield/ plant
Plant height (cm)	1.000										
LAI	0.851	1.000									
Dry matter (g)	0.923	0.954	1.000								
Spikes/plant	0.948	0.871	0.942	1.000							
Primary spike length (cm)	0.963	0.821	0.978	0.949	1.000						
Secondary spike length (cm)	0.967	0.811	0.923	0.879	0.953	1.000					
Capsules/plant	0.967	0.828	0.944	0.937	0.988	0.971	1.000				
Seeds/capsule	0.317	0.708	0.389	0.441	0.352	0.273	0.292	1.000			
Capsule weight (g)	0.961	0.930	0.929	0.951	0.937	0.928	0.955	0.525	1.000		
Test weight (g)	0.944	0.872	0.846	0.861	0.897	0.937	0.942	0.328	0.943	1.000	
Castor Bean yield/plant (g)	0.978	0.829	0.967	0.969	0.989	0.955	0.983	0.310	0.950	0.911	1.000

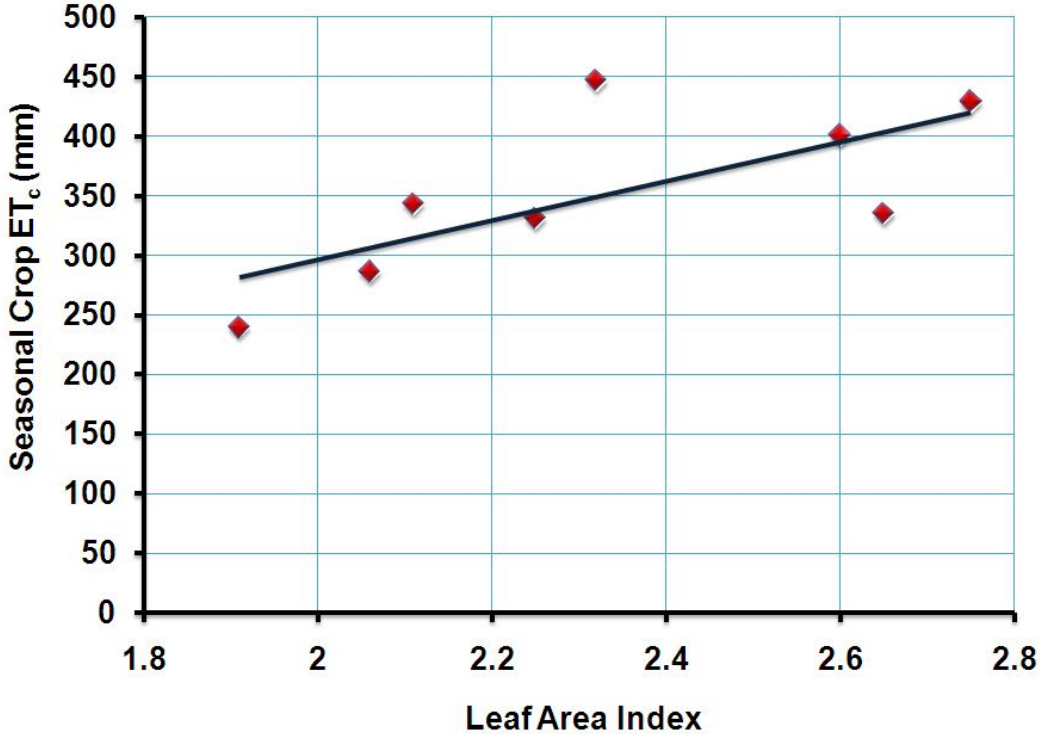

Fig. 27. Releationship between seasonal crop ET$_c$ and leaf area index

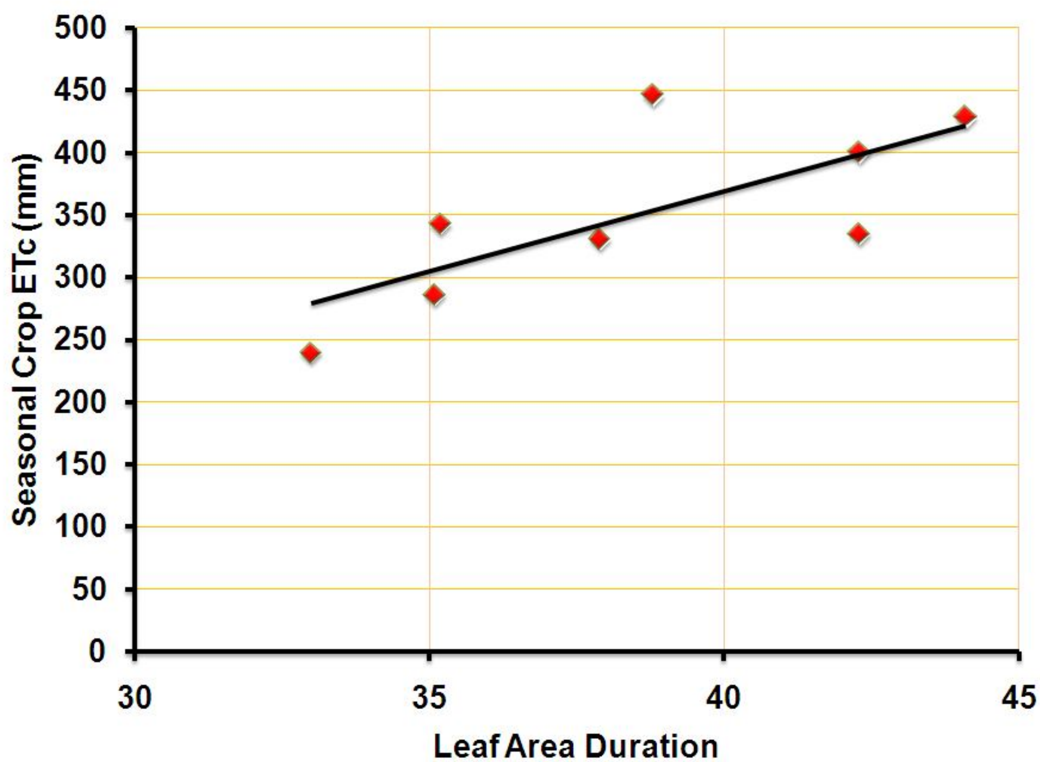

Fig. 28. Releationship between seasonal crop ET$_c$ and leaf area duration

Crop ETc : LAI relation

$$Crop\ ET_c = 31.183\ + 162.85\ LAI$$

$$R^2 = 0.505\ \ F\ value = 22.5$$

Crop ETc : LAD relation

$$Crop\ ET_c = 146.61\ + 12.89\ LAD$$

$$R^2 = 0.504\ \ F\ value = 23.5$$

The leaf area index accounted for about 0.505 of coefficient of determination (R^2) in crop ETc. Likewise the R^2 for crop ET_c**:**LAD function was 0.504. The variance ratio for testing R^2 and linear regression coefficients were highly significant (P = 0.01) in both the cases. The regression coefficients were positive suggesting that the ET_c increased linearly with increase in LAI and LAD (Fig. 27 and 28). The ET_c increased by 163.85 mm per unit of leaf area index and 12.89 mm per unit of LAD.

CHAPTER V

DISCUSSION

The importance of castor (*Ricinus communis* L.) as a non-edible oil seed crop in recent years has been greatly realized in India owing to growing world demand. The crop is also a major Forex earner for the country (FAO, 2010). Raising castor during winter (*rabi*) season under assured irrigation using hybrids is a new dimension in the castor cultivation which promises greater stability with higher productivity.

Water is a key limiting and costly input in irrigated agriculture. Judicious application of water both in time and quantity needs special attention for optimizing castor bean yields with maximum water productivity. Due to the economic importance of castor and the need to increase irrigation efficiency, drip irrigation is being investigated as a possible alternative. Further, drip being a capital-intensive technology there is a need to evaluate empirically the economic viability of drip irrigation impact on profitability of castor within a more systematical methodological framework.

Hence, the present field study was under taken with an objective to generate information on response of castor to drip irrigation scheduling, crop water requirement, crop coefficients and economic viability of drip irrigation in castor.

5.1 WEATHER IN RELATION TO CROP

For realizing potential yield, every crop has its characteristic cardinal limits of meteorological (weather) parameters but these conditions seldom prevail in field during crop growing season. If the fluctuations in the cardinal meteorological parameters are too wide, the crop plants fail to adjust to the prevailing weather conditions leading to poor growth and development resulting in lower crop yields. Hence, the weather conditions prevailed during crop growing season was examined before drawing any valid conclusions based on the experimental results.

Mild weather conditions prevailed during the crop experimentation period favouring normal growth and development of castor. The mean ambient temperatures registered at germination, establishment, vegetative, flowering, capsule development, seed filling and maturity periods of castor were found to match very well with the critical cardinal limits suggested for castor (Weiss, 1983). Solar radiation was adequate (8.1 to 9.6 hours as against the maximum possible sunshine duration of 11.0 to 12.4 hours). Wind speed varied from low (2.0 Km hour^{-1}) to marginally moderate (3.6 Km hour^{-1}), while the mean vapor pressure deficit calculated varied between 9.38 mbars to 20.75 mbars day^{-1} during the crop growing season of castor resulting in moderate to high ET_c rates (Table 26). Nevertheless, the moisture index ($P - ET_o/ET_o$) was negative (–0.91) since the precipitation was considerably lower (46.8 mm) than seasonal ET_o (524.5 mm) during the experimental period, emphasizing the need for supplemental irrigation for meeting the crop water (ET_c) requirements. According to Hargreaves (1975), values of moisture index < 0.33 reflect a moisture environment insufficient for active plant growth and need to be supplemented through irrigation for successful crop production; while values between 0.33 and 0.99 show adequate rainfall to satisfy plant water needs, values above 1.0 suggest that water is available in excessive amounts. The available moisture holding capacity of the experimental soil was 124.6 mm in 1.0 m depth of soil profile.

5.2 EFFECT OF IRRIGATION METHODS AND IRRIGATION LEVELS ON GROWTH, YIELD AND WATER PRODUCTIVITY OF CASTOR

Average castor bean yield was highest (4280.5 Kg ha^{-1}) when irrigations were scheduled by drip at 0.6Epan up to flowering and 0.8Epan later on (I_6) but it was statistically on par with I_3 (drip irrigation at 0.8Epan throughout the crop life) and I_2 (0.6Epan throughout the crop life) and significantly superior over I_1, I_4, I_5, I_7 and I_8 irrigation treatments. On an average I_6 treatment registered 56.5%, 33.4%, 35.1%, 32.0% and 40.4% more yield over I_1, I_4, I_5, I_7 and I_8, respectively. Among all the treatments lowest castor bean yield was observed in I_1 (drip irrigation at 0.4Epan throughout the crop life) treatment. Bean yield under surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life (I_8) was also statistically inferior in comparison to drip irrigation treatments (I_2 to I_7) except I_1. These trends could be traced to soil water balance in the crop root zone depth as was observed by variation in soil moisture reflected through ET_c/ET_o ratios (i.e., K_c values) under drip and conventional check basin irrigation treatments (Table 27 and 28). The regression of bean yield on seasonal ET_c revealed a significant correlation (r = 0.99, see Fig. 14).

Further, under drip irrigation the soil water content in the wetted portion of the plant root zone remains fairly constant because irrigation water is supplied slowly and frequently on daily basis as per the crop water requirement. Thus with high frequency drip irrigation the time-average soil water potential increases (soil water suction decreases) in the crop root zone and is restricted to a narrow range with elimination of the wide fluctuations in the soil water content, which typically result from conventional surface irrigation methods, as factors affecting plant growth and yield as was evident from variation in soil moisture content (based on crop ET_c) in drip irrigated (I_6) crop versus surface irrigated check basin (I_8) treatment (Fig. 11, Table 24 and 26). The maintenance of continuously high soil water potential, thus minimizing wide fluctuations in soil water content during the irrigation cycle, is an important and advantageous feature of drip irrigation (Bresler, 1977 and Bar Yosef, 1999). Other discussions (Childs and Hanks, 1975; Rawlins and Raats, 1975; Bar Yosef, 1999) also imply that the best irrigation policy is to apply water as frequently as possible.

Thus, maintained favourable soil water balance under I_6, I_3 and I_2 drip irrigation treatments as was evident from better soil moisture regimes and ET_c/ET_o ratios (K_c), which aided the crop plants to put forth improved performance over other treatments, since water plays a vital role in the carbohydrate metabolism, protein synthesis, cell wall synthesis and cell enlargement (Gardener et.al., 1985). Therefore, crop plants in I_6, I_3 and I_2 treatments had more plant height (Table 10), which in turn helped the plants to put forth more canopy i.e., LAI and as leaves continue to grow until a leaf area

(Table 11) that maximizes canopy photosynthesis with high photosynthetic efficiency i.e., NAR (Table 16) resulting in high crop growth rates (Table 15). Nagabhushanum and Raghavaiah (2005) reported that fully irrigated (0.8 IW/CPE ratio) castor crop had 32.7% more plant height than stressed crop (0.4 IW/CPE ratio). Further, the LAI was found to be positively and significantly (P=0.01) correlated (r = 0.851) to plant height. On an average the I_2, I_3 and I_6 treatments accumulated 12.4% to 27.9%, 15.6% to 30.5% and 10.7% to 26.5% more LAI, respectively over I_1, I_4, I_5, I_7 and I_8 irrigation treatments. Leaf area expansion is dependent on leaf turgor potential (Boyer, 1970). Further, it is well documented that cell enlargement is very sensitive to water deficits and the consequence is a marked reduction in leaf area (Begg and Turner, 1976 and Hasio et. al., 1976). Sudhakar and Rao (1998) reported that stressed crop had 3.16 LAI as compared to 4.5 LAI for non-stressed crop, a reduction of 30.0%. Development of adequate leaf area necessary for interception and utilization of incident solar radiation is important and has been shown to be closely related to final bean yield (Sudhakar and Rao, 1998; Sudha Rani, 2001; Nagabhushanam, 2002; Kiran, 2003). In the present study bean yield was found to be significantly (P=0.01) and positively correlated (0.829) to LAI.

All these factors together contributed to significantly higher dry matter in I_6, I_3 and I_2 treatments as compared to other irrigation treatments (I_1, I_4, I_5, I_7 and I_8). On an average, the I_2, I_3 and I_6 treatments accumulated 24.6% to 45.1%, 25.4% to 45.8% and 26.0% to 46.2% more dry matter, respectively over I_1, I_4, I_5, I_7 and I_8 irrigation treatments. Dry matter accumulation in castor is a result of leaf and stems growth during vegetative period and a combination of spike, capsules and seed growth concurrent with shifts in leaf and stem mass during reproductive period. Dry matter plant^{-1} was found to be significantly (P=0.01) and positively correlated with plant height (r = 0.923), LAI (r = 0.954), spikes plant^{-1} (r = 0.942), primary spike length (r = 0.978), secondary spike length (r = 0.923), capsules plant^{-1} (r = 0.944), and capsule weight (r = 0.929). Sudhakar and Rao (1998) opined that the LAI was the growth characteristic which limited the rate of dry matter accumulation of castor under soil water deficits. Likewise Nagabhushanam (2002) and Kiran (2003) observed that maintenance of higher soil water regime (0.8 IW/CPE ratio) favoured higher dry matter accumulation.

Thus, improved growth performance in the form of plant height, LAI, leaf area duration, NAR, CGR and dry matter by the crop in I_6, I_3 and I_2 treatments might have been responsible for more number of spikes plant^{-1} with longer primary and secondary spike length in these treatments (Table 19). These in turn contributed to large number of capsules plant^{-1} and seeds capsule^{-1} under I_6, I_3 and I_2 treatments (Table 18 and 20). The dependence of capsules plant^{-1} and capsule weight on growth traits was evident from significant (P=0.01) and positive association between them (Table 33). Further, these trends may be assigned to the fact that high frequency drip irrigation seem to provide favourable soil water potential and plant water balance contributing to more number capsules plant^{-1}, seeds capsule^{-1} and capsule weight (Bresler, 1977; Bucks et.al., 1982; Firake et. al., 1998;).

Castor test (100-seed) weight is an index of seed density and is important with respect to castor bean yield. The higher test weight was associated with treatments where the crop was adequately irrigated during the capsule development and seed filling period (I_2, I_3, I_5 and I_6) when compared to other irrigation treatments. These results emphasize the importance of adequate water supply during capsule development and seed filling periods for obtaining more number of seeds capsule^{-1} and higher test weight that contribute to higher harvest indices (Table 21), in turn higher bean yield (DOR, 1994; Sudhakar and Rao, 1998; Kiran, 2003). The regression of bean yield on number of capsules plant^{-1} (R^2 = 0.902), number of seeds capsule (R^2 = 0.844) and test weight (R^2= 0.912) showed a significant (P=0.01) and positive association between them.

On the other hand, lower evaporation replenishment factor in I_1, I_4, I_5 and I_7 drip irrigated treatments during individual growth sub-periods of vegetative, flowering and capsule development induced soil water deficits in the crop root zone. This caused ET_c to fall below in I_1, I_4, I_5 and I_7 drip irrigated treatments relative to ET_c under I_2, I_3 and I_6 treatments. This unfavourable soil moisture environment not only reduced the plant height, LAI, NAR, CGR, LAD and dry matter (Table 11, 15, 16 and 17) but also brought significant reduction in yield contributing characters like number of spikes plant^{-1}, primary & secondary spike length, capsules plant^{-1}, test weight and harvest index (Table 18, 19, 20 and 21).

The greater sensitivity of flowering and capsule development period to ET_c deficits in I_1, I_4, I_5 and I_7 treatments could be partly related to the fact that crop reached its peak ET_c requirement (3. 97mm day^{-1}) during this period. Additionally, this is the period in which the potential spike size and capsule number is determined. Thus, water deficits at flowering period might have caused abortion of flowers as is evident from the number of spikes, spike length and capsules plant^{-1} in I_1, I_4, I_5 and I_7 treatments, which limited the total number of seeds per plant and possibly non-availability of assimilates to capsules might have reduced the bean weight and harvest index. Similar observations were made Sudhakar and Rao (1998) and Firake et.al., (1998). All these effects finally reduced the bean yield in I_1, I_4, I_5 and I_7 treatments and the effect of water deficits is well marked (Table 21). The dependence of bean yield was evident from significant and positive association between them (Table 33).

Whereas the irrigation cycle under conventional check basin irrigation method (I_8 treatment) consisted of a short period of infiltration followed by a long period of redistribution, evaporation and extraction of water by growing plants starting from field capacity moisture content down towards permanent wilting point. It was well documented that during this transition phase in soil moisture variation, it becomes increasingly difficult for the crop plants to extract water with every passing day since progressive decrease in soil-water content increases soil water tension. This decrease in soil water potential and wide fluctuation in soil moisture owing to longer irrigation interval (8 – 12 days) as compared to drip irrigation (1 – 2 days irrigation interval) affected the crop growth & development and yield contributing characters resulting in reduced crop yields as is evident from I_8 treatment (Table 18 to 21) (Firake et. al., 1998; Patel et. al., 1998; Patel et. al., 2004).

Water productivity in general was highest in drip irrigated treatments (0.777 to 1.137 kg m^{-3}) as compared with conventional check basin irrigated crop in I_8 (0.571 kg m^{-3}). This is expected since decrease in water (ET_c) without significant reduction in bean yield promotes water productivity. Among drip irrigated treatments I_2 registered highest water productivity over other irrigation treatments. On an average the I_2 registered 31.6%, 18.8%, 12.2%, 26.1%, 5.9%, 25.4% and 49.8% more water productivity, respectively over I_1, I_3, I_4, I_5, I_6, I_7 and I_8 irrigation treatments. There is general agreement in the literature that irrigation water requirements under drip irrigation are less than the traditional furrow, basin & overhead sprinkler irrigation systems (Bresler, 1977 and Bucks *et. al.,* 1982). The savings of course depend on the crop, soil, environmental conditional and the attainable on farm irrigation efficiency. Much of the water saving under drip irrigation was achieved by restricting the water application to the extent of the most efficient root zone (Dasberg and Steinhardt, 1974). Primary reasons assessed for water savings using drip irrigation include irrigation of a smaller portion of soil volume, decreased surface evaporation, reduced irrigation runoff from the field (the dry soil between rows could also store more precipitation) and controlled deep percolation losses below the crop root zone (Aljibury, 1974; Davis, 1975; Shoji, 1977). Similar results of increased water productivity due to saving in water without any reduction in bean yield due to optimal irrigation schedules was reported by Wackchaure et.al. (1999) and Patel et. al. (1998). On the other hand reduction in water productivity caused by water deficits due to sub-optimal irrigation schedules using low evaporation replenishment factor were also reported by (Firake et. al., 1998; Sudhakar & Rao, 1998; Patel et. al., 2004).

Higher moisture regimes viz., I_2, I_3 and I_6 had higher oil content over I_1, I_4, I_5, I_7 and I_8. Lowest oil content was registered in conventionally irrigated surface irrigation treatment. This trend could be expected since the oil content is directly related to carbohydrate metabolism which in turn is a function of adequate soil water availability (Sudha Rani, 2001; Kiran, 2003). On the contrary Firake et. al. (1998) reported that oil content was not significantly influenced by different moisture regimes.

5.3 CROP COEFFICIENTS FOR PREDICTION OF CROP ET_c

Models or water production functions which explain yield as a function of ET_c will be of limited use until methodologies are developed for predicting ET_c. The better known approach is the prediction of ET_c i.e., the ET_c requirement of the crop not just as a simple value for the season, but as a cumulative value over time which shows the differential ET_c needs in each individual crop growth sub-period ($ET_c = K_c \,.\, ET_o$). The experimentally derived crop coefficients ($K_c = ET_c \div ET_o$) in the present study which are required to carry out prediction of ET_c for castor are shown in Fig. 12. The K_c curves exhibited several discernible trends with crop ontogeny.

Initially the K_c was low due to incomplete canopy cover (Table 27 and 28) reflecting that most of the water loss may constitute evaporation from bare soil, while germination, emergence and establishment of the crop took place. With advancement of crop age through vegetative & flowering period, the K_c increased linearly reflecting the increased water loss due to increased transpiring surface as a consequence of rapid leaf area development and persistence. The LAI and LAD increased from 0.067 to 2.05 and 0.2 to 33.3 m^2 days, respectively. During capsule development period the K_c reached a peak value of 0.822, 0.804, 0.874 and 0.688 based on Penman Monteith, Modified Penman, Adjusted Pan evaporation and Pan evaporation from USWB Class A Pan methods, indicating the peak water requirement of the crop as a consequence of full canopy cover (LAI = 2.60) and its persistence (LAD = 42.3 m^2 days) intercepting maximum photosynthetically active incident radiation. Over the penultimate crop growth sub-period of maturity the K_c precipitously reached a low value due to leaf senescence (LAI = 2.15) and possibly due to reduced root activity.

To use the K_c values in Fig. 12 for predicting ET_c throughout the crop growing season, only ET_o estimates based on Penaman Monteith, Modified Penman and Adjusted Pan evaporation; and pan evaporation data from USWB Class A pan evaporimeter are needed for the new planting site.

5.4 WATER PRODUCTION FUNCTION AND OPTIMIZATION OF CROP WATER REQUIREMENT

The castor bean yield response to seasonal crop ET_c was adequately described by a quadratic water production function i.e., the castor bean yield increased with increase in crop ET_c, but the increase in bean yield was not proportional to the crop evapotranspiration (Fig. 14) as was evident from the explained total variation (R^2) and the significant variance ratio for testing R^2. These results are contrary to the best fit obtained with linear water production function for several oil seed crops viz., sunflower (Chamundeshwari et. al., 1996; Kumar and Rao, 2000; Kumar and Rao, 2003), groundnut (Devi and Rao, 2001a), mustard (Manjula and Rao, 1998a and 1998b; Kumar et. al., 2002; Kumar et. al., 2004) and soybean (Sudhakar and Rao, 1998) under Rajendranagar agroclimatic conditions. The predicted maximum castor bean yield (Y_{max}) of 3611.3 kg ha^{-1} was obtained with 383.25 mm of seasonal water (ET_c) requirement. The water production function did not emerge through the origin and the value of regression constant (a) was negative, indicating that some minimum amount of irrigation water i.e., crop ET_c (182.5 mm) was required to be expended to realize the economic yield (beans) in castor grown in *rabi* season. Rao *et. al.,* (1992) opined that non-forage crops require some water for evapotranspiration to put forth vegetative growth before reaching the stage of reproduction, because in these crops yield is a specialized portion of the plant (castor beans) unlike foliage in forage crops.

Further, the economic optimum levels of water under different appraised prices of output (bean yield) and input (water) showed that the optimum level of irrigation water was inversely related to increase in the price of water (P_w), whereas it (ET_{opt}) had a direct positive relationship with the price of castor bean yield (Table 29). It indicates that an increase in the cost of irrigation water, keeping the price of bean yield constant, requires the use of less water to derive maximum profit. But if the price of bean yield increases, greater amount of irrigation water can be used profitably. For instance, the increase in price of water from Rs. 7.5 mm^{-1} to Rs. 15.0 mm^{-1} under a given price of bean yield, say Rs. 20 kg^{-1}, is associated with only 2.1mm decrease in the demand for water (Table 29). This low decrease in demand was due partly to fixed level of all inputs other than water, and high value of the marginal physical product of water, and hence the price of water did not substantially affect the quantity of water demanded. Similar trends were noted with net returns and net return per rupee invested. The gross returns, net returns and net return per rupee invested varied from Rs. 72194.2 to 144447.6 ha^{-1}, Rs. 46708.3 to 121781.1 ha^{-1} and 1.832 to 5.732, respectively under appraised prices of output and input.

5.5 ECONOMIC VIABILITY OF DRIP IRRIGATION SYSTEM

It was clear from the previous sections that per ha profit (farm business income) of castor cultivated with drip irrigation was significantly higher than under conventional check basin method of irrigation. However, it cannot be treated as the effective (real) profit of castor cultivated with drip irrigation, since it does not take into account the capital cost of drip system, its depreciation and interest accrued on the fixed capital. The life period of the drip system is one of the important variables which determine per ha profit. Moreover since it is a capital-intensive technique, the huge initial investment needed for installing the drip system remains the main deterrent to the wide spread adoption of drip irrigation. The extent to which this discouragement effect is real and the extent to which this effect can be counterbalanced by government subsidy are important policy issues requiring empirical answers. Past studies (INCID, 1994; Sivanappan, 1994) on the subject for various drip irrigated crops have either conducted benefit cost analysis without a proper methodology or relied heavily on the experience of one or a few farmers adopting drip irrigation. There is therefore need to evaluate empirically the economic viability of drip irrigation impact on profitability within a more systematical methodological framework through field experimental results but not on survey results. Hence, in this study the net cash flow, NPV at 12%, BEP for price, BEP for yield and pay-back period were calculated under both conventional (I_8) and drip irrigated castor (I_6) utilizing the discounted cash flow technique (Table 30). Since the NPV is the difference between the sum of the present value of benefits and that of costs for a given life period of the drip system, it collates the total benefits with the total costs covering items like capital and depreciation costs of the drip system. In terms of the NPV criterion, the investment on drip system can be treated as economically viable if the present value of benefits is greater than the present value of costs.

Thus the economic viability analysis revealed that total investments on irrigation infrastructure spread over 10-year life period were markedly higher, by 88.4% under drip irrigated castor as compared to surface check basin method of irrigation owing to drip system cost (Table 30). However, the production expenses were less in case of drip irrigated castor by 8.8% in view of low labour costs for weed control and irrigation scheduling, and low plant protection and electricity bills, as compared to castor crop irrigated by conventional check basin method.

The farm income of drip irrigated castor was markedly higher (Rs. 1.28 lakh ha^{-1}) than conventional check basin irrigated crop (Rs. 0.76 lakh ha^{-1}) owing to significantly higher bean yield (Table 30).

Though the NPV was positive for both methods of irrigation, the NPV obtained with drip irrigated castor was significantly higher (Rs. 76,323 ha^{-1}) than conventional check basin irrigated crop (Rs. 45,568 ha^{-1}) owing to enhanced bean yields (Table 30). The breakeven point (BEP) for price indicated that the profitability was achieved above Rs. 9.98 kg^{-1} and Rs. 10.02 kg^{-1} price under check basin and drip irrigated castor, respectively. Similarly BEP for yield suggested that profitability was achieved above 33.21% and 33.43% of castor bean yield data plugged each year under conventional check basin and surface drip irrigated castor, respectively (Table 30).

The important issue in the context of drip irrigation adoption in castor is the number of years needed to recover the full capital costs involved in drip installation. The results of the present study of NPV for castor clearly showed that the farmers can recover the entire capital cost of their drip set from their net profit in the very first year i.e., with in two crop seasons. This finding contradicts the general belief that the capital cost recovery for drip investment takes longer. More importantly, when farmers can recover the capital costs within a year, the role of the discount rate as a device to capture their time preference seems to be of considerably less importance than one might think. On the whole the economic indices suggest that the drip investment in castor is technically feasible and economically viable even without a government subsidy.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Raising castor during winter (*rabi*) season with assured irrigation using high yielding varieties and hybrids is a new dimension in castor production with promise that provides greater stability and higher productivity. Due to the economic importance of castor and the need to increase irrigation efficiency, drip irrigation is being investigated as a possible alternative for irrigation of castor.

Keeping the above in view, the present field experiment entitled **"Irrigation management in drip irrigated castor"** was conducted at Water Technology Centre Unit, College Farm, College of Agriculture, Rajendranagar, Hyderabad, during rabi season 2009 – 2010. The objectives were to study the effect of variable water supply levels on growth, yield, oil content and water use efficiency of Palem Castor Hybrid – 111 (PCH – 111) under drip irrigation; to optimize the crop water requirement for castor under Rajendranagar agro-climatic conditions and to evaluate the economic viability of drip irrigation for hybrid castor.

There were seven irrigation treatments based on surface drip method of irrigation and irrigation scheduling levels in the form of pan evaporation replenishment. The evaporation replenishment factor *viz.,* 0.4, 0.6 and 0.8 was either kept constant throughout the crop life or was combinations of the above at vegetative, flowering and capsule development stages (treatments I_1 to I_7). Besides the seven drip irrigation scheduling treatments one treatment consisted of irrigation through a surface check basin system (I_8) scheduled at an IW/CPE ratio of 0.8 with an irrigation water depth of 50 mm. The pan evaporation data used in the irrigation scheduling was measured from USWB Class A Pan evaporimeter. The experiment was laid out in randomized block design with three replications.

Surface drip irrigation system consisted of 16 mm integral dripperlines laid out on the ground surface along the crop rows with emitters spaced at 0.50 m apart delivering 4 L/hour giving an application rate of 6.66 mm/hour.

The experimental soil was sandy clay in texture, alkaline in reaction, non-saline, low in available N, medium in available P_2O_5 and high in available K_2O. The infiltration rate was 2.3 cm hour^{-1} and hydraulic conductivity was 2.5 cm hour^{-1}. The total plant available water i.e., the difference between –0.1MPa and –1.5 MPa in 0–100 cm soil depth amounted to 124.61 mm. Irrigation water was marginally alkaline (pH = 7.6) and was classified in to C_3S_1 class suggesting that it is suitable for irrigation by following good management practices.

The castor crop variety PCH–111 was sown on 7th November 2009 adopting a spacing of 1.2 m between rows and 0.5 m between plants with in a row to maintain a desired plant population of 16667 plants ha^{-1}.

Growth parameters *viz.,* plant height, leaf area index, dry matter, RGR, CGR, NAR and LAD were measured at periodic intervals. Similarly, yield attributes *viz.,* spike length, number of spikes plant^{-1}, capsules plant^{-1}, seeds capsule^{-1}, capsule weight, test weight, bean yield plant^{-1} and ha^{-1}, dry matter yield ha^{-1}, harvest index, oil content and oil yield were measured at harvest. Water studies included crop ET_c, reference crop ET_o and crop coefficients for different crop growth sub-periods; water use efficiency, water production function and economic viability analysis of drip irrigation in castor. Weather elements *viz.,* temperature, sunshine duration, relative humidity, wind velocity and pan evaporation from USWB class A pan evaporimeter were also measured during the crop growing season. The data generated on various aspects in this study on response of castor crop to varying levels of irrigation under drip and surface methods of irrigation was analysed through standard statistical methods for drawing valid and logical conclusions.

The salient features of the experimental findings are summarized below.

1. Mild weather conditions prevailed during the crop growing season, which were conducive for growth and development of castor. Nevertheless the precipitation was considerably lower than seasonal crop ET_c.

2. Castor bean yield and dry matter yield was highest when irrigations were scheduled by drip at 0.6Epan up to flowering and 0.8Epan later on (I_6), however, it was on par with I_2 (0.6Epan throughout the crop life) and I_3 (0.8Epan throughout the crop life) and significantly superior over I_1, I_4, I_5, I_7 and I_8. Among all the treatments lowest castor bean yield was observed in I_1 (drip irrigation at 0.4Epan throughout the crop life) treatment. Bean yield under surface check basin irrigation at 0.8 IW/CPE ratio with an IW of 50 mm throughout the crop life (I_8) was also statistically inferior in comparison to drip irrigation treatments (I_2 to I_7) except I_1. These trends were due to similar variation in growth and yield attributes under these treatments.

3. Water productivity in general was highest in drip irrigated treatments (0.777 to 1.137 kg m^{-3}) when compared to conventional check basin (I_8) irrigated crop (0.571 kg m^{-3}).

4. Higher moisture regimes observed in I_2, I_3 and I_6 had recorded higher oil content and oil yield over I_1, I_4, I_5, I_7 and I_8. Lowest oil content and oil yield was registered in conventionally irrigated surface irrigation treatment (I_8).

5. The seasonal ET_c requirements of castor varied from 239.3 mm to 428.08 mm among different drip irrigated treatments tried in this study. It was highest in I_3 (428.08 mm) followed by I_6 as compared to other irrigation treatments. The seasonal ET_c under surface check basin irrigated crop was highest (445.87 mm).

6. The average daily ET_c rate varied from 1.58 mm to 2.87 mm under different treatments. It was highest in I_8, followed by I_3 and I_2 when compared to other irrigation treatments.

7. The seasonal ET_o derived by different empirical methods during crop growing season was 524.4 mm, 557.8 mm and 537.9 mm under Penman Monteith, Modified Penman, Adjusted Pan evaporation, respectively. Whereas the seasonal pan evaporation from USWB Class A Pan evaporimeter for the cropping period was 679.8 mm.

8. Crop coefficients for castor were determined based on ET_o derived by Penman Monteith, Modified Penman, Adjusted Pan evaporation and pan evaporation

data from USWB Class A pan evaporimeter for predicting castor ET_c at different crop growth sub-periods and seasonal ET_c at new planting site.

9. The castor bean yield response to seasonal crop ET_c was adequately described by a quadratic water production function i.e., yield increased with increase in crop ET_c, but the increase in bean yield was not proportional to the seasonal crop ET_c. The explained total variation (R^2) was 99% with a significant variance ratio for testing R^2.

10. The predicted maximum castor bean yield (Y_{max}) of 3611.3 kg ha^{-1} was obtained at 383.25 mm of seasonal water (ET_c) requirement. The water production function did not emerge through the origin and the value of regression constant (a) was negative, indicating that some minimum amount of irrigation water i.e., crop ET_c (182.5 mm) was required to be expended to realize the economic yield (beans) of castor.

11. Based on economic optimum levels of water under spectrum of appraised prices of output (Rs. 20.0, 30.0 and 40.0 kg^{-1} of yield) and input (Rs. 7.5, 10.0 and Rs. 15.0 mm^{-1} of water) the gross returns, net returns and net return per rupee invested varied from Rs. 72194.2 to 144447.6 ha^{-1}, Rs. 46708.3 to 121781.1 ha^{-1} and 1.832 to 5.732, respectively. .

12. The farm income of drip irrigated castor was markedly higher (Rs. 1.28 lakh ha^{-1}) than conventional check basin irrigated crop (Rs. 0.76 lakh ha^{-1}). Though the NPV was positive for both methods of irrigation, the NPV obtained with

drip irrigated castor was significantly higher (Rs. 76,323 ha^{-1}) than conventional check basin irrigated crop (Rs. 45,568 ha^{-1}).

13. The Breakeven Point (BEP) for price indicated that the profitability was achieved when the price was above Rs. 9.98 kg^{-1} and Rs. 10.02 kg^{-1} under check basin and drip irrigated castor, respectively. Similarly BEP for yield suggested that profitability was achieved above 33.21% and 33.43% of castor bean yield data plugged each year under conventional check basin and surface drip irrigated castor, respectively.
14. The results of NPV for castor clearly showed that the farmers can recover the entire capital cost of their drip set installed from their net profit in the very first year i.e., with in two crop seasons.
15. On the whole the economic analysis (farm income, NPV, net cash flow, BEP for price and water and payback period) suggested that the drip irrigation in castor is technically feasible and economically viable even without a government subsidy.
16. The bean yield of castor was found to be positively and significantly correlated with all the growth and yield attributes.

Thus from the above, it was concluded that castor grown in winter (*rabi*) season under Rajendranagar conditions irrigated with drip system at 0.6Epan up to flowering and 0.8Epan at later stages with an optimal seasonal water requirement of 381 mm gave maximum bean yield (3611.3 kg ha^{-1}) and found most remunerative under the prevailing prices of output and input. Further, it was observed that the entire capital cost of drip set installed in castor can be recovered from the net profit in the very first year itself i.e., with in two crop seasons. Under limited water supply situations scheduling irrigations at 0.6Epan throughout the crop growing season with an optimal seasonal water requirement of 335 mm was most productive and remunerative.

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Plate 1. Sowing of castor in experimental plot

Plate 2. Castor crop at flower initiation stage

Plate 3. Castor crop in Surface irrigated check basin method (I_8)

Plate 4. Castor crop in surface drip irrigated method (I_6)

Plate 5. Castor crop in Surface drip irrigation at capsule development stage (I_6)

Plate 6. Access tube for measuring soil moisture