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Radiation interception, photosynthetic performance and dry matter accumulation of onion (*Allium cepa* L.) under an onion-okra sequence cropping system

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Abstract

The present investigation was conducted at the Instructional Farm, All India Coordinated Research Project (AICRP) on Irrigation Water Management, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Maharashtra, India, during two consecutive years, 2023-24 and 2024-25. The experiment was laid out in a split-plot design with three replications. Onion and okra were grown on raised beds measuring 4.0 m × 1.8 m (gross plot size), with a net plot size of 3.8 m × 1.5 m for each crop. Onion seedlings were transplanted at a spacing of 15 cm × 10 cm, whereas okra was sown at a spacing of 30 cm × 15 cm. The experiment consisted of three irrigation regimes as main plot treatments and six fertigation levels as sub-plot treatments during the *rabi* and summer seasons. The main plot treatments comprised three levels of irrigation based on crop evapotranspiration (ET_c), while the sub-plot treatments included six fertigation levels involving different proportions of nutrient application. Thus, a total of 18 treatment combinations were evaluated in a split plot design with three replications, consisted of three irrigation regimes as main plot treatments - A total of 18 treatment combinations were evaluated in a split-plot design with three replications. The main-plot treatments comprised three irrigation regimes based on crop evapotranspiration (ET_c), viz., 1.0 ET_c (I₁), 0.8 ET_c (I₂) and 0.6 ET_c (I₃) and six fertigation levels as sub-plot treatments during the *rabi* and summer seasons - 100% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with no basal (F₁); 75% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with 25% N: P₂O₅: K₂O as basal (F₂); 75% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with no basal (F₃); 56% N: P₂O₅: K₂O through fertigation with 19% N: P₂O₅: K₂O kg ha⁻¹ as basal (F₄); 100% N: P₂O₅: K₂O kg ha⁻¹ through conventional fertilizers (F₅); and Absolute control (F₆). Dry matter accumulation, absorbed photosynthetically active radiation (APAR) and photosynthetic rate of onion were significantly influenced by irrigation regimes and fertigation levels during both years of experimentation. Irrigation scheduled at 1.0 ET_c recorded the highest dry matter accumulation at harvest (15.95 and 14.24 g plant⁻¹ during 2023-24 and 2024-25, respectively) and maintained superior APAR (326 and 346 μmol photons m⁻² s⁻¹) and photosynthetic rate (14.1 and 12.6 μmol CO₂ m⁻² s⁻¹) at harvest compared with lower irrigation levels. Likewise, application of 100% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with no basal (F₁) produced the highest dry matter accumulation (16.70 and 14.93 g plant⁻¹), APAR (328 and 350 μmol photons m⁻² s⁻¹) and photosynthetic rate (15.2 and 13.5 μmol CO₂ m⁻² s⁻¹) at harvest during the respective years. The treatment combination 1.0 ET_c + 100% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with no basal (I₁F₁) consistently recorded the highest physiological performance, indicating that optimum irrigation coupled with balanced fertigation enhanced biomass accumulation, radiation interception and photosynthetic efficiency. Overall, irrigation at 1.0 ET_c combined with 100% N: P₂O₅: K₂O kg ha⁻¹ through fertigation without basal application proved to be the most effective management practice for improving the physiological performance of onion under an onion-okra sequence cropping system.

Keywords: Onion, okra, sequence cropping, irrigation, fertigation, absorbed photosynthetically active radiation, dry matter, photosynthetic rate etc

Introduction

Onion (*Allium cepa* L.) is the third most important vegetable crop in the world after potato and tomato. It is cultivated in about 58.42 lakh ha across nearly 140 countries, with an annual production of 111.27 million tonnes (Gupta *et al.* 2026)^[7]. India has the largest area under onion cultivation (17.40 lakh ha) and is the leading producer (30.21 million tonnes), followed by China (11.29 lakh ha and 24.92 million tonnes). Together, India and China contribute nearly half of the

world's onion production. The global average productivity of onion is 27.06 t ha⁻¹, while the Republic of Korea records the highest productivity (67.87 t ha⁻¹). Despite being the largest producer, India has a relatively low productivity of 17.36 t ha⁻¹, ranking 93rd globally. In India, onion is mainly cultivated in Maharashtra, Karnataka, Gujarat, Bihar, Madhya Pradesh, Rajasthan, Andhra Pradesh and Tamil Nadu, with Maharashtra and Karnataka contributing about 57% of the country's total production (Gupta *et al.* 2026) [7]. Onion contains carbohydrates (11.0 g), proteins (1.2 g), fiber (0.6 g), moisture (86.8 g) and several vitamins like vitamin A (0.012 mg), vitamin C (11 mg), thiamin (0.08 mg), riboflavin (0.01 mg) and niacin (0.2 mg) and also some minerals like phosphorus (39 mg), calcium (27 mg), sodium (1.0 mg), iron (0.7 mg) and potassium (157 mg) (Suresh, 2007) [22]. The outstanding characteristics of onion are the pungency, which is due to a volatile compound known as "Allyl-propyl disulphide". It has got the effects of lowering the blood sugar fat and also having good coagulation effect (Vashi *et al.* 2011) [24].

Absorbed photosynthetically active radiation (APAR) and photosynthetic rate are key physiological determinants of crop productivity, as they regulate the conversion of intercepted solar radiation into biomass through photosynthesis. Efficient absorption and utilization of photosynthetically active radiation are essential for improving dry matter accumulation, growth and yield in onion (Gitelson *et al.* 2015) [4]. The availability of soil moisture and nutrients strongly influences canopy development, radiation absorption and photosynthetic efficiency, thereby affecting overall crop performance (Gregory *et al.* 1997) [6]. Although several studies have evaluated the individual effects of irrigation or nutrient management on onion productivity, information on their combined influence on APAR and photosynthetic rate under an onion-okra sequence cropping system remains limited. Therefore, understanding the physiological responses of onion under different irrigation and fertigation regimes is essential for developing resource-efficient production strategies and enhancing crop productivity. It was hypothesised that the optimisation of irrigation and fertigation under an onion-okra sequence cropping system would improve the absorption of photosynthetically active radiation, enhance photosynthetic efficiency and promote dry matter accumulation in onion. The combined application of appropriate irrigation scheduling and fertigation was expected to improve crop physiological performance through better water and nutrient availability. Therefore, the present study was undertaken to evaluate the effects of different irrigation regimes and fertigation levels on dry matter accumulation, absorbed photosynthetically active radiation (APAR) and photosynthetic rate of onion (*Allium cepa* L.) under an onion-okra sequence cropping system.

Materials and Methods

Experimental site

The present investigation was conducted *rabi* and summer seasons of 2023-24 and 2024-25 at Instructional Farm, All India Coordinated Research Project (AICRP) on Irrigation Water Management, MPKV, Rahuri is situated between 19° 36' 58" and 19° 36' 65" North latitude and between 74° 64' 40" and 74° 36' 44" East longitude. The altitude is 521 meter above mean sea level.

Experimental design and treatments

The experiment was conducted using a split-plot design with three replications, comprising 18 treatment combinations. The main plot treatments comprised three levels of irrigation based on crop

evapotranspiration (ETc): 1.0 Etc (I₁), 0.8 Etc (I₂) and 0.6 Etc (I₃). While the sub-plot treatments included six fertigation levels: 100% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with no basal (F₁), 75% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with 25% N: P₂O₅: K₂O as basal (F₂), 75% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with no basal (F₃), 56% N: P₂O₅: K₂O through fertigation with 19% N: P₂O₅: K₂O kg ha⁻¹ as basal (F₄), 100% N: P₂O₅: K₂O kg ha⁻¹ through conventional fertilizers (F₅) and Absolute control (F₆). Irrigation treatments will be scheduled at an alternate day and depending on crop evapo-transpiration rate. The drip irrigation system consisted of 16 mm laterals with in-line drippers of 4.0 lph discharge spaced at 50 cm distance. Nutrients were applied through fertigation in 10 weekly splits according to crop growth stages of *rabi* onion. Nitrogen was applied uniformly throughout the crop period with 20, 30, 30 and 20% during 1-15, 16-45, 46-75 and 76-90 DAT, respectively. Phosphorus was applied in higher proportion during early growth stages to support root establishment and vegetative growth, while potassium application was increased during bulb development stage for better bulb enlargement and quality. Water soluble fertilizers viz., Urea, 19:19:19 and 12:61:00 were used as nutrient sources. Observations for dry matter, APAR and were recorded at 30, 60 and 90 DAT and at harvest.

Soil type

The soil of the experimental field (0-30 cm depth) was characterised as clayey in texture, alkaline in reaction (pH 8.13), moderate in organic carbon (0.49%), low in available nitrogen (254.3 kg ha⁻¹), moderate in available phosphorus (18.7 kg ha⁻¹) and very high in potassium (461.3 kg ha⁻¹), respectively. The soil moisture constants viz., field capacity (33.33%), permanent wilting point (16.43%), bulk density (1.31 g cm⁻³) and porosity (49.34%) indicate that soil was good in water retention capacity. The available nutrient status of the soil was 254.3 kg ha⁻¹ nitrogen, 18.7 kg ha⁻¹ phosphorus and 451.3 kg ha⁻¹ potassium.

Weather data

Weather data was collected daily from Meteorological Observatory located at AICRP on Irrigation Water Management Project, MPKV, Rahuri.

Measurement of dry matter (g plant⁻¹)

Five plants plot⁻¹ were sampled randomly for determination of total dry matter including component parts i.e. leaves and bulb. The leaves and bulb were separated and chopped into small pieces, packed into brown paper bags and labeled properly. The samples were first air dried and then dried in hot air oven at about 65 ± 2°C temperature for 24 hours, until the final constant weight was observed.

Measurement of absorbed photosynthetically active radiation

Absorbed photosynthetically active radiation (APAR) was measured following the method described by Gallo and Daughtry (1986) [3]. Measurements were taken on a clear sunny day between 11:00 am and 1:00 pm to ensure uniform solar radiation. A LI-191SA Line Quantum Sensor (Li-COR, USA) was used for recording PAR values. The observations were recorded across the rows. Incident (PAR_i) was recorded by placing the line quantum sensor 1 ft above the crop canopy, facing upward towards the sky (upward direction). Transmitted PAR (PAR_t) was measured at ground level beneath the canopy with the sensor facing upward. Reflected PAR by soil (PAR_s) was measured by holding the sensor 1 ft above the soil surface and facing downward towards the soil, while reflected PAR by canopy plus soil (PAR_r) was

measured by positioning the sensor 1 ft above the canopy and facing downward towards the crop canopy. Absorbed photosynthetically active radiation was calculated using the formula:

$$APAR = (PAR_i + PAR_s) - (PAR_t + PAR_c)$$

Where,

APAR = absorbed photosynthetically active radiation

PAR_i = Incident radiation

PAR_c = reflected photosynthetically active radiation by canopy

PAR_t = transmitted photosynthetically active radiation

PAR_s = reflected photosynthetically active radiation by soil

Measurement of photosynthetic rate

The net photosynthetic rate (P_n) of onion leaves was measured using a LI-6400 Portable Photosynthesis System (LI-COR Biosciences, Lincoln, Nebraska, USA). Observations were recorded on the fully expanded, healthy third leaf from the top of five randomly selected plants in each treatment during the morning hours (09:00-11:00 h) under clear sky conditions to minimize diurnal variation and to ensure stable light and atmospheric conditions. The selected leaf was enclosed in the leaf chamber of the portable photosynthesis system and the net photosynthetic rate was determined based on infrared gas analysis (IRGA) following the manufacturer's operating procedure. For each plant, observations were taken on upper, middle and lower fully expanded leaves and the average value was used for statistical analysis. The photosynthetic rate was expressed as $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$.

Principle: The Infrared Gas Analyzer (IRGA) operates on the principle that carbon dioxide (CO₂) and water vapour (H₂O) selectively absorb infrared radiation at specific wavelengths. During measurement, the leaf is enclosed in a chamber through which air of known CO₂ concentration is circulated. The reduction in CO₂ concentration due to photosynthesis and the increase in water vapour concentration due to transpiration are measured by infrared detectors. Based on these gas exchange measurements, the instrument automatically computes the photosynthetic rate.

Statistical analysis and interpretation of the data

The experimental data recorded during the two years of investigation were subjected to analysis of variance (ANOVA) appropriate for a split-plot design as described by Gomez and Gomez (1984) [5]. The irrigation regimes were considered as the main-plot treatments, whereas the fertigation levels were assigned to the sub-plots. The significance of treatment effects was tested at the 5% probability level ($P \leq 0.05$). Whenever the treatment effects were found to be significant, treatment means were compared using the Critical Difference (CD) test at the 5% level of significance. Standard error of the mean [SE(m) $\pm$] and critical difference (CD) values were computed for all the parameters. Pooled analysis over the two years was carried out after testing the homogeneity of error variances following the procedure described by Gomez and Gomez (1984) [5].

Results and Discussion

The influence of irrigation regimes and fertigation levels on the physiological growth parameters of onion (*Allium cepa* L.), namely dry matter accumulation, absorbed photosynthetically active radiation (APAR) and photosynthetic rate, under an onion-okra sequence cropping system was investigated during the study period. The experimental findings are presented and discussed in

relation to the treatment effects and relevant published literature.

Dry matter (g plant⁻¹)

The periodical data on dry matter accumulation of onion as influenced by different irrigation regimes and fertigation levels are presented in Table 1.a and illustrated in Fig. 1. Dry matter accumulation increased progressively with crop growth, reflecting continuous biomass production and assimilate partitioning into vegetative and bulb tissues. The mean dry matter accumulation across treatments increased from 1.51 g plant⁻¹ at 30 DAT to 5.71 g plant⁻¹ at 60 DAT, 9.19 g plant⁻¹ at 90 DAT and reached 14.49 g plant⁻¹ at harvest on a pooled mean basis.

Effect of irrigation regimes

Irrigation regimes had no significant effect on dry matter accumulation at 30 DAT during either year. However, significant differences were observed at 60 and 90 DAT and at harvest. Irrigation scheduled at 1.0 ET_c (I₁) recorded the highest dry matter accumulation at all later growth stages and remained statistically at par with 0.8 ET_c (I₂). On a pooled basis, 1.0 ET_c produced 5.78, 9.42 and 15.10 g plant⁻¹ at 60 and 90 DAT and harvest, respectively, whereas the lowest dry matter accumulation was recorded under 0.6 ET_c (I₃). The superior dry matter accumulation under 1.0 ET_c may be attributed to the maintenance of favourable soil moisture throughout the crop growth period, which enhanced photosynthetic activity, nutrient uptake and assimilate translocation, resulting in greater biomass production. In contrast, moisture deficit under 0.6 ET_c likely restricted physiological and metabolic activities, thereby reducing dry matter accumulation. Similar observations have been reported by Ramadass and Ramanathan (2017) [18], Rani *et al.* (2018) [19], Nandle *et al.* (2018) [14] and Maske (2021) [12].

Effect of fertigation levels

Dry matter accumulation was not significantly influenced by fertigation treatments at 30 DAT; however, significant differences were observed at 60 and 90 DAT and harvest during both years. The application of 100% recommended N: P₂O₅: K₂O through fertigation without basal application (F₁) recorded the highest dry matter accumulation throughout the crop growth period. On a pooled mean basis, F₁ produced 5.90, 9.75 and 15.82 g plant⁻¹ at 60 and 90 DAT and harvest, respectively and remained statistically at par with F₂ and F₃ at most growth stages. The lowest dry matter accumulation was consistently observed under the absolute control (F₆). Higher dry matter accumulation under F₁ could be attributed to the continuous and efficient supply of nutrients through fertigation, which enhanced nutrient availability, photosynthetic efficiency and assimilate production, thereby promoting greater biomass accumulation. These findings are in close agreement with those reported by Kakade *et al.* (2015) [11], Yadav (2016) [26], Pol (2017) [17], Sushma Prasad (2019) [23], Pathare (2021) [15] and Heredia *et al.* (2023) [10].

Interaction effect

The interaction between irrigation regimes and fertigation levels significantly influenced dry matter accumulation at 90 DAT during both years and in the pooled analysis. The treatment combination 1.0 ET_c + 100% recommended N: P₂O₅: K₂O through fertigation without basal application (I₁F₁) recorded the highest dry matter accumulation (10.21 g plant⁻¹ on pooled mean basis) and remained statistically at par with I₁F₂ and I₁F₃. In contrast, the minimum dry matter accumulation (8.22 g plant⁻¹ on pooled mean basis) was recorded under 0.6 ET_c + absolute control (I₃F₆). The superior performance of I₁F₁ may be attributed to the synergistic effect of optimum soil moisture and continuous

nutrient availability through fertigation, which enhanced photosynthetic efficiency, assimilate production and dry matter partitioning. Conversely, moisture stress coupled with inadequate nutrient supply under I₃F₆ adversely affected crop growth, resulting in reduced biomass accumulation.

Absorbed photosynthetically active radiation (APAR)

The periodical data on absorbed photosynthetically active radiation (APAR) of onion as influenced by different irrigation regimes and fertigation levels are presented in Table 1. b and

illustrated in Fig. 2. APAR increased progressively from 30 to 90 DAT and declined slightly at harvest during both years as well as in the pooled analysis. This trend reflected rapid canopy development and enhanced light interception during the active vegetative and bulb development stages, followed by a decline at maturity owing to leaf senescence and reduction in the photosynthetically active leaf area. On a pooled basis, the mean APAR increased from 132 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ at 30 DAT to 348 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ at 60 DAT and 394 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ at 90 DAT, before decreasing to 332 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ at harvest.

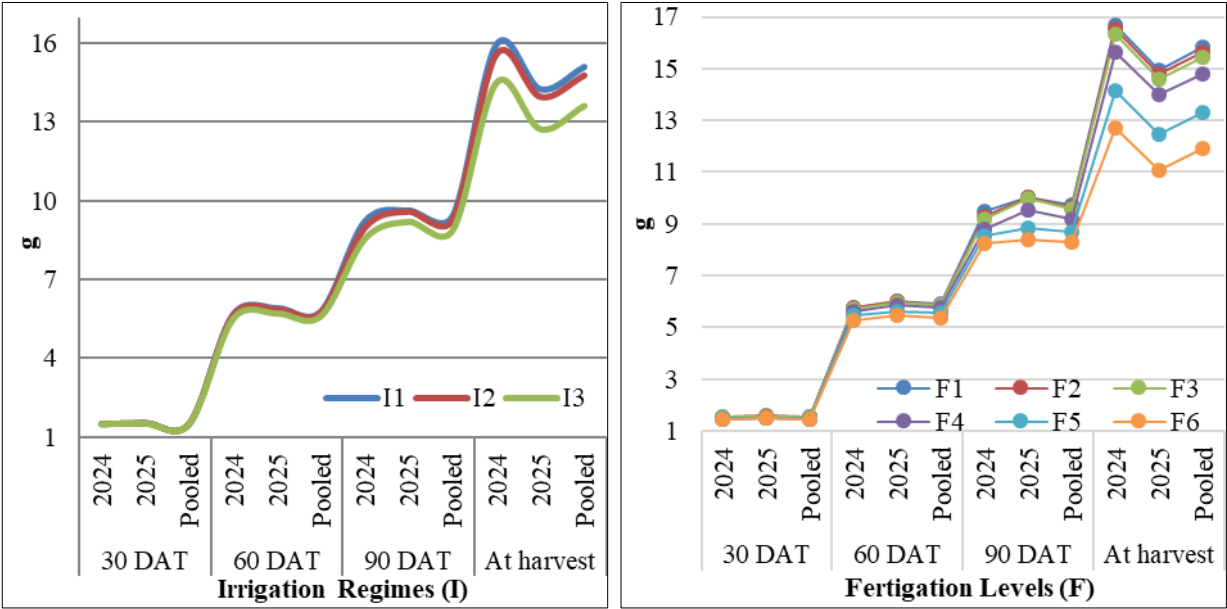


Fig 1: Dry matter (g plant⁻¹) of onion as influenced periodically by different treatment

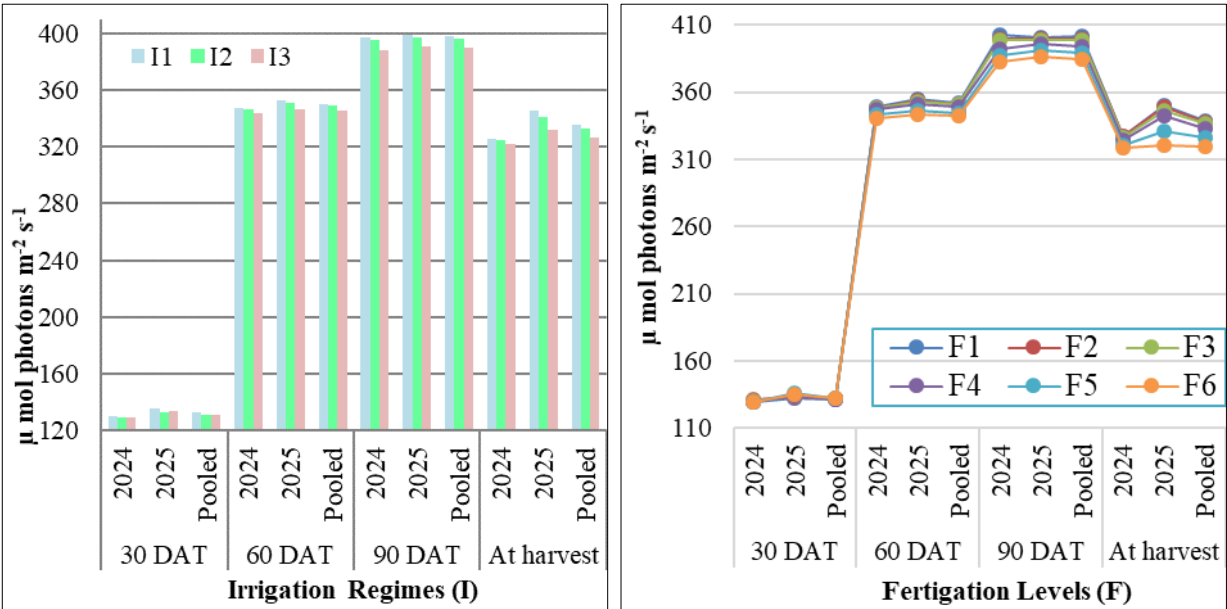


Fig 2: APAR ($\mu\text{mol photons m}^{-2} \text{s}^{-1}$) of onion as influenced periodically by different treatment

Table 1: Dry matter and Absorbed PAR of onion as influenced periodically by different treatments

Treatments	1.a Dry matter (g plant ⁻¹)												1.b Absorbed PAR (μmol photons m ⁻² s ⁻¹)											
	30 DAT			60 DAT			90 DAT			At harvest			30 DAT			60 DAT			90 DAT			At harvest		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
A. Irrigation Regimes (I)																								
I ₁	1.49	1.52	1.50	5.67	5.90	5.78	9.21	9.63	9.42	15.95	14.24	15.10	131	135	133	348	353	350	397	399	398	326	346	336
I ₂	1.49	1.52	1.50	5.63	5.86	5.74	8.97	9.58	9.28	15.59	13.96	14.77	129	133	131	346	351	349	395	397	396	324	341	333
I ₃	1.50	1.52	1.51	5.51	5.71	5.61	8.55	9.19	8.87	14.49	12.72	13.60	129	133	131	344	347	345	389	391	390	322	332	327
SE m ±	0.02	0.01	0.01	0.01	0.02	0.01	0.06	0.02	0.02	0.10	0.12	0.10	0.43	0.53	0.18	0.35	0.88	0.39	0.53	0.60	0.43	0.48	1.20	0.62
CD @ 5%	NS	NS	NS	0.06	0.09	0.05	0.24	0.10	0.09	0.38	0.46	0.40	NS	NS	NS	1.38	3.44	1.54	2.08	2.34	1.68	1.89	4.71	2.43
B. Fertigation Levels (F)																								
F ₁	1.51	1.54	1.52	5.76	6.03	5.90	9.46	10.04	9.75	16.70	14.93	15.82	129	133	131	349	355	352	402	400	401	328	350	339
F ₂	1.52	1.57	1.55	5.75	5.99	5.87	9.28	10.03	9.65	16.52	14.78	15.65	132	133	132	348	354	351	400	399	400	327	349	338
F ₃	1.53	1.55	1.54	5.73	5.97	5.85	9.21	9.96	9.59	16.32	14.58	15.45	131	134	132	348	353	351	399	399	399	326	346	336
F ₄	1.45	1.48	1.46	5.62	5.86	5.74	8.77	9.55	9.16	15.64	14.00	14.82	129	134	131	347	351	349	392	396	394	324	342	333
F ₅	1.49	1.51	1.50	5.47	5.62	5.54	8.52	8.83	8.67	14.16	12.46	13.31	129	136	132	343	346	345	387	391	389	321	331	326
F ₆	1.45	1.49	1.47	5.28	5.46	5.37	8.22	8.40	8.31	12.73	11.09	11.91	129	135	132	341	344	342	382	387	384	318	320	319
SE m ±	0.02	0.02	0.02	0.02	0.03	0.11	0.09	0.04	0.05	0.15	0.14	0.24	0.80	1.14	0.97	0.85	0.90	2.03	1.54	1.00	2.85	0.44	1.30	1.44
CD @ 5%	NS	NS	NS	0.06	0.09	0.31	0.27	0.11	0.15	0.43	0.39	0.70	NS	NS	NS	2.45	2.60	2.52	4.46	2.88	3.67	1.26	3.76	4.15
Interaction (I × F)																								
Between two sub plots means at same level of main plot means																								
SE m ±	0.04	0.04	0.01	0.04	0.05	0.02	0.16	0.07	0.13	0.26	0.24	0.03	1.38	1.97	0.90	1.47	1.56	0.57	2.67	1.73	1.38	0.76	2.25	4.03
CD @ 5%	NS	NS	NS	NS	NS	NS	0.47	0.19	0.37	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	2.18	6.51	11.56
Between two main plots means at same level of sub plot means																								
SE m ±	0.04	0.04	0.02	0.04	0.05	0.01	0.16	0.07	0.05	0.25	0.25	0.06	1.33	1.87	1.10	1.39	1.67	0.38	2.50	1.69	1.12	0.84	2.38	1.03
CD @ 5%	NS	NS	NS	NS	NS	NS	0.49	0.20	0.15	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	2.71	7.51	2.96
General mean	1.49	1.52	1.51	5.60	5.82	5.71	8.91	9.47	9.19	15.34	13.64	14.49	130	134	132	346	350	348	394	395	394	324	340	332

Table 1 a: Dry matter plant⁻¹ of onion as influenced by interaction effect between irrigation regimes and fertigation levels at 90 DAT

Irrigation Regimes (I) Fertigation Levels (F)	Dry matter (g plant ⁻¹) at 90 DAT												Absorbed PAR (μmol photons m ⁻² s ⁻¹) at harvest											
	2023-24				2024-25				Pooled				2023-24				2024-25				Pooled			
	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean
F ₁	10.07	9.57	8.74	9.46	10.35	10.25	9.53	10.04	10.21	9.91	9.14	9.75	330	328	324	328	358	353	340	350	344	340	332	339
F ₂	9.73	9.37	8.73	9.28	10.27	10.12	9.68	10.03	10.00	9.75	9.21	9.65	329	327	324	327	357	350	339	349	343	339	331	338
F ₃	9.61	9.31	8.70	9.21	10.27	10.11	9.50	9.96	9.94	9.71	9.10	9.59	329	327	323	326	355	348	337	346	342	337	330	336
F ₄	8.87	8.84	8.61	8.77	9.70	9.71	9.25	9.55	9.29	9.27	8.93	9.16	326	325	322	324	348	343	334	342	337	334	328	333
F ₅	8.58	8.54	8.43	8.52	8.79	8.86	8.83	8.83	8.68	8.70	8.63	8.67	322	321	320	321	331	330	330	331	326	325	325	326
F ₆	8.40	8.19	8.07	8.22	8.38	8.44	8.36	8.40	8.39	8.32	8.22	8.31	319	319	317	318	325	323	313	320	322	321	315	319
Mean	9.21	8.97	8.55	8.91	9.63	9.58	9.19	9.47	9.42	9.28	8.87	9.19	326	324	322	324	346	341	332	340	336	333	327	332
Between two sub plots means at same level of main plot means																								
SE m ±	0.16		0.16		0.07		0.07		0.13		0.05		0.76		0.84		2.25		2.38		4.03		1.03	
Between two main plots means at same level of sub plot means																								
CD @ 5%	0.47		0.49		0.19		0.20		0.37		0.15		2.18		2.71		6.51		7.51		11.56		2.96	

NOTE: Fertigation Levels (F): F₁-100% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with no basal, F₂-75% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with 25% N: P₂O₅: K₂O as basal, F₃-75% N: P₂O₅: K₂O kg ha⁻¹ through fertigation with no basal, F₄-56% N: P₂O₅: K₂O through fertigation with 19% N: P₂O₅: K₂O kg ha⁻¹ as basal, F₅-100% N: P₂O₅: K₂O kg ha⁻¹ through conventional fertilizers F₆- Absolute control

Table 2: Photosynthetic rate of onion as influenced periodically by different treatments

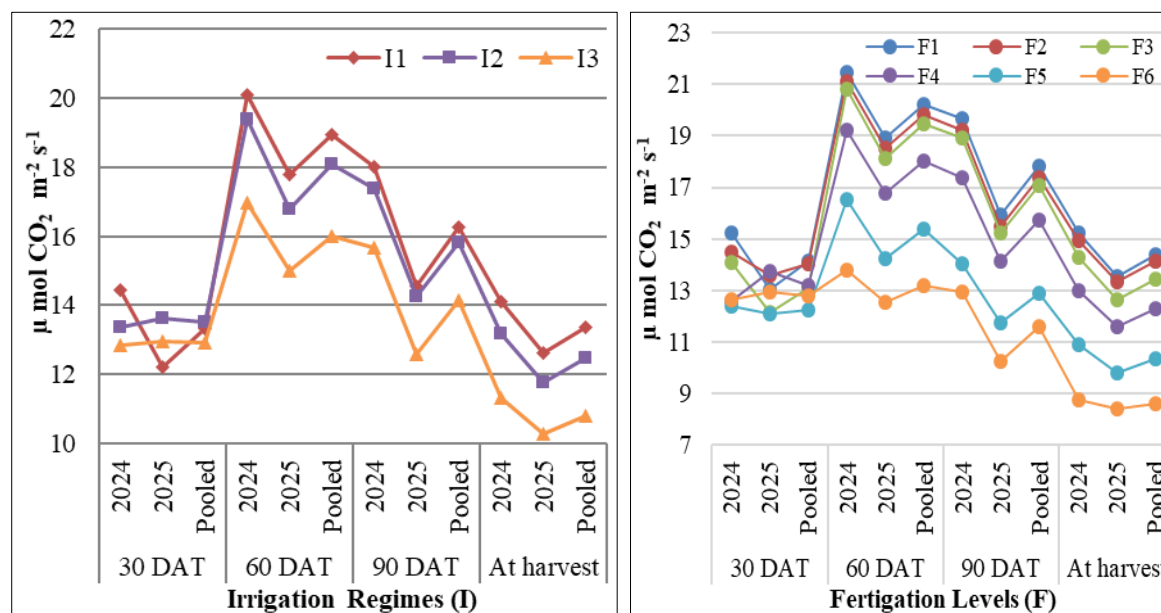
Treatments	Photosynthetic rate ($\mu\text{ mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$)											
	30 DAT			60 DAT			90 DAT			At harvest		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
A. Irrigation Regimes (I)												
I ₁ -1.0 ETc	14.5	12.2	13.3	20.1	17.8	18.9	18.0	14.5	16.3	14.1	12.6	13.4
I ₂ -0.8 ETc	13.4	13.6	13.5	19.4	16.8	18.1	17.4	14.3	15.8	13.2	11.8	12.5
I ₃ -0.6 ETc	12.8	12.9	12.9	17.0	15.0	16.0	15.7	12.6	14.1	11.3	10.3	10.8
SE m $\pm$	0.76	0.53	0.46	0.21	0.28	0.23	0.22	0.16	0.16	0.50	0.22	0.31
CD @ 5%	NS	NS	NS	0.84	1.12	0.90	0.88	0.62	0.64	1.95	0.88	1.20
B. Fertigation Levels (F)												
F ₁ -100% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with no basal	15.2	13.1	14.1	21.5	18.9	20.2	19.7	16.0	17.8	15.2	13.5	14.4
F ₂ -75% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with 25% N: P ₂ O ₅ : K ₂ O as basal	14.5	13.6	14.0	21.1	18.5	19.8	19.2	15.5	17.4	15.0	13.3	14.1
F ₃ -75% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with no basal	14.1	12.1	13.1	20.8	18.1	19.5	18.9	15.2	17.1	14.3	12.6	13.4
F ₄ -56% N: P ₂ O ₅ : K ₂ O through fertigation with 19% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ as basal	12.6	13.7	13.2	19.2	16.8	18.0	17.4	14.1	15.8	13.0	11.6	12.3
F ₅ -100% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through conventional fertilizers	12.4	12.1	12.2	16.6	14.2	15.4	14.0	11.7	12.9	10.9	9.8	10.3
F ₆ -Absolute control	12.6	12.9	12.8	13.8	12.5	13.2	12.9	10.2	11.6	8.8	8.4	8.6
SE m $\pm$	0.78	0.82	0.85	0.26	0.29	1.53	0.27	0.26	0.26	0.50	0.42	0.56
CD @ 5%	NS	NS	NS	0.76	0.83	0.80	0.78	0.74	0.76	1.45	1.20	1.33
Interaction (I $\times$ F)												
Between two sub plots means at same level of main plot means												
SE m $\pm$	1.36	1.43	0.64	0.46	0.50	0.26	0.47	0.44	0.31	0.87	0.72	0.26
CD @ 5%	NS	NS	NS	1.32	1.44	0.74	1.35	1.28	0.88	NS	NS	NS
Between two main plots means at same level of sub plot means												
SE m $\pm$	1.45	1.41	0.83	0.47	0.54	0.26	0.48	0.44	0.08	0.94	0.70	0.22
CD @ 5%	NS	NS	NS	1.46	1.71	0.74	1.50	1.32	0.24	NS	NS	NS
General mean	13.6	12.9	13.2	18.8	16.5	17.7	17.0	13.8	15.4	12.9	11.5	12.2

Table 2 a: Photosynthetic rate of onion as influenced by interaction effect between irrigation regimes and fertigation levels at 60 DAT

Irrigation Regimes (I) Fertigation Levels (F)	Photosynthetic rate ($\mu\text{ mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$) at 60 DAT											
	2023-24				2024-25				Pooled			
	I ₁ -1.0 ETc	I ₂ -0.8 ETc	I ₃ -0.6 ETc	Mean	I ₁ -1.0 ETc	I ₂ -0.8 ETc	I ₃ -0.6 ETc	Mean	I ₁ -1.0 ETc	I ₂ -0.8 ETc	I ₃ -0.6 ETc	Mean
F ₁ -100% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with no basal	23.4	22.3	18.7	21.5	20.8	19.1	16.9	18.9	22.1	20.7	17.8	20.2
F ₂ -75% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with 25% N: P ₂ O ₅ : K ₂ O as basal	23.0	21.6	18.7	21.1	20.5	18.8	16.2	18.5	21.7	20.2	17.5	19.8
F ₃ -75% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with no basal	22.3	21.4	18.6	20.8	20.0	18.5	16.0	18.1	21.1	19.9	17.3	19.5
F ₄ -56% N: P ₂ O ₅ : K ₂ O through fertigation with 19% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ as basal	20.1	20.0	17.6	19.2	17.8	17.4	15.2	16.8	18.9	18.7	16.4	18.0
F ₅ -100% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through conventional fertilizers	16.8	16.4	16.5	16.6	14.7	14.3	13.7	14.2	15.7	15.3	15.1	15.4
F ₆ -Absolute control	15.0	14.6	11.8	13.8	13.0	12.6	12.1	12.5	14.0	13.6	11.9	13.2
Mean	20.1	19.4	17.0	18.8	17.8	16.8	15.0	16.5	18.9	18.1	16.0	17.7
Source	SE m $\pm$			CD @ 5%	SE m $\pm$			CD @ 5%	SE m $\pm$			CD @ 5%
Between two sub plots means at same level of main plot means	0.46			1.32	0.50			1.44	0.26			0.74
Between two main plots means at same level of sub plot means	0.47			1.46	0.54			1.71	0.26			0.74

Table 2 b: Photosynthetic rate of onion as influenced by interaction effect between irrigation regimes and fertigation levels at 90 DAT

Irrigation Regimes (I) Fertigation Levels (F)	Photosynthetic rate ($\mu\text{mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$) at 90 DAT											
	2023-24				2024-25				Pooled			
	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean	I1-1.0 ETc	I2-0.8 ETc	I3-0.6 ETc	Mean
F ₁ -100% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with no basal	21.0	20.3	17.7	19.7	17.2	16.7	14.0	16.0	19.1	18.5	15.9	17.8
F ₂ -75% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with 25% N: P ₂ O ₅ : K ₂ O as basal	20.9	19.6	17.1	19.2	16.8	16.0	13.7	15.5	18.9	17.8	15.4	17.4
F ₃ -75% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through fertigation with no basal	20.3	19.3	17.1	18.9	16.4	15.8	13.5	15.2	18.3	17.6	15.3	17.1
F ₄ -56% N: P ₂ O ₅ : K ₂ O through fertigation with 19% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ as basal	18.1	18.1	16.0	17.4	14.9	14.6	12.9	14.1	16.5	16.3	14.4	15.8
F ₅ -100% N: P ₂ O ₅ : K ₂ O kg ha ⁻¹ through conventional fertilizers	14.5	13.9	13.8	14.0	11.8	11.9	11.5	11.7	13.1	12.9	12.6	12.9
F ₆ -Absolute control	13.3	13.2	12.3	12.9	10.3	10.5	9.9	10.2	11.8	11.9	11.1	11.6
Mean	18.0	17.4	15.7	17.0	14.5	14.3	12.6	13.8	16.3	15.8	14.1	15.4
Source	SE m ±		CD @ 5%		SE m ±		CD @ 5%		SE m ±		CD @ 5%	
Between two sub plots means at same level of main plot means	0.47		1.35		0.44		1.28		0.31		0.88	
Between two main plots means at same level of sub plot means	0.48		1.50		0.44		1.32		0.08		0.24	

**Fig 3:** Photosynthesis rate ($\mu\text{mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$) of onion as influenced periodically by different treatment

Effect of irrigation regimes

Irrigation regimes had no significant effect on APAR at 30 DAT; however, significant differences were observed at 60 and 90 DAT and harvest during both years. Irrigation scheduled at 1.0 ETc (I_1) recorded the highest APAR throughout the later growth stages. On a pooled basis, I_1 recorded 350, 398 and 336 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ at 60 and 90 DAT and harvest, respectively and remained statistically at par with 0.8 ETc (I_2). The lowest APAR was consistently recorded under 0.6 ETc (I_3). The higher APAR observed under 1.0 ETc (I_1) may be attributed to adequate soil moisture, which promoted vigorous canopy development, greater leaf area and improved interception of incident photosynthetically active radiation. Efficient canopy architecture under optimum irrigation enhanced the proportion of radiation absorbed by the crop, thereby favouring greater biomass production. Conversely, moisture stress under 0.6 ETc restricted canopy growth and reduced radiation interception, resulting in lower APAR values.

Effect of fertigation levels

Fertigation levels significantly influenced APAR at 60 and 90 DAT and at harvest, whereas their effect at 30 DAT was non-significant during both years. Application of 100% recommended N: P_2O_5 : K_2O through fertigation without basal application (F_1) recorded the highest APAR, with pooled values of 352, 401 and 339 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ at 60 and 90 DAT and harvest, respectively. The treatment remained statistically at par with F_2 and F_3 at most growth stages. In contrast, the absolute control (F_6) consistently recorded the lowest APAR. The higher APAR recorded under 100% recommended N: P_2O_5 : K_2O through fertigation (F_1) could be attributed to the continuous and balanced supply of nutrients, which enhanced leaf expansion, canopy development and radiation interception. Improved nutrient availability maintained a larger photosynthetically active canopy, thereby increasing APAR. Similar findings were reported by Yadav (2016)^[26] and Hasure *et al.* (2019)^[9].

Interaction effect

The interaction between irrigation regimes and fertigation levels significantly influenced APAR at harvest during both years and on pooled mean basis. The treatment combination 1.0 ETc + 100% recommended N: P_2O_5 : K_2O through fertigation without basal application (I_1F_1) recorded the highest APAR, with pooled values of 344 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ and remained statistically at par with I_1F_2 , I_1F_3 and I_1F_4 . The lowest APAR (315 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$) was recorded under 0.6 ETc + absolute control (I_3F_6). The superior performance of I_1F_1 indicates the synergistic effect of adequate irrigation and balanced nutrient supply through fertigation in maintaining a larger and more active photosynthetic canopy, thereby maximizing the absorption of photosynthetically active radiation. Conversely, the combined effect of moisture deficit and nutrient limitation under I_3F_6 adversely affected canopy development and radiation interception.

Photosynthetic rate

The periodical data on the photosynthetic rate of onion as influenced by different irrigation regimes and fertigation levels are presented in Table 2 and illustrated in Fig. 3. The photosynthetic rate increased progressively from 30 to 60 DAT, reached its maximum at 90 DAT and subsequently declined at harvest during both years and on pooled mean basis. The increase during the vegetative and bulb development stages reflected enhanced physiological activity and carbon assimilation, whereas the decline at harvest was associated with crop maturity and leaf senescence. On a pooled basis, the mean photosynthetic rate increased from 13.2 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 30 DAT to 17.7 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 60 DAT, reached 15.4 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 90 DAT and declined to 12.2 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at harvest.

CO₂ m⁻² s⁻¹ at 60 DAT, reached 15.4 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 90 DAT and declined to 12.2 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at harvest.

Effect of irrigation regimes

Irrigation regimes had no significant influence on photosynthetic rate at 30 DAT during either year. However, significant differences were observed at 60 and 90 DAT and harvest. Irrigation scheduled at 1.0 ETc (I_1) recorded the highest photosynthetic rate throughout the later growth stages. On a pooled basis, I_1 recorded 18.9, 16.3 and 13.4 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 60 and 90 DAT and harvest, respectively and remained statistically at par with 0.8 ETc (I_2). The lowest photosynthetic rate was consistently recorded under 0.6 ETc (I_3). The superior photosynthetic performance under 1.0 ETc may be attributed to adequate soil moisture, which maintained favourable leaf water status, improved stomatal conductance and facilitated efficient CO₂ diffusion into the leaf, thereby enhancing carbon assimilation. In contrast, moisture stress under 0.6 ETc likely induced partial stomatal closure and reduced metabolic activity, resulting in lower photosynthetic rates. Similar observations have been reported by Yanglem and Tumbare (2014)^[27], Cetin *et al.* (2015)^[1], Chaturvedi *et al.* (2019)^[2], Pinnamaneni *et al.* (2022)^[16] and Rumani *et al.* (2024)^[20].

Effect of fertigation levels

Fertigation levels had no significant effect on photosynthetic rate at 30 DAT but significantly influenced the parameter at 60 and 90 DAT and harvest during both years. The application of 100% recommended N: P_2O_5 : K_2O through fertigation without basal application (F_1) recorded the highest photosynthetic rate, with pooled values of 20.2, 17.8 and 14.4 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 60 and 90 DAT and harvest, respectively and remained statistically at par with F_2 and F_3 . The lowest photosynthetic rate was consistently recorded under the absolute control (F_6). Higher photosynthetic activity under F_1 may be attributed to the continuous and balanced supply of nutrients, particularly nitrogen, through fertigation. Adequate nitrogen availability promotes chlorophyll synthesis, Rubisco activity and leaf metabolic processes, thereby improving photosynthetic efficiency and carbon fixation. Conversely, nutrient deficiency under the control treatment limited photosynthetic capacity and reduced carbon assimilation. These findings are consistent with those reported by Wang *et al.* (2009), Moinuddin *et al.* (2014)^[13], Cetin *et al.* (2015)^[1], Hasure *et al.* (2019)^[9], Han *et al.* (2025)^[8] and Singh *et al.* (2026)^[21].

Interaction effect

The interaction between irrigation regimes and fertigation levels significantly influenced photosynthetic rate at 60 and 90 DAT during both years and on pooled mean basis. The treatment combination 1.0 ETc + 100% recommended N: P_2O_5 : K_2O through fertigation without basal application (I_1F_1) recorded the highest photosynthetic rate at both stages and remained statistically at par with I_1F_2 and I_1F_3 on pooled mean basis. In contrast, the lowest photosynthetic rate was observed under 0.6 ETc + absolute control (I_3F_6). The superior photosynthetic performance of I_1F_1 demonstrates the synergistic effect of optimum soil moisture and balanced nutrient supply through fertigation, which maintained favourable stomatal behaviour, enhanced chlorophyll formation and increased photosynthetic carbon assimilation. Conversely, the combined effect of moisture deficit and nutrient stress under I_3F_6 adversely affected leaf physiological processes, resulting in reduced photosynthetic efficiency.

Conclusion

The present investigation demonstrated that irrigation regimes and fertigation levels significantly influenced dry matter accumulation, absorbed photosynthetically active radiation (APAR) and photosynthetic rate of onion under an onion-okra sequence cropping system. Irrigation scheduled at 1.0 ETc consistently enhanced biomass accumulation, radiation interception and photosynthetic activity compared with lower irrigation levels, indicating the importance of maintaining adequate soil moisture for optimum crop physiological performance. Likewise, application of 100% recommended N: P₂O₅: K₂O through fertigation without basal application (F₁) recorded superior dry matter accumulation, APAR and photosynthetic rate, reflecting the beneficial effect of continuous and balanced nutrient supply on crop growth and carbon assimilation. The interaction of 1.0 ETc + 100% recommended N: P₂O₅: K₂O through fertigation without basal application produced the highest values for the studied physiological parameters, demonstrating the synergistic effect of optimum irrigation and fertigation in improving canopy development, radiation utilisation and photosynthetic efficiency. Overall, the study suggests that irrigation at 1.0 ETc combined with 100% recommended N: P₂O₅: K₂O through fertigation without basal application is an effective management strategy for enhancing physiological efficiency and biomass production of onion under an onion-okra sequence cropping system.

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