



Optimisation of Epan-based drip irrigation and nitrogen-potassium fertigation for enhancing yield, water productivity and profitability of marigold (*Tagetes erecta* L.)

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Abstract

A field experiment was conducted during rabi 2023–24 and 2024–25 at the College Farm, Rajendranagar, Telangana, India, to evaluate the effects of drip irrigation regimes and nitrogen and potassium (NK) fertigation levels on yield, water productivity and economics of marigold (*Tagetes erecta* L.). The experiment was laid out in a split-plot design with three irrigation levels based on pan evaporation (Epan) (0.75, 1.0 and 1.25) in main plots and four fertigation levels (75 %, 100 %, 125 % and 150 % of recommended dose of nitrogen and potassium) in subplots, replicated thrice. Results revealed that irrigation at 1.0 Epan significantly improved yield attributes and recorded higher fresh flower yield (6558 and 6481 kg ha⁻¹ during 2023 and 2024, respectively) compared to deficit irrigation (0.75 Epan). However, higher irrigation (1.25 Epan) showed variable response across seasons. Among fertigation levels, application of 100 % recommended dose of N and K (RDNK) resulted in superior yield and was statistically at par with 125 % RDNK, while further increase did not enhance productivity. Water use efficiency was highest under 0.75 Epan, indicating a trade-off between water saving and yield maximisation. Economic analysis indicated that 1.0 Epan irrigation recorded the highest net returns and benefit cost ratio, while 100 % RDNK fertigation achieved the highest benefit cost ratio. The study demonstrates that drip irrigation at 1.0 Epan combined with 100 % RDNK fertigation is the most efficient strategy for maximising productivity, resource-use efficiency and profitability of marigold under semi-arid conditions.

Keywords: drip irrigation; Epan scheduling; floriculture; nitrogen and potassium fertigation; resource-use efficiency; semi-arid; water use efficiency

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1. Introduction

Marigold (*Tagetes erecta* L.), a prominent member of the family Asteraceae, is one of the most widely cultivated commercial flower crops in tropical and subtropical regions (1). Native to Mexico and Central America, it has become an integral component of the Indian floriculture industry due to its adaptability, high flower yield, prolonged blooming period and multiple ends uses (2). In India, marigold occupies a significant share (24.5 %) of the total floricultural area owing to its demand for garlands, religious ceremonies, landscaping and extraction of xanthophyll pigments used in poultry feed and food coloring industries (3). Besides ornamental value, marigold also possesses medicinal properties including anti-inflammatory and antimicrobial activities (4). Its adaptability to varied soil types and climatic

conditions makes its cultivation suitable for semi-arid regions such as Telangana.

Efficient water and nutrient management are critical determinants of productivity and quality in floricultural crops (5). Conventional surface irrigation methods often lead to excessive water application, nutrient leaching, low fertiliser use efficiency and environmental problems such as nitrate contamination of groundwater (6). Among all the vital key nutrients that are required by the plants, nitrogen (N) and potassium (K) play a crucial role in influencing vegetative growth, flowering behaviour, flower size and yield in marigold (7). Nitrogen is involved in chlorophyll synthesis and vegetative development, while K regulates enzyme activation, photosynthate translocation, water relations and flower quality parameters (8). However, imbalanced

or excessive fertiliser application can reduce nutrient-use efficiency and increase production costs without proportionate yield gains (9).

Drip irrigation has been recognised for improving soil moisture. It is an efficient micro-irrigation system that improves water productivity by delivering water directly to the root zone with minimal losses (10). Irrigation scheduling based on pan evaporation (Epan) or crop evapotranspiration (ET_c) has been shown to optimise soil moisture availability and enhance yield performance in horticultural crops (11). Integration of fertigation with drip irrigation further enhances nutrient use efficiency by supplying water-soluble fertilisers in small, frequent doses synchronised with crop demand (12). Several studies have reported that drip fertigation improves growth attributes, nutrient uptake and flower yield in marigold (13–15). Higher flower yield with 100 % RDF applied through water-soluble fertilisers has been reported (7), while the integration of drip irrigation with 100 % recommended dose of fertilisers (RDF) improves flowering duration and flower diameter (16).

Despite these findings, responses of marigold to varying irrigation levels and graded NK fertigation under irrigated Alfisol/Vertisol conditions of Telangana are not well documented. Moreover, the interactive effects of irrigation scheduling based on Epan and different fertigation levels on water use efficiency, nutrient uptake and economic returns require further investigation. Sustainable intensification of floriculture systems demands optimisation of water and nutrient inputs to enhance productivity while conserving natural resources.

Therefore, the present study was undertaken to evaluate the effects of different drip irrigation regimes and NK fertigation levels on growth, yield attributes, water productivity, nutrient uptake and economics of marigold cultivation under irrigated conditions of Telangana with the aim of identifying an efficient and economically viable irrigation–fertigation strategy. The study is significant for developing an efficient drip irrigation and fertigation strategy to enhance flower yield, water and nutrient use efficiency and economic returns while promoting sustainable marigold production under semi-arid conditions of Telangana.

2. Materials and Methods

Experimental site and soil characteristics

A field experiment was conducted during rabi seasons of 2023–24 and 2024–25 at the College Farm, Rajendranagar, Telangana, India (17.326978° N, 78.410274° E). The region experiences a semi-arid tropical climatic, with mean minimum and maximum temperatures ranging from approximately 15.1 to 21.5 °C and 28.7 to 35.9 °C respectively, during the rabi growing season. The soil of the experimental site was classified as Alfisol, moderately well-drained and suitable for irrigated cultivation. Before the

commencement of the experiment, composite soil samples from a depth of 0–15 cm were collected and analysed for physico-chemical properties using standard laboratory procedures. The soil was sandy clay in texture, with a bulk density of 1.46 g cm⁻³, pH of 7.9, electrical conductivity of 0.71 dSm⁻¹, organic carbon of 0.61 % and available N, P₂O₅ and K₂O contents of 253.6, 48.5 and 362.5 kg ha⁻¹, respectively.

Experimental design and treatment details

The experiment was laid out in a split-plot design with 3 replications. Drip irrigation levels were assigned to main plots and NK fertigation levels to subplots. The main plot treatments comprised three irrigation regimes based on pan evaporation (Epan): 0.75 Epan (I₁), 1.0 Epan (I₂) and 1.25 Epan (I₃). The subplot treatments comprised four NK fertigation levels: 75 % recommended dose of nitrogen and potassium (RDNK) (F₁: N₁₃₀K₁₅₀ kg ha⁻¹), 100 % RDNK (F₂: N₁₇₅K₂₀₀ kg ha⁻¹), 125 % RDNK (F₃: N₂₂₀K₂₅₀ kg ha⁻¹) and 150 % RDNK (F₄: N₂₆₀K₃₀₀ kg ha⁻¹). The recommended fertiliser dose for marigold was 175–200–200 kg N–P₂O₅–K₂O ha⁻¹. The entire phosphorus (P₂O₅) was applied as basal through soil application prior to transplanting. Nitrogen and K were applied through fertigation at four-day intervals as per treatment schedule.

Crop establishment and management

The African marigold (*T. erecta*) cultivar 'Big Ball' was used in the experiment and the seedlings were produced at the Agricultural Research Institute (ARI), Floriculture, Rajendranagar, Hyderabad. Seedlings were transplanted at a spacing of 40 cm × 20 cm. The seed rate adopted was 2 kg ha⁻¹. All recommended agronomic practices for weed control, plant protection and intercultural operations were followed uniformly for all treatments to avoid confounding effects.

Drip irrigation system and fertigation scheduling

The drip irrigation system consisted of 16 mm diameter laterals with emitters spaced at 40 cm and a discharge rate of 2.0 L hr⁻¹. The drip system was operated at a pressure of 2.5 kg cm⁻² and irrigation was scheduled once every three days based on daily pan evaporation data recorded from a Class A pan evaporimeter installed at the experimental site. The irrigation duration for each treatment was calculated based on the corresponding Epan treatment level using the following equations:

$$\text{Application rate (mm hr}^{-1}\text{)} = Q/DL \times DE$$

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

Nitrogen and K were applied in three growth phases using urea and sulphate of potash (SOP), respectively: transplanting to establishment (10 % of total N and K₂O for 20 days), vegetative stage (40 % for 55 days) and flowering stage (50 % for 45 days). Fertigation was carried out once in 4 days using water-soluble fertilisers.



Observations recorded

Growth parameters such as plant height, leaf area and number of branches per plant were recorded at 30, 60 and 90 days after transplanting (DAT). Yield attributes including number of flowers per plant, flower diameter, pedicel length and fresh flower weight per plant were measured at peak flowering. Fresh flower yield and stalk yield were recorded on a plot basis and expressed in kg ha⁻¹. Duration of flowering was also noted.

Total water consumption was calculated by summing irrigation water applied, effective rainfall and water used for special operations. Water use efficiency (WUE) was computed as the ratio of fresh flower yield (kg ha⁻¹) to total water consumption (mm), as follows:

WUE (kg ha⁻¹ mm⁻¹) = Fresh flower yield (kg ha⁻¹) / Total water consumption (mm).

Plant samples collected at 30-day intervals were analysed for N, P and K content using standard analytical procedures to estimate nutrient uptake.

Economic analysis was carried out by calculating gross returns, net returns and benefit–cost (B : C) ratio based on prevailing market prices and cost of cultivation.

Statistical analysis

The recorded data were subjected to analysis of variance (ANOVA) appropriate for split-plot design using OPSTAT statistical software. The significance of treatment effects was tested using the F-test at the 5 % probability level. When significant differences were observed, treatment means were compared using the critical difference (CD) at 5 % probability level.

3. Results

Analysis of variance

The analysis of variance indicated that drip irrigation regimes and NK fertigation levels exerted significant effects on yield attributes, fresh flower yield, water use efficiency and economic returns of marigold. Irrigation levels significantly influenced yield parameters, water use efficiency and economics, while fertigation levels significantly affected yield attributes, fresh flower yield and water use efficiency. However, most growth parameters such as plant height and leaf area were not significantly influenced by either irrigation regimes or fertigation levels. The interaction effect (Irrigation (I) × Fertigation (F)) was significant for fresh flower yield but non-significant for water use efficiency, indicating that the combined effects of irrigation and fertigation differed between yield and WUE.

Yield attributes

Irrigation levels significantly influenced the number of flowers per plant and flower diameter during both rabi 2023 and 2024 (Table 1). Drip irrigation at 1.0 Epan (I₂) recorded significantly higher number of flowers per plant (77.18 and 55.00 during 2023 and 2024, respectively) compared to 0.75 Epan (I₁: 61.79 and 51.00). The treatment I₃ (1.25 Epan) was statistically comparable to I₂ during 2023 (76.53) but recorded higher values in 2024 (60.00). The critical difference (CD_{0.05}) values of 3.30 (2023) and 6.90 (2024) confirmed the significant effect of irrigation levels.

Table 1. Yield attributes of marigold as influenced by varied drip irrigation and fertigation levels during rabi 2023 and 2024

Treatments	No. of flowers plant ⁻¹		Flower diameter (cm)		Flower pedicel length (cm)	
	2023	2024	2023	2024	2023	2024
Main plots : Irrigation levels (I)						
I ₁ :Drip irrigation at 0.75Epan	61.79	51.00	5.15	5.24	5.52	5.65
I ₂ :Drip irrigation at 1.0Epan	77.18	55.00	5.69	5.78	5.87	5.92
I ₃ :Drip irrigation at 1.0Epan	76.53	60.00	5.00	5.12	5.63	5.70
SEm±	0.850	1.70	0.21	0.23	0.50	0.53
C.D (p = 0.05)	3.30	6.90	0.83	0.65	NS	NS
Subplots : Fertigation levels (F)						
F ₁ :75 % RDNK (N ₁₃₀ K ₁₅₀)	52.26	54.00	4.39	4.45	5.64	5.70
F ₂ :100 % RDNK (N ₁₇₅ K ₂₀₀)	57.39	60.00	6.05	6.15	5.71	5.80
F ₃ :125 % RDNK (N ₂₂₀ K ₂₅₀)	56.26	53.00	6.02	6.10	5.69	5.75
F ₄ :150 % RDNK (N ₂₆₀ K ₃₀₀)	55.23	54.00	4.67	4.80	5.65	5.68
SEm±	0.53	1.1	0.18	0.20	0.30	0.32
C.D (P=0.05)	1.50	3.40	0.54	0.56	NS	NS
I × F Interaction						
SEm±	1.16	3.40	0.34	0.36	0.46	0.48
C.D (p = 0.05)	NS	7.00	NS	1.00	NS	NS

Epan: pan evaporation; RDNK: recommended dose of nitrogen and potassium; N: nitrogen; K: potassium; SEm±: standard error of mean; CD: critical difference; NS: non-significant; I × F: interaction between irrigation and fertigation levels.



The higher flower number under I_2 was due to optimum soil moisture conditions, which improved photosynthetic efficiency and assimilate partitioning towards reproductive growth. In contrast, deficit irrigation (I_1) imposed moisture stress, while higher irrigation (I_3) reduced root aeration, resulting in comparatively lower efficiency.

Flower diameter was also significantly affected by irrigation levels. During 2023, I_2 recorded the maximum flower diameter (5.69 cm), followed by I_1 (5.15 cm), while I_3 recorded the lowest (5.00 cm). A similar trend was observed during 2024, with I_2 maintaining higher values (5.78 cm), though I_3 showed comparable performance (5.12 cm). The $CD_{0.05}$ values (0.83 in 2023 and 0.65 in 2024) indicated significant differences among treatments. The improvement in flower diameter under optimum irrigation is due to enhanced nutrient uptake and cell expansion under favourable moisture conditions.

Flower pedicel length was not significantly influenced by irrigation levels during both years, indicating relative stability of this trait under varying moisture regimes.

Among fertigation levels, significant differences were observed for number of flowers plant⁻¹ and flower diameter. The treatment F_2 (100 % RDNK: N175 K200 kg ha⁻¹) recorded higher number of flowers (57.39 and 60.00 during 2023 and 2024, respectively) compared to F_1 (75 % RDNK), while F_3 (125 % RDNK) remained statistically on par with F_2 . The CD values (1.50 in 2023 and 3.40 in 2024) confirmed the significance.

Similarly, flower diameter was highest under F_2 (6.05 and 6.15 cm during 2023 and 2024, respectively), followed closely by F_3 (6.02 and 6.10 cm), while F_1 and F_4 recorded comparatively lower values. These results indicate that balanced nutrient supply at 100 % RDNK enhanced reproductive growth, whereas higher nutrient levels did not produce proportional benefits, suggesting reduced nutrient use efficiency at excessive application rates.

Fertigation levels did not significantly influence flower pedicel length during both years.

The interaction effect ($I \times F$) was non-significant for all yield attributes, indicating that irrigation and fertigation factors acted independently within the tested range.

Fresh flower yield and associated traits

Fresh flower yield, flower fresh weight per plant and stalk yield were significantly influenced by irrigation and fertigation levels (Table 2), while their interaction effect was significant only for fresh flower yield.

Effect of irrigation

Among irrigation levels, drip irrigation at 1.0 Epan (I_2) recorded higher flower fresh weight (553.06 and 275 g plant⁻¹) and fresh flower yield (6558 and 6481 kg ha⁻¹) during 2023 and 2024, respectively, compared to 0.75 Epan (I_1). However, during 2024, I_3 (1.25 Epan) produced the highest fresh flower yield (6947 kg ha⁻¹) and flower fresh weight (332 g plant⁻¹), indicating seasonal variation in crop water requirement.

Table 2. Fresh flower yield and stalk yield of marigold as influenced by varied drip irrigation and fertigation levels during rabi 2023 and 2024

Treatments	Flower fresh weight (g plant ⁻¹)		Fresh flower yield (kg ha ⁻¹)		Stalk yield (kg ha ⁻¹)	
	2023	2024	2023	2024	2023	2024
Main plots : Irrigation levels (I)						
I_1 : Drip irrigation at 0.75 Epan	433	214	5801	5520	3338	2968
I_2 : Drip irrigation at 1.0 Epan	553.06	275	6558	6481	3582	2417
I_3 : Drip irrigation at 1.25 Epan	455.24	332	6202	6947	3773	2224
SEm±	10.61	3.0	70.40	98.00	76.16	90.00
C.D ($p = 0.05$)	41.67	13.00	284	394	307.00	363
Subplots : Fertigation levels (F)						
F_1 : 75 % RDNK (N ₁₃₀ K ₁₅₀)	384.32	266	5689	6045	3418	2767
F_2 : 100 % RDNK (N ₁₇₅ K ₂₀₀)	400.02	334	6587	6600	3538	3134
F_3 : 125 % RDNK (N ₂₂₀ K ₂₅₀)	386.23	258	6296	6437	3667	2179
F_4 : 150 % RDNK (N ₂₆₀ K ₃₀₀)	385.10	237	6177	5799	3634	2065
SEm±	11.15	15	75.30	184	58	179
C.D ($p = 0.05$)	33.15	44	225.40	551	174	535
I × F Interaction						
SEm±	19.81	5.60	133.10	195	116	180
C.D ($p = 0.05$)	NS	NS	437.20	991	NS	NS

Epan: pan evaporation; RDNK: recommended dose of nitrogen and potassium; N: nitrogen; K: potassium; SEm±: standard error of mean; CD: critical difference; NS: non-significant; $I \times F$: interaction between irrigation and fertigation levels.

The higher yield under I_2 is due to optimal soil moisture, which improved nutrient uptake and reproductive efficiency. In contrast, deficit irrigation (I_1) reduced yield due to moisture stress, while higher irrigation (I_3) showed inconsistent performance, likely due to excess moisture leading to reduced root aeration and nutrient losses.

Stalk yield also varied significantly with irrigation levels. I_3 recorded higher stalk yield during 2023 (3773 kg ha^{-1}), while I_1 recorded relatively higher stalk yield in 2024 (2968 kg ha^{-1}), indicating that irrigation levels influenced biomass partitioning between flowers and vegetative components.

Effect of fertigation

Fertigation levels significantly influenced all yield parameters. Application of 100 % RDNK (F_2) recorded the highest flower fresh weight (400.02 and 334 g plant^{-1}) and fresh flower yield (6587 and 6600 kg ha^{-1}) during 2023 and 2024, respectively and was significantly superior to 75 % RDNK (F_1). The treatments F_3 (125 % RDNK) and F_4 (150 % RDNK) did not show further improvement in yield, indicating diminishing returns at higher nutrient levels.

The superior performance of F_2 is due to balanced nutrient supply, which enhanced reproductive growth and yield formation. The absence of yield improvement beyond 100 % RDNK indicates reduced nutrient use efficiency at higher application levels.

Stalk yield followed a similar trend, with F_2 recording higher values, particularly during 2024 (3134 kg ha^{-1}), while F_3 and F_4 remained comparable or lower,

indicating efficient biomass production under optimum nutrient supply.

Interaction effect ($I \times F$)

The interaction between irrigation and fertigation levels was significant for fresh flower yield but non-significant for flower fresh weight and stalk yield. The highest yield was observed under the combination of 1.0 Epan irrigation with 100 % RDNK fertigation (I_2F_2), indicating that synchronised water and nutrient supply improved crop productivity.

Water use efficiency

The WUE was significantly influenced by irrigation and fertigation levels (Table 3), reflecting variations in water consumption and yield response.

Effect of irrigation

Irrigation levels had a pronounced effect on WUE. The highest WUE was recorded under 0.75 Epan (I_1 : 18.5 and $15.0 \text{ kg ha}^{-1} \text{ mm}^{-1}$ during 2023 and 2024, respectively), followed by 1.0 Epan (I_2 : 15.7 and $13.2 \text{ kg ha}^{-1} \text{ mm}^{-1}$), while the lowest was observed under 1.25 Epan (I_3 : 11.8 and $11.3 \text{ kg ha}^{-1} \text{ mm}^{-1}$). The differences were statistically significant ($CD_{0.05} = 0.95$).

The higher WUE under deficit irrigation (0.75 Epan) can be attributed to lower irrigation applied water (317 and 369 mm during 2023 and 2024, respectively) with comparatively stable yield levels, thereby improving water productivity. In contrast, increased irrigation levels (I_2 and I_3) resulted in higher water application, which reduced WUE despite improvement in yield. This clearly indicates a trade-off between maximising yield and optimising water productivity.

Table 3. Water use efficiency of marigold as influenced by varied drip irrigation and fertigation levels during rabi 2023 and 2024

Treatments	Water use efficiency ($\text{kg ha}^{-1}\text{mm}$)			Irrigation water applied (mm)	
	2023	2024	Pooled	2023	2024
Main plots : Irrigation levels (I)					
I_1 : Drip irrigation at 0.75Epan	18.5	15.0	16.7	317	369
I_2 : Drip irrigation at 1.0Epan	15.7	13.2	14.4	375	492
I_3 : Drip irrigation at 1.25Epan	11.8	11.3	11.5	449	615
SEm $\pm$	0.24	0.23	-	-	-
C.D (P=0.05)	0.95	0.95	-	-	-
Subplots : Fertigation levels (F)					
F_1 : 75 % RDNK ($N_{130} K_{150}$)	13.9	13.7	13.8	-	-
F_2 : 100 % RDNK ($N_{175} K_{200}$)	16.3	13.8	15.1	-	-
F_3 : 125 % RDNK ($N_{220} K_{250}$)	15.7	13.1	14.4	-	-
F_4 : 150 % RDNK ($N_{260} K_{300}$)	15.4	11.9	13.7	-	-
SEm $\pm$	0.18	0.18	-	-	-
C.D ($p = 0.05$)	0.53	0.79	-	-	-

Epan: pan evaporation; RDNK: recommended dose of nitrogen and potassium; SEm $\pm$: standard error of mean; CD: critical difference.



Effect of fertigation

Fertigation levels significantly influenced WUE. The highest WUE was recorded under 100 % RDNK (F_2 : 16.3 and 13.8 kg ha⁻¹ mm⁻¹ during 2023 and 2024, respectively), followed by 125 % RDNK (F_3 : 15.7 and 13.1 kg ha⁻¹ mm⁻¹) and 75 % RDNK (F_1 : 13.9 and 13.7 kg ha⁻¹ mm⁻¹). The lowest WUE was observed under 150 % RDNK (F_4 : 15.4 and 11.9 kg ha⁻¹ mm⁻¹).

The superior performance of F_2 indicates that balanced nutrient application improved water productivity through efficient biomass production per unit water consumed. The decline in WUE at higher fertigation levels might be resulting from reduced nutrient use efficiency and possible luxury consumption without proportional yield gains.

Interaction effect

The interaction between irrigation and fertigation levels was non-significant for WUE, indicating that the effect of irrigation on WUE did not vary significantly with fertigation level within the range of treatments evaluated."

Economics

Economic analysis revealed significant variation in gross returns, net returns and B : C ratio due to irrigation and fertigation levels (Fig. 1, Table 4).

The economic analysis clearly indicated that both irrigation scheduling and fertigation levels had a pronounced effect on gross returns, net returns and B : C ratio of marigold during rabi 2023 and 2024.

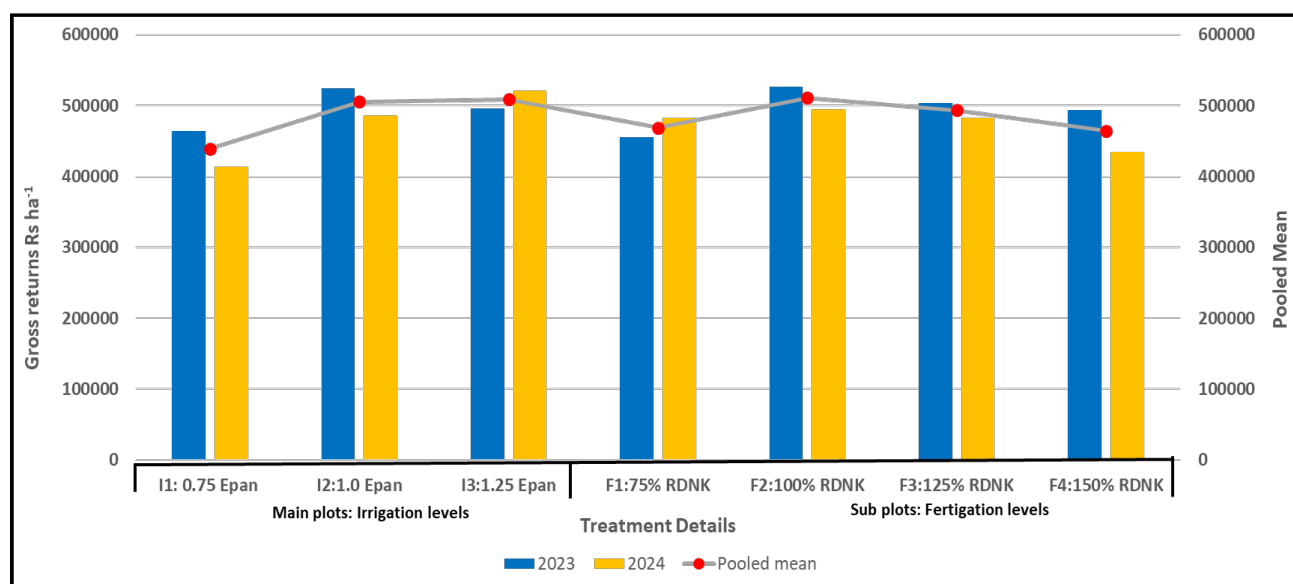
Among the irrigation levels, drip irrigation scheduled at 1.0 Epan (I_2) recorded the highest gross returns, net returns and B : C ratio over 0.75 Epan (I_1) and 1.25 Epan (I_3) during both years and in pooled analysis. The superior economic performance under I_2 can be attributed to the maintenance of optimum soil moisture throughout the crop growth period, which

facilitated better vegetative growth, higher flower yield and improved quality. Adequate moisture availability under this treatment enhanced nutrient uptake and photosynthetic efficiency, resulting in higher assimilation production and partitioning towards flowers, thereby increasing marketable yield and economic returns. In contrast, I_1 (0.75 Epan) resulted in lower returns, likely due to mild moisture stress that restricted growth and flower development.

Although I_3 (1.25 Epan) recorded relatively higher gross returns in certain instances, the net returns and B : C ratio were comparatively lower than I_2 , which is due to excessive irrigation leading to nutrient leaching, reduced aeration in the root zone and increased cost of irrigation.

With respect to fertigation levels, application of 100 % recommended dose of N and K (F_2) resulted in the highest gross returns, net returns and B : C ratio, followed by 125 % RDNK (F_3). The higher profitability under F_2 suggests that balanced nutrient supply through fertigation ensured optimum nutrient availability in the root zone, leading to efficient nutrient uptake, enhanced growth and increased flower yield. The slight reduction in economic returns at higher fertigation level (150 % RDNK, F_4) indicates that excess nutrient application increased the cost of cultivation without a proportional increase in yield, thereby reducing economic efficiency. Similarly, the lower returns observed under 75 % RDNK (F_1), can be attributed to inadequate nutrient supply, which limited crop growth and yield potential.

The pooled results further confirmed that optimum irrigation (1.0 Epan) combined with balanced fertigation (100 % RDNK) is the most economically viable practice for marigold cultivation under drip system (Fig. 1). The higher B : C ratio under these treatments reflects better resource-use efficiency in terms of water and nutrients, ultimately leading to enhanced profitability.



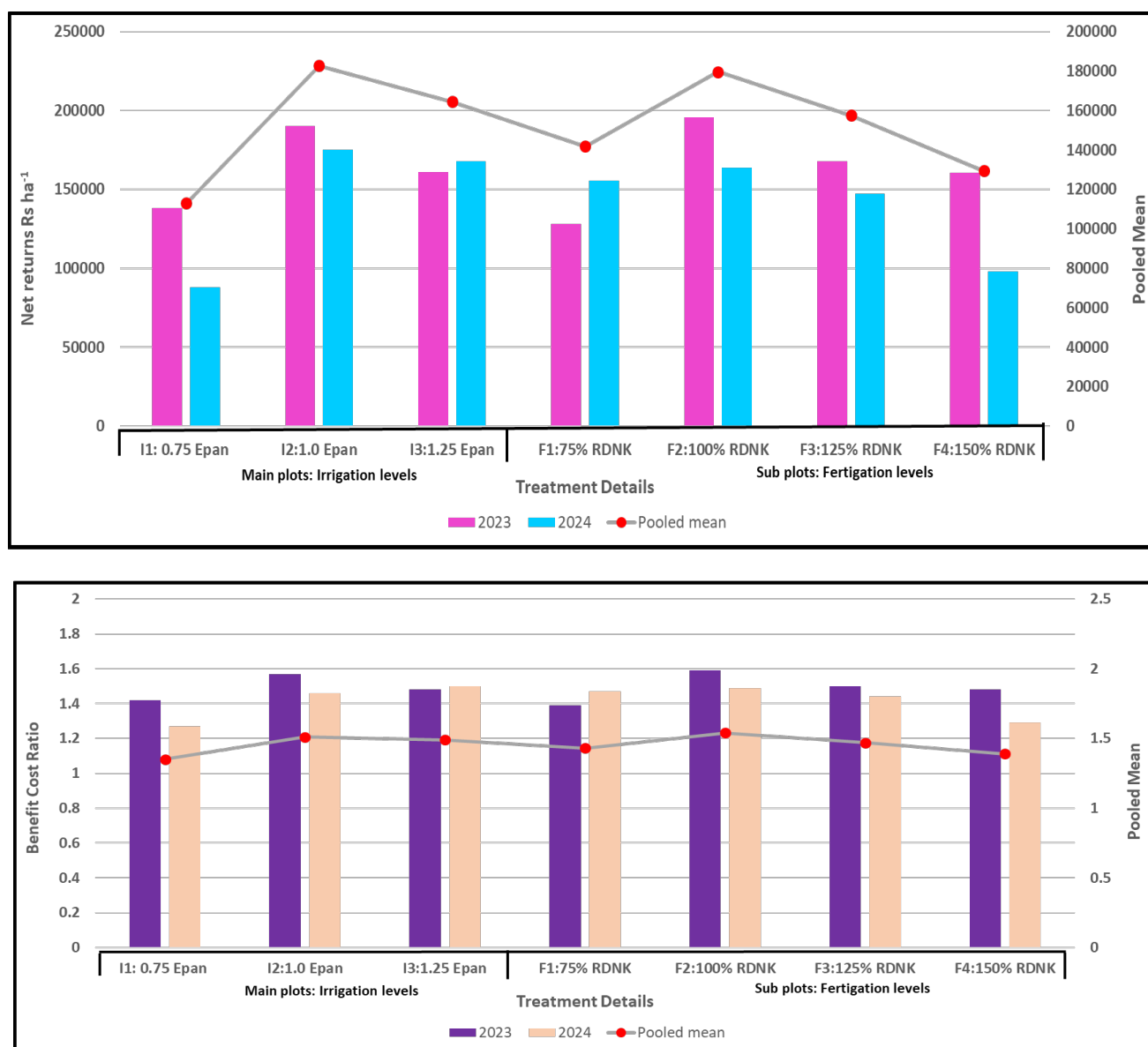


Fig. 1. Economics of marigold as influenced by drip irrigation and fertigation during rabi 2023 and 2024.

Table 4. Economics of marigold as influenced by drip irrigation and fertigation during rabi 2023 and 2024

Treatments	Gross returns (Rs. ha ⁻¹)			Net returns (Rs. ha ⁻¹)			B : C ratio		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Main plots : Irrigation levels (I)									
I ₁ : Drip irrigation at 0.75 Epan	464113	414069	439091	138030	87986	113008	1.42	1.27	1.35
I ₂ : Drip irrigation at 1.0 Epan	524666	486125	505396	190335	175000	182668	1.57	1.46	1.51
I ₃ : Drip irrigation at 1.25Epan	496000	521029	508515	161079	168000	164540	1.48	1.50	1.49
Subplots : Fertigation levels (F)									
F ₁ : 75 % RDNK (N ₁₃₀ K ₁₅₀)	455111	482301	468706	128181	155371	141776	1.39	1.47	1.43
F ₂ : 100 % RDNK (N ₁₇₅ K ₂₀₀)	526960	494981	510971	195660	163681	179671	1.59	1.49	1.54
F ₃ : 125 % RDNK (N ₂₂₀ K ₂₅₀)	503707	482754	493231	168036	147083	157560	1.50	1.44	1.47
F ₄ : 150 % RDNK (N ₂₆₀ K ₃₀₀)	494142	434929	464536	160714	98168	129441	1.48	1.29	1.39

B : C ratio: benefit-cost ratio; Epan: pan evaporation; RDNK: recommended dose of nitrogen and potassium; SEM±: standard error of mean; CD: critical difference.

Overall, the study demonstrates that precise irrigation scheduling coupled with balanced fertigation plays a crucial role in maximising economic returns of marigold by improving both yield and input-use efficiency, which is in line with earlier findings reported in flower crops under drip fertigation systems.

4. Discussion

The response of marigold to drip irrigation and NK fertigation indicates that optimum water and nutrient supply is more important for achieving higher productivity than increasing either input beyond the crop requirement. Drip irrigation provides a controlled soil-water environment, while fertigation enables nutrients to be supplied directly to the wetted root zone in relatively small and frequent applications. The combined management of these inputs is therefore important for maintaining favourable conditions for crop growth and reproductive development, particularly under the semi-arid conditions of Telangana. Similar benefits of integrated irrigation and fertigation management in marigold have been reported previously (2, 14, 17).

Effect of irrigation

The superior performance under 1.0 Epan irrigation can be attributed to the maintenance of a favourable soil-moisture regime during crop growth and flowering. Adequate water availability supports stomatal functioning, photosynthetic carbon assimilation and translocation of assimilates towards developing reproductive sinks. Under water deficit, reduced plant-water availability can restrict stomatal activity and cell expansion, thereby limiting flower development and final yield. These physiological responses are consistent with the established effects of deficit irrigation on crop productivity (18).

Compared with 0.75 Epan, irrigation at 1.0 Epan increased fresh flower yield by 13.0 % in 2023 and 17.4 % in 2024, corresponding to an average improvement of approximately 15.2 % across the two seasons. Previous researchers reported a flower yield of 12.11 t ha⁻¹ under 1.2 Epan, compared with 10.33 t ha⁻¹ under 1.0 Epan, representing an increase of approximately 17.2 % (17). The comparable magnitude of response indicates that maintaining adequate water availability can substantially improve marigold productivity, although the optimum irrigation level may vary with seasonal demand, soil conditions and production environment. However, the response to 1.25 Epan was not consistent between seasons, indicating that increasing water supply beyond the optimum level does not necessarily result in a proportional increase in productivity. Excessive soil moisture can reduce root-zone aeration and may increase nutrient losses, thereby decreasing the efficiency of additional irrigation water (18). The seasonal variation observed in the present study further suggests that the optimum irrigation requirement of marigold may depend on prevailing evaporative demand and crop water requirement.

Effect of nitrogen-potassium fertigation

The response to NK fertigation demonstrates the importance of balanced N and K supply during reproductive development. Nitrogen supports chlorophyll formation, protein synthesis and photosynthetic activity, whereas potassium contributes to stomatal regulation, enzyme activation, osmotic adjustment and assimilate translocation. Adequate availability of these nutrients can therefore support reproductive growth and flower development. Previous studies have also demonstrated beneficial responses of marigold to appropriate fertigation levels under drip irrigation (7, 13, 16).

Increasing NK fertigation from 75 to 100 % RDNK increased fresh flower yield by 15.8 % in 2023 and 9.2 % in 2024, indicating a consistent advantage of the recommended nutrient supply. However, increasing the application rate beyond 100 % RDNK did not provide a proportional increase in yield. This response indicates that the recommended nutrient level was adequate to support crop productivity, while additional N and K provided limited additional yield benefit. Similar diminishing responses at higher fertigation levels have been reported in marigold (7, 13, 16). From an agronomic perspective, this is important because excessive nutrient application can increase production costs and reduce nutrient-use efficiency without providing a corresponding increase in marketable flower yield.

Irrigation × fertigation interaction

The significant I × F interaction with fresh flower yield indicates that the response of marigold to nutrient supply was influenced by the prevailing irrigation regime. Adequate soil moisture facilitates nutrient dissolution and movement within the wetted root zone and supports nutrient acquisition by the crop. Consequently, synchronisation between water availability and nutrient supply can enhance the efficiency of both inputs. Similar advantages of integrating irrigation and fertigation have been reported in marigold (14, 16).

In contrast, the I × F interaction for WUE was non-significant. This indicates that the effect of fertigation on WUE did not vary significantly across the irrigation regimes evaluated. The different responses of yield and WUE can be explained by the basis of WUE calculation, which relates flower yield to total water consumption. Irrigation primarily influenced water consumption, whereas fertigation affected yield formation; consequently, their individual effects on the numerator and denominator of WUE did not result in a statistically detectable interaction. Thus, within the range of treatments evaluated, there was no statistically detectable combined effect of irrigation and fertigation on WUE.

Water-use efficiency and yield trade-off

A key finding of practical importance is the trade-off between water-use efficiency and flower yield. The greater WUE under 0.75 Epan was primarily associated



with reduced water irrigation use rather than increased flower production. Compared with 1.0 Epan, the deficit treatment saved approximately 58 mm of irrigation water in 2023 and 123 mm in 2024, but this saving was accompanied by a reduction in flower yield. Therefore, the treatment that maximised WUE did not simultaneously maximise land productivity or economic return.

This distinction is particularly important in floriculture, where the objective is generally to obtain high marketable flower yield and profitability. Under severe water scarcity, 0.75 Epan may be advantageous because it conserves irrigation water and increases productivity per unit of water. However, when sufficient irrigation water is available, 1.0 Epan provides a more favourable balance between water use and flower production. Similar trade-offs between water productivity and crop productivity under different irrigation regimes have been reported in marigold (19, 20). Hence, WUE should not be considered independently; it should be interpreted together with yield, water consumption and economic returns.

Economic and practical implications

The economic response further supports the agronomic advantage of optimum rather than excessive input application. Irrigation at 1.0 Epan provided a favourable balance between water input and flower production, resulting in greater economic returns than deficit irrigation. Likewise, 100 % RDNK provided an appropriate nutrient input level without the additional fertiliser expenditure associated with higher application rates. Similar economic benefits from appropriate irrigation and fertigation management have been reported in marigold and other flower crops (21, 22).

Accordingly, drip irrigation at 1.0 Epan combined with 100 % RDNK fertigation represents the most suitable strategy among the treatments evaluated for balancing flower productivity, water use and profitability under the semi-arid conditions of the experimental site. Where irrigation water is severely limited, 0.75 Epan can be considered as a water-saving strategy, provided that some reduction in flower yield is acceptable. In contrast, increasing irrigation to 1.25 Epan or NK fertigation beyond 100 % RDNK may not provide sufficient additional productivity to justify the additional resource use and cost.

Overall, the findings demonstrate that sustainable marigold production requires balanced irrigation and nutrient management rather than maximum application of individual inputs. The variation in crop response between seasons also highlights the need to account for seasonal water demand when scheduling irrigation. Future research should evaluate irrigation and fertigation strategies under different climatic conditions, soil types and crop evapotranspiration regimes, together with detailed measurements of soil-moisture dynamics and nutrient uptake, to further refine water- and nutrient-management recommendations for semi-arid floriculture.

5. Conclusion

The findings of the present study demonstrated that drip irrigation significantly influenced flower yield and water use efficiency of marigold under irrigated conditions. Although, deficit irrigation (0.75 Epan) improved water use efficiency but reduced yield, whereas higher irrigation (1.25 Epan) increased water use without proportional yield benefits. Similarly, fertigation beyond 100 % RDNK did not enhance productivity, indicating diminishing returns at higher nutrient levels. Among the treatments, drip irrigation scheduled at 1.0 Epan combined with 100 % recommended NK fertigation (N175 K200 kg ha⁻¹) gave the best overall balance of yield, water productivity and economic returns. Therefore, drip irrigation at 1.0 Epan combined with 100 % recommended NK fertigation (N175 K200 kg ha⁻¹) is recommended for efficient and sustainable marigold production under semi-arid conditions. However, the recommendations are based on two Rabi seasons and the specific soil and climatic conditions of the experimental site; therefore, further multi-location and multi-season studies are required to validate the optimum irrigation and fertigation combination under contrasting soil and water-availability conditions.

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Authors' contributions

PR conducted and supervised the experiment, designed the study and guided the research work. KPV provided overall guidance, resources and institutional support while SMSR assisted in compiling and editing the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to improve language and clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.



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