



RESEARCH ARTICLE

Response of rabi mustard (*Brassica juncea* L.) to varying irrigation regimes and fertigation schedules under maize-mustard cropping system

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Abstract

The limited availability of irrigation water and inefficient nutrient use are major constraints affecting mustard (*Brassica juncea* L.) productivity in India. To enhance yield and resource-use efficiency, a field experiment was conducted at the Regional Agricultural Research Station (RARS), Jagtial, during rabi seasons of 2019–20, 2020–21 and 2021–22 to study the effect of irrigation regimes and fertigation levels on growth, yield, water productivity and economics of mustard under drip irrigation. The experiment was laid out in a split-plot design with three irrigation levels [0.8, 1.0 and 1.2 times the cumulative Class A pan evaporation (Epan)] in the main plots and four fertigation levels (75 %, 100 %, 125 % and 150 % of recommended dose of nitrogen and potassium) in the subplots, replicated thrice. Pooled results indicated that irrigation at 1.2 Epan recorded the highest seed yield (982 kg ha⁻¹), stalk yield (2771 kg ha⁻¹) and gross returns (₹48197 ha⁻¹), whereas the highest water productivity (0.54 kg m⁻³) was achieved with 0.8 Epan. Among fertigation treatments, 150 % RDN + K significantly enhanced plant height, siliqua plant⁻¹, seeds siliqua⁻¹, seed yield (1040 kg ha⁻¹) and net returns (₹25811 ha⁻¹) compared to 75 % RDN + K. The interaction between irrigation and fertigation was non-significant for most parameters. The above findings highlight that adopting 1.2 Epan irrigation with 150 % RDN + K fertigation can substantially improve mustard productivity and farm profitability under drip systems, making it a viable strategy for farmers facing resource constraints. Additionally, the higher water productivity observed with 0.8 Epan suggests that growers in water-limited regions can optimise water use without severe yield penalties by adjusting irrigation levels appropriately.

Keywords: drip fertigation; economics; irrigation regimes; mustard; water productivity; yield

Introduction

Oilseed crops are a vital component of Indian agriculture, providing raw materials for the edible oil industry and contributing significantly to the agricultural gross domestic product (GDP). Among these, rapeseed–mustard (*Brassica juncea* L.) occupies a prominent position as the second most important oilseed crop after groundnut in India. It is predominantly grown during the rabi season across northern and central India, contributing around 30 % of the total oilseed production and about 27 % of the total oilseed area in the country (1). India's rapeseed–mustard cultivation has expanded remarkably from 2.07 million ha in 1950–51 to 9.18 million ha in 2023–24, while production has risen from 0.76 million t to 13.26 million tonnes during the same period, with an average productivity of 1444 kg ha⁻¹ (2). Despite this progress, the yield levels remain considerably lower than the global average, mainly due to suboptimal input use and resource limitations.

India's edible oil production currently meets only about half of the domestic requirement, resulting in substantial imports. According to Vision 2050, India will require 28.5 million tonnes of vegetable oil for direct consumption by 2050—a target difficult to achieve with current levels of resources, technology and management efficiency in Indian agriculture (3). This underscores the urgent need to improve oilseed productivity through scientific water and nutrient management strategies.

Efficient use of water and nutrients is crucial for enhancing mustard productivity, especially in semi-arid regions where water scarcity and nutrient losses constrain yield potential. Drip irrigation combined with fertigation—a technique of applying soluble fertilisers through the irrigation system—offers multiple benefits, including improved fertiliser-use efficiency, uniform distribution of nutrients and reduced leaching losses (4, 5). Studies have demonstrated that irrigation scheduling based on the Irrigation Water/Cumulative Pan Evaporation (IW/CPE) ratio is an effective method for optimising water use without compromising yield (6).

However, information on site-specific irrigation and fertigation scheduling for mustard under drip irrigation is limited in the semi-arid zone of northern Telangana, particularly under maize–mustard cropping systems. Understanding the combined effect of irrigation regimes and fertigation schedules is essential for developing region-specific management practices that improve yield, water-use efficiency and profitability.

Therefore, the present investigation was undertaken to assess the growth, yield, water-use efficiency and economics of mustard under varying irrigation regimes and fertigation schedules and to develop an optimised irrigation-fertigation strategy for sustainable mustard production in the maize–mustard cropping system of Northern Telangana.

Material and Methods

Experimental site

The field experiment was conducted for three consecutive rabi seasons (2019–20, 2020–21 and 2021–22), at the Regional Agricultural Research Station (RARS), Jagtial, under the Northern Telangana zone (18° 48' N latitude, 78° 56' E longitude, 240 m above mean sea level). The region experiences a semi-arid tropical climate with an average annual rainfall of 850 mm. During the experimental period, the mean maximum and minimum temperatures ranged between 28–35 °C and 13–19 °C, respectively.

The experimental soil was a sandy clay loam, neutral in reaction (pH 7.6), low in available nitrogen (182 kg ha⁻¹), medium in available phosphorus (21 kg ha⁻¹) and high in available potassium (K) (312 kg ha⁻¹). Organic carbon content was 0.49 %. Prior to sowing, composite soil samples (0–30 cm) were collected and analysed following standard procedures (7).

Experimental design and treatments

The experiment was laid out in split-plot design with three replications. Two factors were studied during the investigation i.e. irrigational regimes at 3 levels and fertigation schedule at 4 levels (Table 1). Each plot measured 5.0 m × 3.6 m (18 m²) with 1.0 m buffer between plots to avoid lateral water movement.

Crop management

Mustard (*Brassica juncea* L.) variety 'Pusa Bold' was sown manually at a spacing of 45 cm × 15 cm with a seed rate of 5 kg ha⁻¹ immediately after the harvest of kharif maize. Two seeds per hill were dibbled and later thinned to one healthy seedling per hill. A 100 % P is applied as basal dose using single super phosphate as source of fertiliser and N and K was applied via drip fertigation as per the treatment schedule (Table 2). Standard intercultural and plant-protection measures were followed uniformly across treatments.

Table 1. Treatment details

Factor	Treatment	Description
Irrigation regime (I)	I ₁	0.8 IW/CPE ratio
	I ₂	1.0 IW/CPE ratio
	I ₃	1.2 IW/CPE ratio
Fertigation schedule (F)	F ₁	75 % RDN, K (45 kg N /ha, 30 kg K ha ⁻¹)
	F ₂	100 % RDN, K (60 kg N /ha, 40 kg K ha ⁻¹)
	F ₃	125 % RDN, K (75 kg N /ha, 50 kg K ha ⁻¹)
	F ₄	150 % RDN, K (90 kg N /ha, 60 kg K ha ⁻¹)

Table 2. Fertigation schedule for mustard

Crop stages	Quantity (%)	
	N	K
Vegetative stage	25	25
Reproductive stage	50	50
Maturity stage	25	25
Total	100	100

Drip irrigation scheduling

Irrigation scheduling was done based on daily evaporation data recorded from United States Weather Bureau (USWB) class 'A' pan evaporimeter in agro-meteorological station, RARS, Polasa, Jagtial.

The irrigation duration was based on the number of laterals, emitter spacing and emitter discharge for a given design area. To calculate the application rate and irrigation time of the drip system following formulae were used:

$$\text{Application rate (mm h}^{-1}\text{)} = \frac{Q}{D_L \times D_E}$$

$$Q = \text{Dripper discharge (L h}^{-1}\text{)}$$

$$D_L = \text{Distance between laterals (m)}$$

$$D_E = \text{Distance between drippers (m)}$$

$$\text{Irrigation time (min)} = \frac{\text{Epan (mm)} \times 60}{\text{Application rate (mm h}^{-1}\text{)}}$$

Fertigation schedule

Drip fertigation with 100 % recommended dose of fertilisers (60–40 kg N- K₂O ha⁻¹) and irrigation [0.8 times the cumulative Class A pan evaporation (Epan)] with 226.2 mm of water, irrigation (1.0 Epan) with 282.7 mm of water and irrigation (1.2 Epan) with 339.2 mm of water has given 3 days interval under open field conditions. The fertigation was given at 6 days interval in 10 splits using the fertilisers Urea, white MOP (Table 3 and 4).

Observations and data recording

Growth and yield observations were recorded on five randomly selected plants per plot for Plant height (cm), number of branches plant⁻¹, number of siliquae plant⁻¹ and 1000-seed weight (g), Seed yield (kg ha⁻¹) and stover yield (kg ha⁻¹) were recorded from the net plot area and adjusted to 8 % seed moisture. Oil content (%) was determined by Soxhlet extraction (8). Economic analysis included cost of cultivation, gross return, net return and benefit : cost (B : C) ratio following standard economic methods (9).

Water use efficiency (WUE) was computed as:

$$\text{WUE (kg ha}^{-1}\text{mm}^{-1}\text{)} = \frac{\text{Seed yield (kg ha}^{-1}\text{)}}{\text{Total water used (mm)}}$$

Table 3. Nitrogen fertigation schedule (60 kg ha⁻¹)

Crop duration	Days	% of N applied	No. of Splits	N kg day ⁻¹	N (kg ha ⁻¹)				Urea in (kg ha ⁻¹)			
					6 days interval				6 days interval			
					75 (%)	100 (%)	125 (%)	150 (%)	75 (%)	100 (%)	125 (%)	150 (%)
10 – 25 DAS	15	25	3	1.0	4.50	6.00	7.50	9.00	9.78	13.04	16.30	19.57
26–50 DAS	25	50	4	1.2	5.40	7.20	9.00	10.80	11.74	15.65	19.57	23.48
51–65 DAS	15	25	3	1.0	4.50	6.00	7.50	9.00	9.78	13.04	16.30	19.57

Table 4. Potassium fertigation schedule (40 kg ha⁻¹)

Crop duration	Days	% of K applied	No. of Splits	K kg day ⁻¹	K (kg ha ⁻¹)				White potash in (kg ha ⁻¹)			
					6 days interval				6 days interval			
					75 (%)	100 (%)	125 (%)	150 (%)	75 (%)	100 (%)	125 (%)	150 (%)
10 – 25 DAS	15	25	3	0.67	3.00	4.00	5.00	6.00	5.00	6.67	8.33	10.00
26–50 DAS	25	50	4	0.80	3.60	4.80	6.00	7.20	6.00	8.00	10.00	12.00
51–65DAS	15	25	3	0.67	3.00	4.00	5.00	6.00	5.00	6.67	8.33	10.00

Statistical analysis

Data were subjected to analysis of variance (ANOVA) appropriate for factorial randomised block design (10). Treatment means were compared using the least significant difference (LSD) test at 5 % probability. Homogeneity of variances across years was tested using Bartlett's test before performing pooled analysis. Since the test was non-significant, the error variances were considered homogeneous and the data were pooled for combined analysis over years.

Results and Discussion

Plant height (cm)

Pooled data indicated that irrigation regimes had a no significant influence on plant height of mustard at harvest (Table 5). However, numerically, plants grown under 1.2 Epan (I₃) recorded the tallest height (168.1 cm), followed by 1.0 Epan (I₂) (163.2 cm), whereas the shortest plants were noted under 0.8 Epan (I₁) (161.2 cm). Among fertigation treatments, 150 % recommended dose of nitrogen (RDN) + K (F₄) registered a significantly higher plant height (168.4 cm) compared to 75 % RDN + K (F₁) (159.1 cm). This suggests that, the synergistic role of higher nutrient availability and optimum soil moisture in promoting vegetative growth.

Similar results were reported by (11, 12), who found that increased irrigation frequency and nutrient application enhanced canopy development and cell elongation in mustard under drip irrigation.

Number of primary and secondary branches per plant

The number of primary and secondary branches was significantly influenced by both irrigation and fertigation levels (Table 6). Irrigation scheduled at 1.2 Epan (I₃) recorded a higher number of primary branches (5.5) and secondary branches (11.0) compared to 0.8 Epan (I₁). Among fertigation levels, F₄ (150 % RDN + K) recorded the maximum number of primary (5.6) and secondary branches (11.5), which were significantly superior to F₁ (4.9 and 8.9, respectively). The increase in branching may be attributed to enhanced availability of nutrients and water through frequent drip fertigation, which improved plant vigour and photosynthate distribution.

These findings agree with previous reports, which observed that balanced fertigation with adequate irrigation promoted lateral growth and increased branching in oilseed crops (13, 14).

Number of siliquae per plant

The pooled data showed a significant improvement in the number of siliquae plant⁻¹ with increased irrigation and fertigation levels (Table 7). Plants under 1.2 Epan (I₃) produced the highest number of siliquae (257), which was superior to I₁ (206). Similarly, F₄ (150 % RDN + K) produced a significantly higher number of siliquae (272) than F₁ (194). This enhancement can be attributed to better nutrient uptake and water availability during flowering and pod formation stages, resulting in improved sink development. (15,16) also reported similar findings, linking adequate irrigation and nitrogen and K fertigation with improved siliqua formation in mustard.

Table 5. Plant height (cm) of mustard at harvest as influenced by different irrigation regimes and fertigation treatments

Treatments	Plant height (cm) at harvest			
	2019-20	2020-21	2021-22	Pooled
Irrigation regime (I)				
I ₁ :- Surface drip irrigation at 0.8 Epan	154.3	151.9	177.3	161.2
I ₂ :- Surface drip irrigation at 1.0 Epan	155.9	154	179.5	163.2
I ₃ :- Surface drip irrigation at 1.2 Epan	161.7	157.3	185.1	168.1
SEm ±	2.9	2.0	1.7	1.4
CD (P = 0.05)	NS	NS	NS	NS
Fertigation schedule (F)				
F ₁ :- 75 % RDN, K	150.4	149.7	177.3	159.1
F ₂ :- 100 % RDN, K	158.1	151.7	179.6	163.3
F ₃ :- 125 % RDN, K	159.9	156.2	180.9	165.7
F ₄ :- 150 % RDN, K	160.7	160.1	184.7	168.4
SEm ±	1.9	1.7	1.1	1.0
CD (p = 0.05)	5.5	5.1	3.3	3.0
Interaction (F×I)				
SEm ±	5.8	3.2	3.3	2.8
CD (p = 0.05)	NS	NS	NS	NS
Interaction (I × F)				
SEm ±	4.0	4.0	2.3	2.0
CD (p = 0.05)	NS	NS	NS	NS

Table 6. Number of primary and secondary branches of mustard influenced by different irrigation regimes and fertigation treatments

Treatments	Number of primary branches plant ⁻¹				Number of secondary branches plant ⁻¹			
	2019-20	2020-21	2021-22	Pooled	2019-20	2020-21	2021-22	Pooled
Irrigation regime (I)								
I ₁ :- Surface drip irrigation at 0.8 Epan	4.4	5.3	5.2	5.0	9.2	9.6	10.2	9.7
I ₂ :- Surface drip irrigation at 1.0 Epan	4.6	5.6	5.5	5.2	9.7	10.7	10.9	10.4
I ₃ :- Surface drip irrigation at 1.2 Epan	4.9	5.9	5.7	5.5	9.9	11.6	11.5	11.0
SEm ±	0.1	0.2	0.2	0.1	0.3	0.5	0.3	0.1
CD (p = 0.05)	0.4	NS	NS	0.3	NS	NS	NS	0.6
Fertigation schedule (F)								
F ₁ :- 75 % RDN and K	4.3	5.3	5.1	4.9	8.5	8.4	9.8	8.9
F ₂ :- 100 % RDN and K	4.6	5.5	5.4	5.2	9.2	10.4	10.6	10.0
F ₃ :- 125 % RDN and K	4.6	5.6	5.6	5.3	10.4	11.2	11.3	11.0
F ₄ :- 150 % RDN and K	5.1	5.9	5.7	5.6	10.3	12.4	11.8	11.5
SEm ±	0.3	0.2	0.2	0.1	0.2	0.5	0.4	0.3
CD (p = 0.05)	NS	NS	NS	0.4	0.7	1.5	1.3	0.8
Interaction (F × I)								
SEm ±	0.2	0.3	0.3	0.2	0.6	0.9	0.7	0.3
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Interaction (I × F)								
SEm ±	0.4	0.3	0.4	0.2	0.5	1.1	0.5	0.4
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Table 7. Number of Siliquae Plant⁻¹ and Siliquae length (cm) of mustard influenced by different irrigation regimes and fertigation treatments

Treatments	Number of siliquae per plant				Siliquae length (cm)			
	2019-20	2020-21	2021-22	Pooled	2019-20	2020-21	2021-22	Pooled
Irrigation regime (I)								
I ₁ :- Surface drip irrigation at 0.8 Epan	164	197	306	206	4.2	4.5	5.1	4.5
I ₂ :- Surface drip irrigation at 1.0 Epan	173	231	376	243	4.4	4.7	5.3	4.7
I ₃ :- Surface drip irrigation at 1.2 Epan	186	244	391	257	4.5	4.8	5.5	4.8
SEm ±	4.0	3.0	12.0	5.0	0.1	0.0	0.1	0.0
CD (p = 0.05)	NS	13.0	49.0	22.0	0.2	0.1	NS	0.1
Fertigation schedule (F)								
F ₁ :- 75 % RDN and K	149	170	311	194	4.2	4.4	4.9	4.4
F ₂ :- 100 % RDN and K	159	216	342	223	4.2	4.6	5.2	4.6
F ₃ :- 125 % RDN and K	189	244	377	254	4.5	4.8	5.4	4.8
F ₄ :- 150 % RDN and K	200	265	400	272	4.6	4.9	5.6	4.9
SEm ±	9.0	8.0	9.0	6.0	0.1	0.1	0.1	0.1
CD (p = 0.05)	28.0	22.0	28.0	17.0	0.4	0.2	0.3	0.2
Interaction (F × I)								
SEm ±	9.0	12.0	19.0	11.0	0.1	0.1	0.2	0.0
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Interaction (I × F)								
SEm ±	15.0	7.0	24.0	10.0	0.2	0.1	0.2	0.1
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Siliqua length (cm)

The siliqua length increased progressively with higher irrigation and fertigation levels (Table 7). The longest siliquae (4.8 cm) were recorded under I₃ (1.2 Epan), while F₄ (150 % RDN + K) recorded 4.9 cm, both being significantly superior to the lowest treatments. Adequate soil moisture coupled with balanced nutrient supply supports better pod elongation and seed filling, as observed by previous researchers (17, 18).

Number of seeds per siliqua

The pooled data indicated a gradual increase in the number of seeds siliqua⁻¹ with increasing irrigation and fertigation levels (Table 8). The maximum number of seeds per siliqua (12.4) was recorded under I₃, while F₄ also resulted in significantly higher seeds per siliqua (12.7) compared to F₁ (11.0). Improved nutrient and moisture regimes likely enhanced pollen viability and seed setting, in line with observations by (19, 20) in mustard and similar oilseed crops.

Seed yield (kg ha⁻¹)

Pooled data (Table 9) revealed a significant effect of irrigation and fertigation on seed yield. The highest seed yield (982 kg ha⁻¹) was obtained under 1.2 Epan (I₃), which was significantly superior to 1.0 Epan (I₂) (886 kg ha⁻¹) and 0.8 Epan (I₁) (817 kg ha⁻¹). Among fertigation levels, F₄ (150 % RDN + K) recorded the maximum seed

yield (1040 kg ha⁻¹), followed by F₃ (125 % RDN + K) (956 kg ha⁻¹), both significantly higher than F₁ (748 kg ha⁻¹). The interaction effect was non-significant.

The increase in seed yield with higher irrigation and fertigation levels can be attributed to improved growth and yield components such as number of siliquae, seeds per siliqua and siliqua length. Similar yield enhancement under higher irrigation and fertigation schedules was reported by previous researchers (21, 22).

Stalk yield (kg ha⁻¹)

Although stalk yield differences were statistically non-significant, a numerical increase was observed with higher irrigation and fertigation levels (Table 9). The maximum stalk yield (2771 kg ha⁻¹) was recorded under I₃, while F₄ recorded 2923 kg ha⁻¹, indicating overall improvement in biomass accumulation. Enhanced vegetative growth under adequate water and nutrient conditions contributed to higher biomass production (23).

Harvest index (%)

The harvest index did not differ significantly across treatments but tended to increase with irrigation and fertigation levels (Table 9). The highest harvest index (27.3 %) was observed under F₄, indicating improved efficiency in partitioning of assimilates to the seed. Previous researchers also reported similar results, linking efficient nutrient use through fertigation to improved harvest index

Table 8. Number of Seeds silique⁻¹ of mustard influenced by different irrigation regimes and fertigation treatments

Treatments	Number of Seeds silique ⁻¹			
	2019–20	2020–21	2021–22	Pooled
Irrigation regime (I)				
I ₁ :- Surface drip irrigation at 0.8 Epan	10.9	10.26	13.2	11.5
I ₂ :- Surface drip irrigation at 1.0 Epan	11.1	10.28	14.3	11.9
I ₃ :- Surface drip irrigation at 1.2 Epan	11.4	11.31	14.5	12.4
SEm ±	0.1	0.08	0.4	0.1
CD ($p = 0.05$)	NS	0.34	NS	0.5
Fertigation schedule (F)				
F ₁ :- 75 % RDN and K	10.4	9.27	13.4	11.0
F ₂ :- 100 % RDN and K	10.7	10.53	13.9	11.7
F ₃ :- 125 % RDN and K	11.5	10.97	14.3	12.3
F ₄ :- 150 % RDN and K	11.8	11.69	14.5	12.7
SEm ±	0.3	0.50	0.4	0.2
CD ($p = 0.05$)	0.9	1.49	NS	0.7
Interaction (F × I)				
SEm ±	0.2	0.75	0.7	0.4
CD ($p = 0.05$)	NS	NS	NS	NS
Interaction (I × F)				
SEm ±	0.4	0.17	0.8	0.2
CD ($p = 0.05$)	NS	NS	NS	NS

Table 9. Seed yield (kg ha⁻¹), Stalk yield (kg ha⁻¹) and Harvest index (%) of mustard influenced by different irrigation regimes and fertigation treatments

Treatments	Seed yield (kg ha ⁻¹)				Stalk yield (kg ha ⁻¹)				Harvest index (%)			
	2019–20	2020–21	2021–22	Pooled	2019–20	2020–21	2021–22	Pooled	2019–20	2020–21	2021–22	Pooled
Irrigation regime (I)												
I ₁ :- Surface drip irrigation at 0.8 Epan	930	851	818	817	2508	2475	2627	2383	27.3	24.46	24.7	26.8
I ₂ :- Surface drip irrigation at 1.0 Epan	1059	881	865	886	2824	2675	2867	2577	28.1	23.68	24.8	26.7
I ₃ :- Surface drip irrigation at 1.2 Epan	1270	910	912	982	3307	3101	2926	2771	29.0	23.81	25.1	27.1
SEm ±	51.0	10.0	16.0	19.0	153.0	157.0	40.0	68.0	0.6	0.36	0.3	0.4
CD ($P = 0.05$)	205.0	39.0	64.0	76.0	NS	NS	163.0	274.0	NS	NS	NS	NS
Fertigation Schedule (F)												
F ₁ :- 75 % RDN and K	834	755	801	748	2273	2162	2421	2194	27.7	24.06	24.8	26.8
F ₂ :- 100 % RDN and K	1002	806	849	836	2690	2590	2564	2445	27.8	23.90	24.4	26.6
F ₃ :- 125 % RDN and K	1208	922	885	956	3205	3079	2942	2747	28.0	23.84	25.0	26.8
F ₄ :- 150 % RDN and K	1302	1040	924	1040	3349	3170	3299	2923	29.1	24.13	25.3	27.3
Sem ±	72.0	59.0	22.0	32.0	157.0	159.0	164.0	71.0	0.6	0.65	0.6	0.4
CD ($p = 0.05$)	216.0	178.0	65.0	96.0	471.0	477.0	490.0	211.0	NS	NS	NS	NS
Interaction (F × I)												
Sem ±	120.0	90.0	36.0	52.0	281.0	314.0	249.0	126.0	1.2	1.0	1.0	0.8
CD ($p = 0.05$)	NS	NS	NS	NS	NS	N/A	NS	NS	NS	NS	NS	NS
Interaction (I × F)												
SEm ±	102.0	20.0	32.0	38.0		286.0	81.0	135.9	1.1	0.7	0.7	0.8
CD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

in mustard (24) .

Water use and water productivity

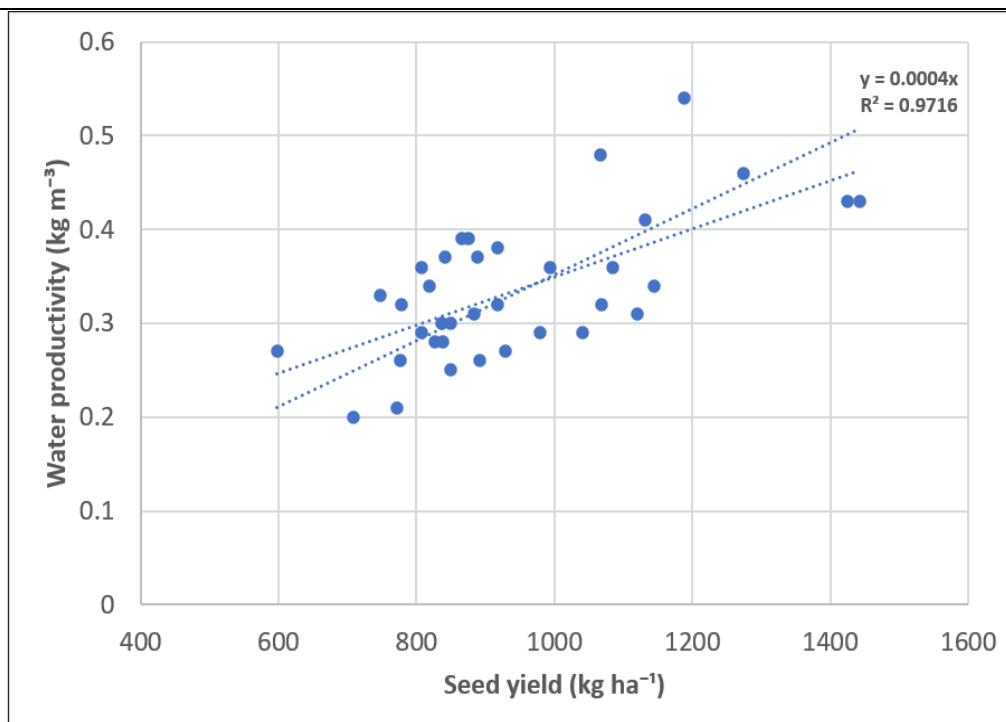
The volume of water applied increased with irrigation regime (Table 10). Water productivity was the highest under I₁F₄ (0.54 kg m⁻³), followed by I₂F₄ (0.46 kg m⁻³), while the lowest productivity (0.27 kg m⁻³) was recorded under I₁F₁. Although yield increased with irrigation level, the highest water productivity was observed at 0.8 Epan (I₁) due to lesser water use (Fig 1.). This indicates that moderate irrigation levels combined with higher fertigation rates optimise water productivity. These observations concur with (25, 26) who emphasised efficient water use through drip fertigation in oilseed crops.

Economics

Economic analysis (Table 11) revealed that gross returns, net returns and B : C ratio increased with higher irrigation and fertigation levels. The maximum net return (₹25811 ha⁻¹) and B : C ratio (2.04) were recorded under F₄ (150 % RDN + K), followed by F₃. Similarly, irrigation at 1.2 Epan (I₃) yielded the highest gross returns (₹48197 ha⁻¹) and B : C ratio (1.99). The higher economic returns are directly related to increased seed yield under optimal fertigation and irrigation management. These findings align with previous studies which also reported that higher fertigation levels improved profitability of drip-irrigated mustard systems (27, 28) .

Table 10. Effect of drip irrigation regimes and fertigation schedules on water applied and water productivity of mustard

Treatments	2019–20, 2020–21 and 2021–22 (Pooled data)			
	Seed yield (kg ha ⁻¹)	Water applied (mm ha ⁻¹)	Water applied (m3)	Water productivity (kg m ⁻³)
I ₁ F ₁	598	222.2	2222	0.27
I ₁ F ₂	866	222.2	2222	0.39
I ₁ F ₃	1067	222.2	2222	0.48
I ₁ F ₄	1189	222.2	2222	0.54
I ₂ F ₁	837	277.8	2778	0.30
I ₂ F ₂	994	277.8	2778	0.36
I ₂ F ₃	1132	277.8	2778	0.41
I ₂ F ₄	1275	277.8	2778	0.46
I ₃ F ₁	1068	333.4	3334	0.32
I ₃ F ₂	1145	333.4	3334	0.34
I ₃ F ₃	1425	333.4	3334	0.43
I ₃ F ₄	1442	333.4	3334	0.43

**Fig 1.** Scatter plot showing relationship between seed yield and water productivity across treatments.**Table 11.** Economics of mustard influenced by different irrigation regimes and fertigation treatments

Treatments	Gross returns (₹ ha ⁻¹)				Net returns (₹ ha ⁻¹)				B : C ratio			
	2019–20	2020–21	2021–22	Pooled	2019–20	2020–21	2021–22	Pooled	2019–20	2020–21	2021–22	Pooled
Irrigation regime (I)												
I ₁ :- Surface drip irrigation at 0.8 Epan	41153	39557	41313	40674	18011	15490	15621	16374	1.77	1.64	1.61	1.67
I ₂ :- Surface drip irrigation at 1.0 Epan	46874	40976	43655	43835	23732	16909	17963	19535	2.02	1.70	1.70	1.81
I ₃ :- Surface drip irrigation at 1.2 Epan	56198	42320	46074	48197	33056	18253	20382	23897	2.42	1.75	1.79	1.99
SEm ±	2253	453	810	852	2253	453	810	852	0.10	0.02	0.03	0.04
CD (p = 0.05)	9085	1827	3265	3436	9085	1827	3265	3436	0.40	0.07	0.13	0.14
Fertigation schedule (F)												
F ₁ :- 75 % RDN and K	36917	35095	40446	37486	14549	11802	15528	13960	1.65	1.51	1.62	1.59
F ₂ :- 100 % RDN and K	44326	37452	42895	41558	21442	13643	17461	17515	1.94	1.57	1.69	1.73
F ₃ :- 125 % RDN and K	53452	42883	44704	47013	30052	18558	18754	22455	2.29	1.76	1.72	1.92
F ₄ :- 150 % RDN and K	57604	48373	46678	50885	33688	23532	20212	25811	2.41	1.95	1.76	2.04
SEm ±	3195	2761	1097	1454	3195	2761	1097	1454	0.14	0.11	0.04	0.06
CD (p = 0.05)	9567	8266	3284	4355	9567	8266	3284	4355	0.41	NS	NS	0.18
Interaction (F × I)												
SEm ±	4507	906	1620	1704	4507	906	1620	1704	0.20	0.04	0.06	0.07
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction (I × F)												
SEm ±	5296	4166	1834	2342	5296	4166	1834	2342	0.23	0.17	0.07	0.10
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Conclusion

The results of the present investigation clearly demonstrated that integration of drip irrigation and fertigation significantly enhanced the growth, yield and resource-use efficiency of mustard under the semi-arid conditions of Telangana. Among the treatments, irrigation scheduled at 1.2 times the cumulative Class A pan evaporation (Epan) coupled with 150 % recommended dose of nitrogen (RDN) and potassium (K) through fertigation recorded the highest seed yield and economic returns. However, irrigation at 0.8 Epan with 150 % fertigation achieved the highest water-use efficiency, suggesting that optimum irrigation combined with higher nutrient supply is most efficient. Therefore, the study suggests that while 1.2 Epan with 150 % RDN + K is ideal for maximising yield and profitability, adopting 0.8 Epan with the same fertigation level offers a more sustainable option for conserving water without substantial yield loss under semi-arid conditions.

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Authors' contributions

NM carried out data analysis and prepared the original draft of the manuscript. PMR conceptualised and supervised the study and contributed to manuscript review and editing. BR assisted in improving the manuscript content. NN performed data retention and interpretation. TLN was involved in data annotation and curation. All authors have read and approved the final manuscript.

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