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Sub-surface Drip Fertigation Enhances Root Growth, Flower Quality, Water-Use Efficiency and Yield Stability of Marigold under Protected Cultivation

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Abstract

Efficient water and nutrient management is essential for improving flower production under protected cultivation. A three-year study (2021–2023) was conducted in a naturally ventilated polyhouse to evaluate the effects of surface and sub-surface drip fertigation, nutrient partitioning, and farmyard manure (FYM) on root growth, flower quality, marketable yield, water-use efficiency (WUE), and yield stability of marigold (*Tagetes erecta* L.). Significant differences among treatments were observed for all measured parameters. Sub-surface drip irrigation at 0.6 PE combined with 25% basal NPK and 75% NPK applied through fertigation (T8) produced the highest root growth, flower diameter, flower weight, shelf life, carotenoid content, marketable yield (19,943.3 kg ha^{-1}), and WUE (54.9 kg ha^{-1} mm^{-1}). Although sustainable yield index varied marginally among treatments, T8 consistently maintained superior productivity and resource-use efficiency over the three experimental years. Principal component analysis identified marketable yield and WUE as the major variables explaining treatment variation. These findings indicate that sub-surface drip fertigation with partial basal fertilization and fertigated NPK is an efficient management strategy for improving flower quality, maximizing water productivity, and maintaining stable productivity of protected marigold cultivation.

Keywords: Fertigation, Irrigation, Water use efficiency, Marigold

Introduction

Agriculture accounts for nearly 70% of global freshwater withdrawals, placing increasing pressure on available water resources and emphasizing the need for efficient irrigation strategies to ensure agricultural sustainability and food security (Dass et al. 2025). Under conditions of climate change and increasing water scarcity, improving irrigation efficiency and agricultural water productivity has become a major priority for irrigated agriculture (El-Nashar and Ahmed, 2023; Mohanty et al. 2025). Consequently, irrigation practices that enhance crop productivity while minimizing water and nutrient losses are essential for sustainable crop production systems. Marigold (*Tagetes erecta* L.) has a moderate water requirement, and adequate soil moisture is important for maintaining growth and flower production. The crop is sensitive to water deficit, with reduced irrigation generally lowering flower number and yield, while appropriate drip irrigation can improve yield and water-use efficiency (Chitra et al., 2023; Yasheshwar et al., 2024). Drip irrigation and fertigation are widely recognized as efficient approaches for delivering water and nutrients directly to the crop root zone, thereby reducing losses through runoff, deep percolation, and soil evaporation while improving nutrient uptake, crop yield, and water-use efficiency (WUE) (Li et al. 2021; Mohanty et al. 2025; Thiyagarajan et al. 2023). Previous studies have demonstrated that drip fertigation significantly improves crop productivity, nitrogen-use efficiency, and water use efficiecy compared with conventional irrigation and fertilizer application methods (Li et al. 2021). Sub-surface drip fertigation further enhances irrigation efficiency by reducing evaporative losses and maintaining a more uniform soil-moisture regime within the active root zone, resulting in improved WUE and profitability (Dass et al. 2025; Singh et al. 2023). Micro-irrigation systems have also been reported to save 27–42% irrigation water compared with traditional methods, indicating their potential for sustainable intensification of horticultural production systems (Gouthami et al. 2025).

While the advantages of drip irrigation have been well established under open-field conditions, its optimization under protected cultivation requires greater precision because irrigation demand and soil-water dynamics differ considerably. Under protected cultivation, precise irrigation scheduling based on pan evaporation and controlled root-zone water delivery is particularly important for improving transpiration efficiency and minimizing non-productive water losses. In this regard, sub-surface drip irrigation has gained increasing attention because it modifies soil moisture distribution, nutrient transport, and root proliferation patterns compared with conventional surface drip systems. Nevertheless, information regarding the interaction between irrigation scheduling and fertigation-based nutrient partitioning under protected floricultural systems remains limited.

Besides efficient irrigation, balanced nutrient management is equally important for maximizing the benefits of precision water application. It is another key determinant of crop productivity and sustainability in intensive horticultural systems where irrigation and nutrient inputs can be precisely controlled. Excessive dependence on chemical fertilizers often leads to deterioration of soil physical and biological properties, nutrient imbalances, and increased risks of nutrient leaching and environmental pollution, ultimately affecting long-term soil productivity. In contrast, integrated nutrient management combining mineral fertilizers with organic amendments has emerged as a sustainable strategy for improving soil fertility, nutrient availability, and crop performance (Kharlukhi et al. 2024; Xing et al. 2025). Organic nutrient sources such as farmyard manure (FYM) improve soil structure, enhance organic matter content, stimulate microbial activity, and support gradual nutrient release, thereby contributing to improved soil health and nutrient-use efficiency. Previous studies have shown that integrating organic amendments with fertigation can improve soil fertility and reduce dependence on chemical fertilizers in intensive cropping systems (Rajput et al. 2024).

Among high-value ornamental crops cultivated under protected conditions, marigold (Tagetes erecta L.) is one of the most economically important species because of its extensive use as loose flowers, garlands, religious offerings, and industrial products such as pigments and essential oils. Marigold (Tagetes erecta L.) is an economically important ornamental crop widely cultivated in India for loose flowers, garlands, religious uses, and industrial applications including pigment extraction and essential oil production. Despite its commercial importance, inefficient irrigation and nutrient management frequently result in suboptimal productivity, excessive input use, nutrient losses, and groundwater contamination (Gouthami et al. 2025). Improper synchronization between irrigation and fertilizer application accelerates nitrate leaching beyond the root zone, increasing environmental risks in intensive horticultural production systems (Abbasi and Sepaskhah, 2023; Ferreira et al. 2024; Singh and Craswell, 2021). Therefore, adoption of precision irrigation and fertigation strategies is essential for improving irrigation efficiency and resource conservation while minimizing environmental degradation in protected floriculture systems (Kaushal et al. 2024).

Although drip fertigation, sub-surface drip irrigation, and integrated nutrient management have each demonstrated benefits for improving crop productivity and resource-use efficiency, their combined effects as an integrated water–nutrient management strategy under protected ornamental production remain poorly understood.

Information regarding their interactive effects under protected cultivation of ornamental crops remains inadequate. This gap is partly related to the crop-specific response of ornamental plants to water and nutrient supply and the complexity of optimizing these inputs under protected environments. Recent work on chrysanthemum has shown that irrigation and fertigation combinations can substantially influence flower yield, water-use efficiency and economic returns, while responses differ among cultivars (Gouthami et al. 2025). Moreover, research on floricultural crops has increasingly emphasized the need for precise irrigation and nutrient management, but crop-specific irrigation strategies and advanced approaches for optimizing water and nutrient delivery remain limited (Singh and Kumar 2024). Studies on long-term protected-cultivation in horticultural crops shows that repeated-season evaluation is important for assessing yield stability and resource-use efficiency (Hu et al. 2021). However, relatively little information is available on the longer-term effects of different irrigation–fertigation combinations on yield stability and resource-use efficiency in ornamental crops under protected cultivation. The use of sustainability indicators such as the Sustainable Yield Index (SYI), together with multivariate analytical approaches, remains limited in floricultural irrigation research. Consequently, the ability of advanced irrigation–fertigation strategies to simultaneously improve productivity, water-use efficiency, and yield stability under protected cultivation is still insufficiently understood.

The novelty of the present study lies in evaluating the combined effects of sub-surface drip irrigation, irrigation scheduling, fertigation-based nutrient partitioning and vermiwash in protected marigold cultivation. The study compares surface and sub-surface drip systems under different nutrient management strategies and evaluates their effects on root growth, flower quality, marketable yield, water-use efficiency and yield stability over three years. This integrated assessment provides useful information on optimizing water and nutrient management for improving productivity and resource-use efficiency in protected marigold production. Based on previous findings, we hypothesized that sub-surface drip fertigation with appropriate irrigation scheduling and nutrient partitioning, with or without vermiwash, would improve root development, flower quality, marketable yield, water-use efficiency and yield stability compared with surface drip fertigation under protected cultivation.

Therefore, the present study was undertaken to evaluate the effects of irrigation method and fertigation strategy on marketable yield, water-use efficiency, and sustainability of marigold under protected cultivation. Specifically, the objectives were to:

(i) compare surface and sub-surface drip fertigation operated at different pan evaporation fractions and their effect on crop and water use efficiency;
(ii) evaluate nutrient partitioning between basal and fertigation applications under different drip systems and their effect on root growth and flower quality; and
(iii) assess yield stability across years using the Sustainable Yield Index and multivariate statistical analyses.

The findings of this study are expected to provide a scientific basis for developing resource-efficient irrigation–fertigation strategies that enhance productivity, water-use efficiency, and long-term sustainability of high-value ornamental crops cultivated under water-limited protected environments.

Materials and Methods

Experimental Site and Conditions

The experiment was conducted during 2021–2023 at the experimental farm of the All India Coordinated Research Project on Water Management located in the Palam Valley of Kangra district, Himachal Pradesh, India (32°6′ N latitude, 76°3′ E longitude, 1290 m above mean sea level). The region falls under the mid-hill sub-humid agro-climatic zone of the North Western Himalayan region and is characterized by cool winters and moderate summer temperatures. According to Thornthwaite's classification, the climate is categorized as wet temperate. Mean air temperature ranges from 2°C during January to 36°C during May–June, while relative humidity varies between 46% and 84%.

The experiment was conducted inside a naturally ventilated polyhouse measuring 15 m × 7 m (105 m²). The soil was silty clay loam in texture and classified as Typic Hapludalf (Alfisol). The soil had an effective depth of 120–150 cm. Initial soil analysis of the 0–15 cm layer revealed a slightly acidic reaction (pH 5.63), organic carbon content of 9.05 g kg^{-1}, available nitrogen of 220.6 kg ha^{-1}, available phosphorus of 28.1 kg ha^{-1} and available potassium of 205.7 kg ha^{-1}.

Experimental Details and Irrigation System

The test crop was marigold (*Tagetes erecta* L.) cv. *Pusa Narangi*. Transplanting was carried out during the second week of July in each experimental year, and harvesting continued until the first week of November.

Land preparation involved cultivation using a power tiller followed by the formation of raised beds. A gravity-fed drip irrigation system was installed inside the polyhouse for precise water application. Irrigation water was supplied from a 1000-L storage tank positioned at a height of 1.5 m adjacent to the polyhouse. The system consisted of two independent 12-m main lines connected to 18 laterals each, spaced 45 cm apart. Laterals were 3 m long with inline emitters spaced at 30 cm intervals and having an average discharge rate of 2.39 L h^{-1}. In total, 36 raised strips of 3.0 m × 0.5 m (1.5 m^2) were prepared. Sub-surface drip laterals were installed below the soil surface at 10 cm soil depth to facilitate efficient root-zone wetting and minimize evaporative losses. A 30-L fertigation tank was connected to the irrigation system for the application of water-soluble fertilizers through drip irrigation.

Treatments and Crop Management

The experiment comprised 12 treatment combinations involving fertigation schedules and drip irrigation methods, laid out in a randomized block design (RBD) with three replications (Table 1). Irrigation scheduling was based on daily pan evaporation (PE) data recorded at a meteorological observatory located approximately 300 m from the experimental site. A pre-sowing irrigation was applied at 1.0 PE to ensure adequate soil moisture before transplanting. Irrigation scheduling commenced 10 days after transplanting, after plant establishment. Irrigation water was then applied daily at 0.8 PE under surface drip irrigation and 0.6 PE under sub-surface drip irrigation. These irrigation levels were selected to provide a higher and a reduced irrigation regime under the two drip systems and are within the range used for pan evaporation-based drip irrigation scheduling in horticultural crops (Shirgure et al. 2001). Pan evaporation is a recognized approach for estimating crop water requirements (Allen et al. 1998). The experiment was conducted continuously for three consecutive years (2021–2023) using the same experimental plots. Treatments were randomly allocated to the plots at the initiation of the experiment and the same plot–treatment allocation was maintained throughout the study period. The respective irrigation and nutrient-management treatments were reapplied during each crop season according to the assigned treatment schedule. Thus, the three-year experiment was designed to evaluate the repeated and cumulative performance of the irrigation–fertigation treatments under protected cultivation rather than independent experiments conducted in separate plots each year.

Table 1: Treatment details

Treatment	Basal	Weekly Fertigation in 10 splits	Drip system
T1	100 %PK	100 % N	surface drip @ 0.8PE
T2	25 % NPK	75 % NPK	surface drip @ 0.8PE
T3	50 % NPK	50 % NPK	surface drip @ 0.8PE
T4	100 % PK	100 % N + Vermiwash@ 75 ml/sqm	surface drip @ 0.8PE
T5	25 % NPK	25 % NPK + Vermiwash@ 75 ml/sqm	surface drip @ 0.8PE
T6	100 % NPK conventional method +Vermiwash@ 75 ml/sqm at weekly intervals in 10 splits		surface drip @ 0.8PE
T7	100 %PK	100 % N	Sub-surface drip @ 0.6PE
T8	25 % NPK	75 % NPK	Sub-surface drip @ 0.6PE
T9	50 % NPK	50 % NPK	Sub-surface drip @ 0.6PE
T10	100 % PK	100 % N + Vermiwash@ 75 ml/sqm	Sub-surface drip @ 0.6PE
T11	25 % NPK	25 % NPK + Vermiwash@ 75 ml/sqm	Sub-surface drip @ 0.6PE
T12	100 % NPK conventional method +Vermiwash@ 75 ml/sqm at weekly intervals in 10 splits		Sub-surface drip @ 0.6PE

The treatments were designed to evaluate integrated irrigation and nutrient management strategies rather than to isolate the independent effect of each individual factor. The two drip systems were associated with different irrigation levels (surface drip at 0.8 PE and sub-surface drip at 0.6 PE), while nutrient partitioning and vermiwash application varied among the fertigation treatments. Therefore, the effects of individual factors cannot be completely separated statistically. The treatment comparisons were used to assess the overall performance of the different irrigation–fertigation combinations under protected marigold cultivation. This approach was intended to identify a practical combination of irrigation and nutrient management that could improve crop productivity and resource-use efficiency. Farmyard manure (FYM) was uniformly applied to all treatments at 2.5 kg m^{-2} before transplanting. Conventional fertilization involved the application of urea, single superphosphate (SSP) and muriate of potash (MoP), whereas water-soluble fertilizers (19:19:19, 0:0:50 and urea) were used under fertigation treatments. In fertigation treatments, fertilizers were applied in split doses beginning three weeks after transplanting and continued up to 15 days before the final harvest. Fertigation schedules for T1–T6 are presented in Table 2. The corresponding schedules for T7–T12 were identical to T1–T6, respectively, and were applied under sub-surface drip irrigation at 0.6 PE.

Table 2: Fertigation schedule

T1	SSP 45 g + MOP 12 g as basal + urea 1.5 g/split, applied weekly in 10 fertigation splits
T2	Urea 6 g + SSP 12 g + MOP 3 g as basal + 19:19:19 3 g + urea 0.5 g/split, applied weekly in 10 fertigation splits
T3	Urea 12 g + SSP 24 g + MOP 6 g as basal + 19:19:19 2 g + urea 0.3 g/split, applied weekly in 10 fertigation splits
T4	SSP 45 g + MOP 12 g as basal + urea 0.25 g/split + vermiwash 75 mL, applied weekly in 10 fertigation splits
T5	Urea 6 g + SSP 12 g + MOP 3 g as basal + 19:19:19 1 g + urea 0.2 g/split + vermiwash 75 mL, applied weekly in 10 fertigation splits
T6	Urea 12 g + SSP 45 g + MOP 12 g + vermiwash 75 mL, applied through the conventional method at weekly intervals in 10 splits

The fertilizer quantities mentioned in Table 2 represent the amount applied per split during each fertigation event.

Root growth parameters

Root growth parameters, namely root length, root volume and root dry weight per plant, were determined at harvest. Soil cores containing roots were soaked overnight in water and washed carefully using a fine jet of water. Cleaned roots were collected on a fine sieve for final washing.

Root length was measured using the line intersection method described by Newman (1966), as modified by Marsh (1971) and Tennant (1975). Roots were spread uniformly in shallow glass-bottom tray (40 cm × 20 cm) containing water over graph paper ruled at 1-cm intervals. Root intersections with vertical and horizontal grid lines were counted, ensuring that counts did not exceed 400 per observation (Kopke, 1979). Root length was calculated as:

$$\text{Root length} = \frac{11}{14} \times \text{number of intersections (N)} \times \text{grid unit} \ldots\ldots\ldots (1)$$

Root volume was determined by the water displacement method. Subsequently, roots were blotted gently using filter paper and oven dried at 65°C until constant weight to determine root dry mass.

Flower quality parameters

Flower quality parameters were recorded at full bloom stage using five randomly selected flowers from each treatment in each replication. Flower diameter was measured across the fully opened flower head using a digital vernier caliper and expressed in centimeters. Individual flower weight was determined using a digital balance with 0.01 g precision.

Shelf life was evaluated under ambient laboratory conditions (25 ± 2°C temperature and 65–70% relative humidity). Flowers were stored in clean trays at room temperature, and shelf life was recorded as the number of days from harvest until 50% wilting, discoloration or loss of marketable appearance occurred.

Total carotenoids were estimated following the method of Ranganna (1995). Fresh flower petals (0.1 g) were ground thoroughly in acetone using a mortar and pestle until the residue became colourless. The extract was transferred to a separating funnel, followed by the addition of petroleum ether and 10% Na_2SO_4. The carotenoid layer was separated and collected in a volumetric flask. Extraction was repeated until the remaining extract became colourless. Absorbance was recorded at 452 nm using a spectrophotometer. Total carotenoid content was calculated using the following equation:

$$\text{Total Carotenoids (mg } 100g^{-1}) = \frac{3.87\times \text{absorbance (452 nm)} \times \text{volume make up} \times \text{dilution factor} \times 100)}{\text{weight of sample (g)} \times 1000} \quad (2)$$

Marketable yield

Flowers were harvested manually at full bloom stage when they attained maximum size, uniform colour and firm texture. Harvesting commenced with the opening of the first flowers and continued at 3–4 day intervals throughout the flowering period. Flowers were harvested during morning hours to minimize post-harvest moisture loss.

Flowers from each treatment plot were harvested separately, excluding diseased or damaged flowers, and weighed using a digital balance. Cumulative flower yield was calculated by summing the yield from all pickings and expressed as kg ha^{-1}.

Water use efficiency (WUE)

Water-use efficiency (WUE) was calculated based on total marketable flower yield and total irrigation water applied during the crop growth period. The volume of irrigation water applied was estimated using emitter discharge rate (average discharge rate: 2.39 L h^{-1}), irrigation duration (11.3 and 15.1 min per irrigation for 0.6 PE and 0.8 PE, respectively) and number of emitters per plot (10 emitters). The applied water volume was converted to irrigation depth using the plot area (1 L m^{-2} = 1 mm) and WUE was computed as:

$$\text{WUE (kg ha}^{-1}\text{ mm}^{-1}) = \frac{Yield\ (kg/ha)}{Total\ water\ use\ (mm)} \quad (3)$$

Sustainable yield index

The Sustainable Yield Index (SYI) was used to assess yield stability and sustainability of treatments over years. SYI was calculated by the formula as mentioned below:

$$SYI = \frac{Ymean - \sigma}{Ymax} \quad (4)$$

Where, Ymean is the mean yield of a treatment over the study period, σ is the standard deviation of yield across years and Ymax is the maximum yield recorded across all treatments and years. A single common Ymax value was therefore used for calculating SYI for all treatments. Higher SYI values indicate greater yield stability and sustainability with lower inter-annual variability.

Statistical analysis

Experimental data were subjected to analysis of variance (ANOVA) appropriate for randomized block design using XLSTAT (trial version). Data pooled across the three experimental years were used to assess the overall treatment effects, and treatment means were compared at the 5% significance level. For yield and water-use efficiency, individual yearly values and the three-year mean were presented to show year-to-year variation. Principal component analysis (PCA) and correlation analysis were performed using PAST software (version 4.03) to evaluate relationships and variability among the studied parameters.

Results

Root growth parameters

Root growth of marigold was significantly influenced by fertigation strategy, FYM application, and drip system configuration (Table 3). Among all treatments, T8 (25% NPK as basal + 75% NPK through fertigation under sub-surface drip at 0.6 PE) recorded the maximum root length, root volume and root weight, followed by T9 and T2. In contrast, the lowest values were recorded under T11, with root length of 18.7 cm, root volume of 10.9 cm^3, and root weight of 3.6 g. Since the observed treatment differences exceeded the respective CD (5%) values, the effect of treatments on all root parameters was statistically significant.

Table 3: Effect of drip fertigation, sub-surface drip, integration of FYM and irrigation scheduling on root characteristics of marigold

Treatment	Basal	Weekly Fertigation in 10 splits	Root length (cm)	Root volume (cm^3)	Root weight (g)
T1	100 %PK	100 % N	21.3	12.5	4.2
T2	25 % NPK	75 % NPK	26.7	16.8	5.6
T3	50 % NPK	50 % NPK	23.9	14.9	4.9
T4	100 % PK	100 % N + Vermiwash@ 75 ml/sqm	22.5	13.7	4.5
T5	25 % NPK	25 % NPK + Vermiwash@ 75 ml/sqm	19.8	11.6	3.8
T6	100 % NPK conventional method +Vermiwash@ 75 ml/sqm at 7 days in 10 splits		24.1	15.2	5.1
T7	100 %PK	100 % N	24.8	15.8	5.2
T8	25 % NPK	75 % NPK	29.4	19.7	6.5
T9	50 % NPK	50 % NPK	27.6	17.9	5.9
T10	100 % PK	100 % N + Vermiwash@ 75 ml/sqm	22.1	13.4	4.4

T11	25 % NPK	25 % NPK + Vermiwash@ 75 ml/sqm	18.7	10.9	3.6
T12	100 % NPK conventional method +Vermiwash@ 75 ml/sqm at weekly intervals in 10 splits		25.3	16.2	5.4
SEm			0.04	0.04	0.01
CD (p=0.05)			0.11	0.12	0.03

The consistently higher values under T8 indicates that root development was favored when a greater proportion of nutrients were supplied through fertigation under sub-surface drip placement. Such a treatment combination likely maintained a more stable soil-moisture regime and improved nutrient availability in the active root zone, thereby promoting root elongation, thicker root proliferation, and higher root biomass. Better root growth under sub-surface drip can also be attributed to reduced surface evaporation and improved soil aeration around the wetted zone. These findings support the view that precise water–nutrient placement enhances root-zone conditions, which in turn strengthens crop establishment and resource acquisition.

Treatments based on vermiwash supplementation alone or lower nutrient synchronization, particularly T5 and T11, remained inferior for root traits. This suggests that although organic supplements may contribute beneficial compounds, they could not compensate for the absence of balanced and precisely delivered NPK nutrition under intensive protected cultivation.

Flower quality parameters

Flower quality attributes varied significantly across treatments, indicating marked effects of nutrient partitioning, fertigation intensity, and drip system type (Table 4). Across all treatments, T8 consistently recorded the highest values for all quality traits, producing the largest flower diameter (8.4 cm), highest flower weight (10.8 g), longest shelf life (5.2 days), and maximum carotenoid content (8.6 mg g^{-1} DW). This was followed by T9 and T2, which also maintained superior flower quality compared with the other treatments. In contrast, T11 and T5 showed the lowest values for most quality parameters. Since treatment differences exceeded the corresponding CD (5%) values for all four traits, the effect was statistically significant.

Table 4: Effect of drip fertigation and sub-surface drip and integration of FYM with varying irrigation schedule on flower quality of marigold

Treatment	Basal	Weekly Fertigation in 10 splits	Flower diameter (cm)	Flower weight (g)	Shelf life (days)	Carotenoid (mg g^{-1} DW)
T1	100 %PK	100 % N	6.5	7.8	3.8	6.4
T2	25 % NPK	75 % NPK	7.8	9.5	4.6	7.9
T3	50 % NPK	50 % NPK	7.1	8.6	4.2	7.1
T4	100 % PK	100 % N + Vermiwash@ 75 ml/sqm	6.8	8.2	4.0	6.8
T5	25 % NPK	25 % NPK + Vermiwash@ 75 ml/sqm	6.1	7.2	3.6	6.2
T6	100 % NPK conventional method +Vermiwash@ 75 ml/sqm at 7 days in 10 splits		7.2	8.7	4.3	7.2
T7	100 %PK	100 % N	7.4	8.9	4.4	7.4
T8	25 % NPK	75 % NPK	8.4	10.8	5.2	8.6
T9	50 % NPK	50 % NPK	8.0	10.1	4.9	8.1
T10	100 % PK	100 % N + Vermiwash@ 75 ml/sqm	6.7	8.0	3.9	6.7
T11	25 % NPK	25 % NPK + Vermiwash@ 75 ml/sqm	6.0	7.1	3.5	6.1
T12	100 % NPK conventional method +Vermiwash@ 75 ml/sqm at weekly intervals in 10 splits		7.5	9.0	4.5	7.5
SEm±			0.14	0.28	0.11	0.18
CD (p=0.05)			0.41	0.83	0.32	0.54

Flower diameter followed a clear positive response to treatments receiving a larger proportion of nutrients through fertigation, especially under sub-surface drip. Larger flowers under T8, T9 and T2 indicate improved cell expansion and better floral meristem activity under balanced nutrient supply. Nitrogen likely supported chlorophyll formation and photosynthesis, phosphorus improved energy transfer and root activity and potassium enhanced assimilates movement toward developing floral tissues.

A comparable trend was observed for flower weight. Heavier flowers under T8 and T9 suggest greater dry matter accumulation and better hydration status in floral tissues, reflecting stronger sink strength. The lower flower weight under T11 and T5 indicates that inadequate nutrient supply restricted biomass accumulation. The sub-surface drip irrigation have consistently shown that better root-zone moisture regulation improves crop growth and biomass production through reduced evaporation and improved root access to water and nutrients.

Shelf life was also longest under T8 and T9, suggesting that pre-harvest nutrient management strongly influenced postharvest performance. Flowers produced under optimized fertigation regimes likely accumulated greater carbohydrate reserves and maintained better membrane stability, thereby delaying senescence. Potassium, in particular, is known to support osmotic regulation, hydration, and metabolite transport, all of which contribute to postharvest longevity. Similar observations have been noted in ornamental crops under improved nutrient management.

Carotenoid content, a major biochemical quality trait in marigold, also increased significantly under the superior fertigation treatments. The highest carotenoid concentration under T8 demonstrates that treatments favorable for flower growth were also favorable for pigment biosynthesis. Since carotenoids determine flower color intensity and commercial value in marigold, this increase is important both ornamentally and industrially. Higher pigment accumulation under better fertigation likely resulted from enhanced metabolic activity, improved precursor availability, and stronger photosynthetic efficiency. Published studies on marigold have similarly shown that carotenoid concentration is influenced by crop management and flower developmental physiology.

Marketable Yield

Marketable yield of marigold varied significantly across treatments and years (2021–2023), reflecting strong effects of fertigation strategy, nutrient partitioning, and drip system configuration. Across all years, treatments receiving 75 % NPK through fertigation consistently outperformed other nutrient regimes under both surface and sub-surface drip systems. The highest mean yield was recorded under T8 (25 % NPK basal + 75 % NPK fertigation with sub-surface drip @ 0.6 PE), indicating the superiority of sub-surface fertigation combined with higher nutrient delivery through irrigation water (table 5). This results suggest that nutrient delivery synchronized with irrigation water under sub-surface placement is more critical than total fertilizer quantity alone, marking a shift from conventional input-centric management to process-oriented nutrient-use efficiency**.** Year-wise, yields showed moderate inter-annual variability, with slightly higher values in 2022 and 2023 for most fertigation treatments, likely due to improved crop establishment and favorable microclimatic conditions under protected cultivation.

Compared to surface drip, sub-surface drip fertigation enhanced yield stability, particularly under reduced irrigation levels (0.6 PE), as evident from treatments T7–T9. This improvement can be attributed to uniform soil

300 moisture distribution in the root zone, reduced surface evaporation losses, and enhanced nutrient availability near
301 active roots. In contrast, treatments involving conventional fertilizer application, even when combined with
302 vermiwash (T6 and T12), produced lower or comparable yields, suggesting limited synchronization between nutrient
303 supply and crop demand.

304 **Table 5: Effect of drip fertigation and sub-surface drip and integration of FYM with varying irrigation schedule on yield and water use efficiency (WUE) of marigold**

Treatment	Basal	Weekly Fertigation in 10 splits	Marketable Yield (kg ha^{-1})				WUE* (kg ha^{-1}mm^{-1})			
			2021	2022	2023	Mean	2021	2022	2023	Mean
T1	100 %PK	100 % N	14956.0	15967.0	15203.0	15375.3	33.2	34.5	29.8	32.5
T2	25 % NPK	75 % NPK	18178.0	18290.0	19212.0	18560.0	40.4	39.5	37.6	39.2
T3	50 % NPK	50 % NPK	16000.0	15778.0	16202.0	15993.3	35.6	34.1	31.7	33.8
T4	100 % PK	100 % N + Vermiwash@ 75 ml/sqm	16489.0	14178.0	15404.0	15357.0	36.3	30.6	30.1	32.4
T5	25 % NPK	25 % NPK + Vermiwash@ 75 ml/sqm	13867.0	14023.0	14211.0	14033.7	30.8	30.3	27.8	29.6
T6	100 % NPK conventional method +Vermiwash@ 75 ml/sqm at 7 days in 10 splits		15567	16867.0	14601.0	15678.3	37.2	32.2	29.8	33.1
T7	100 %PK	100 % N	14844.0	15377.0	15912.0	15377.7	43.6	43.7	39.7	42.3
T8	25 % NPK	75 % NPK	21467.0	18796.0	19567.0	19943.3	62.4	53.4	48.8	54.9
T9	50 % NPK	50 % NPK	17067.0	16584.0	18010.0	17220.3	50.1	47.1	44.9	47.4
T10	100 % PK	100 % N + Vermiwash@ 75 ml/sqm	14711.0	14956.0	15100.0	14922.3	43.2	42.5	37.7	41.1
T11	25 % NPK	25 % NPK + Vermiwash@ 75 ml/sqm	12867.0	13867.0	13974.0	13569.3	37.8	39.4	34.8	37.3
T12	100 % NPK conventional method +Vermiwash@ 75 ml/sqm at weekly intervals in 10 splits		15289	15289.0	14733.0	15103.6	44.9	43.3	40.2	42.8
CD (p= 0.05)			292.3	292.3	232.1	212.4	0.8	0.5	0.6	0.6

305 **Total water use for 0.8 PE and 0.6 PE were, 454 & 346 mm (2021), 463 & 352 mm (2022) and 511 & 401*

306 Treatments with vermiwash supplementation alone did not consistently enhance yield across years,
307 indicating that while organic liquid inputs support microbial activity and nutrient mobilization, they cannot fully
308 substitute balanced NPK fertigation under intensive production systems. The study highlights that organic
309 supplements alone cannot compensate for poor synchronization between nutrient supply and crop demand. This
310 finding refines existing knowledge by clarifying that the effectiveness of organic inputs such as vermiwash depends
311 strongly on their integration within precision fertigation systems**,** rather than their standalone application. Yield
312 reductions observed under lower nutrient supply treatments (25 % NPK basal + 25 % NPK fertigation) highlight the
313 importance of adequate nutrient concentration in the fertigation stream for sustaining flower biomass and marketable
314 yield. Overall, the results confirm that integrated nutrient delivery through fertigation, particularly under sub-surface
315 drip, improves nutrient-use efficiency and yield by minimizing leaching and ensuring continuous nutrient
316 availability throughout the crop growth period.

317 The box plot indicates (Fig. 1) that sub-surface drip irrigation (SSDI) generally produced higher and more variable
318 marketable yields compared to surface drip irrigation (SDI) in the observed dataset (Fig.). This pattern aligns with
319 findings from multiple agronomic studies showing that SSDI often enhances crop yield and water use efficiecy
320 because water is delivered directly into the root zone, reducing surface evaporation, deep percolation losses and non-
321 productive wetting of the soil surface factors that commonly limit plant water uptake in SDI systems. A
322 comprehensive global meta-analysis reported that sub-surface drip systems increased overall crop yield by
323 approximately 5.4 % relative to surface drip, along with significant gains in water use efficiecy and irrigation water
324 use efficiecy under similar environmental conditions (Hashemi et al. 2024).

325 **Water Use Efficiency (WUE)**

326 Water use efficiency (WUE) exhibited pronounced differences among treatments and years, strongly
327 influenced by irrigation level, drip system type, and fertigation regime. Across all three years, sub-surface drip
328 treatments recorded substantially higher WUE than surface drip treatments (table 5); despite receiving lower
329 irrigation water (0.6 PE vs. 0.8 PE). The highest mean WUE was observed under T8, followed by T9 and T12,
330 demonstrating that sub-surface drip fertigation combined with higher fertigation fractions optimizes both water and
331 nutrient utilization. Year-wise, WUE values were generally higher in 2021 and declined marginally in 2023 across
332 most treatments, likely due to cumulative soil moisture dynamics and seasonal variations in evaporative demand.

333 The box plot (Fig. 2) results suggest that sub-surface drip irrigation (SSDI) achieved generally higher water
334 use efficiency (WUE) than surface drip irrigation (SDI), as reflected by a higher median and upper quartile values.
335 This improvement is scientifically attributed to the placement of water directly within the root zone under SSDI,
336 which substantially reduces soil surface evaporation and non-productive water losses, thereby increasing the
337 proportion of applied water used for transpiration and yield formation (Fereres and Soriano, 2007). In addition,
338 SSDI maintains a more uniform and stable soil moisture regime, minimizing plant water stress and enhancing
339 photosynthetic efficiency and biomass accumulation per unit of water consumed (Shock et al. 1998; Wan et al.
340 2024). The wider variability observed under SSDI indicates that its performance is influenced by soil texture,
341 emitter depth, and irrigation scheduling, but even so, the overall WUE advantage remains evident. Similar
342 improvements in WUE under sub-surface drip have been widely reported across crops and environments due to
343 improved root–water–nutrient interactions (Camp, 1998). Unlike earlier studies that reported yield or WUE gains

under fertigation alone, the present results demonstrate that these gains are maximized when fertigation is integrated with sub-surface drip irrigation and optimized nutrient partitioning, highlighting a clear synergistic effect.

Correlation between yield and water use efficiency

The correlation matrix (Fig. 3) indicates a strong positive association between marketable yield and water-use efficiency (WUE) across years, suggesting that improvements in biomass production are closely linked with efficient soil–water–nutrient utilization. This relationship reflects enhanced root-zone moisture availability, improved nutrient mobility, and synchronized nutrient uptake, which together promote higher photosynthetic efficiency and biomass partitioning. Strong inter-year correlations among yield parameters highlight temporal stability of soil moisture regimes and nutrient supply under precision irrigation. Conversely, weaker or negative correlations between early-year WUE and later yield suggest that suboptimal soil water distribution or transient nutrient stress can decouple water use from yield formation (Dass et al. 2025).

The correlation heatmap (Fig. 4) revealed strong positive associations among mean yield, mean WUE, root traits, and flower quality parameters. Mean yield showed close positive relationships with mean WUE, root length, root volume, root weight, flower diameter, flower weight, shelf life, and carotenoid content, indicating that productivity enhancement was accompanied by simultaneous improvement in below-ground growth and floral quality. Mean WUE also showed strong positive correlation with root and quality attributes, confirming that efficient use of irrigation water was linked to stronger root development and superior flower performance.

The positive association among root traits and quality traits suggests that better root proliferation likely improved water and nutrient uptake, which in turn supported larger flowers, greater flower mass, longer shelf life, and higher carotenoid accumulation. Treatments such as T8 and T9, which consistently performed well across yield, WUE, root growth, and flower quality, largely drove this favorable multivariate pattern. These relationships reinforce the interpretation that productivity in protected marigold was determined by integrated soil–water–nutrient processes rather than by any single trait alone.

Integrated performance of treatments

The integrated radar plot of the treatments (Fig. 5) clearly showed that T8 had the broadest and most balanced performance across mean yield, mean WUE, root weight, flower weight, shelf life, carotenoid content, and SYI. T9 ranked next, followed by T2, while T12 showed moderate performance across most indicators. This comparison highlights that the best-performing treatment was not superior in just one trait, but across a wide spectrum of agronomic and quality parameters.

The radar-based comparison is particularly useful for demonstrating treatment superiority in a multi-criteria framework, which is often preferred in high-value protected cultivation studies. It shows that T8 combined high productivity, high water-use efficiency, strong root development, superior flower quality, and better sustainability. Such integrated superiority strengthens the practical relevance of the treatment as a complete production package rather than a single-trait solution.

Sustainable yield index (SYI)

Figure 6 illustrates the year-wise marketable yield (2021–2023) and Sustainable Yield Index (SYI) across treatments (T1–T12), highlighting both productivity and yield stability. Marketable yield varied among treatments across the three years, indicating clear treatment effects on productivity. Treatments such as T2, T8, and T9 generally recorded higher marketable yields, whereas T4, T5, and T11 showed comparatively lower yields. However, the treatment ranking based on SYI differed from that based on marketable yield, indicating that inter-annual yield variability had an important influence on yield stability.

The highest SYI values were recorded for T12 (0.97), T10 (0.96), and T9 (0.92), indicating relatively greater yield stability across the three years. Intermediate SYI values were observed for T8 (0.86), T11 (0.85), and T2 (0.84), whereas T1, T3, T4, T5, T6, and T7 showed lower SYI values (0.65–0.74), indicating comparatively greater inter-annual variability in marketable yield. The particularly low SYI of T5 (0.65) and T4 (0.66) suggests that their yields were less consistent across years despite their performance in individual seasons.

The divergence between marketable yield and SYI highlights the importance of considering both productivity and temporal stability when evaluating treatment performance. Notably, T8 recorded the highest

marketable yield and water-use efficiency, but its SYI of 0.86 indicates that its yield was less stable across years than treatments T9, T10, and T12. Conversely, the high SYI values of T9, T10, and T12 indicate greater consistency in yield performance across years. Thus, the results demonstrate that maximum productivity and yield stability are not necessarily achieved by the same treatment. Sustainable productivity under protected marigold cultivation should therefore be evaluated by considering both the magnitude of marketable yield and its consistency across years.

Descriptive statistics

The descriptive statistics indicate substantial variability in marketable yield and water-use efficiency (WUE) of marigold across treatments and years (table 6). Yield ranged from 12.87 to 21.47 t ha^{-1}, with mean values remaining relatively stable across years (≈15.8–16.1 t ha^{-1}), suggesting consistent crop performance under protected conditions. The moderate coefficients of variation (10–14%) for yield parameters indicate acceptable experimental precision and a measurable treatment effect. Yield distributions showed positive skewness (0.65–1.17), implying that a few high-yielding treatments elevated the mean, while kurtosis values near zero to moderately positive suggest near-normal to slightly peaked distributions.

Table: 6 Descriptive statistics of the variables in marigold

	Min	Max	Mean	Std. error	SD	Median	Skewness	Kurtosis	CV (%)
Yield 2021	12867	21467	16050.17	649.53	2250.04	15644.5	1.17	2.21	14.02
Yield 2022	13867	18796	15831	457.46	1584.69	15577.5	0.65	-0.31	10.01
Yield 2023	13974	19567	16010.75	549.08	1902.05	15303.5	1.03	-0.22	11.88
Mean Yield	13569.3	19943.3	15973.85	524.47	1816.83	15376.5	1.06	0.96	11.37
WUE 2021	30.8	62.4	41.29	2.47	8.57	39.10	1.40	2.49	20.75
WUE 2022	30.3	53.4	39.63	1.98	6.84	39.45	0.44	-0.05	17.27
WUE 2023	27.8	48.8	36.28	1.85	6.42	36.2	0.59	-0.37	17.71
Mean WUE	29.6	54.9	38.59	2.20	7.63	38.25	0.78	0.31	19.76

WUE: Water use efficiency; SD: Standard deviation; CV: Coefficient of variance

In contrast, WUE exhibited much wider dispersion among treatments. Mean WUE values varied from 36.3 to 39.6 kg ha^{-1} mm^{-1}, with minimum values around 28–31 kg ha^{-1} mm^{-1} and maxima reaching 48.8–54.9 kg ha^{-1} mm^{-1}. Higher standard deviations and coefficients of variation (17–20%) for WUE reflect its greater sensitivity to irrigation and fertigation regimes. Strong positive skewness, particularly for WUE 2021, indicates the presence of a few highly efficient treatments under optimized water management. Overall, the statistics suggest that while yield remained relatively stable across years, WUE was more responsive to management interventions, emphasizing the importance of precision irrigation and fertigation in enhancing water use efficiency under protected cultivation.

Principal component analysis (PCA)

The PCA bi-plot illustrates (Fig. 7) the multivariate relationship between marketable yield and water-use efficiency (WUE) across years. The first principal component (PC1) accounted for 91.77% of the total variance and was predominantly associated with the yield variables, with positive loadings for Yield 2021 (0.682), Yield 2022 (0.455) and Yield 2023 (0.572). The second principal component (PC2) explained 4.57% of the variance and showed the strongest association with Yield 2022 (loading = 0.823), whereas PC3 explained 3.66% of the variance and was strongly associated with Yield 2023 (loading = 0.820). In contrast, the WUE variables showed very low loadings on PC1–PC3 and were therefore positioned close to the origin in the PC1–PC2 biplot. Overall, the PCA indicates that the major dimensions of variation among treatments were predominantly associated with marketable yield, whereas WUE exhibited a distinct pattern of variation represented mainly by the subsequent principal components. Thus, the PCA demonstrates distinct multivariate patterns in marketable yield and WUE across the irrigation and fertigation treatments under protected cultivation.

The PCA results (Table 7) further show that the first two principal components together explained 96.34% of the total variance (PC1: 91.77% and PC2: 4.57%), indicating that most of the variability in the dataset was captured by these components. PC1 was associated with all three yield variables, with the highest loading for Yield 2021 (0.682), while PC2 was mainly associated with Yield 2022 (0.823). PC3, although accounting for only 3.66% of the variance, showed a strong association with Yield 2023 (0.820). In contrast, the WUE variables had negligible loadings on PC1–PC3 and showed substantially higher loadings on PC4–PC6. This indicates that the variation in WUE was largely expressed along dimensions distinct from those capturing the major yield-related variation. The PCA therefore provides a multivariate description of the contrasting patterns of yield and WUE responses across the

irrigation and fertigation treatments, without implying a causal relationship between the treatments and either response variable.

Table 7: Principal component analysis of variables in marigold

PC	1	2	3	4	5	6
Eigenvalue	1.02E+07	509582	407382	86.2068	0.608987	0.397553
% variance	91.768	4.5745	3.657	0.000774	5.47E-06	3.57E-06
Loadings						
Yield 2021	0.68237	-0.56705	-0.46132	-0.0016901	-0.0017064	0.0010266
Yield 2022	0.45529	0.82341	-0.33869	0.00073918	0.00034922	0.00023222
Yield 2023	0.57191	0.021079	0.82004	-0.0032481	0.001025	-0.0012502
WUE 2021	0.0019463	-0.0019182	-0.00039624	0.6134	0.62432	-0.4837
WUE 2022	0.0013124	-1.9462E-05	0.0020906	0.60315	-0.7657	-0.22342
WUE 2023	0.0013511	-0.0006084	0.0021895	0.50985	0.1547	0.84624

Discussion

The results of the present study highlight the importance of integrating irrigation method, fertigation strategy, and organic nutrient inputs in determining crop performance under protected cultivation. Rather than acting independently, these factors interacted to influence root growth, flower quality, yield and water-use efficiency and yield stability

Root growth parameters

Root development was significantly influenced by the interaction of irrigation method and fertigation strategy, reflecting the importance of rhizosphere moisture dynamics and nutrient availability. Sub-surface drip fertigation enhanced root length, volume, and biomass possibly because of more targeted water and nutrient delivery within the root zone and reduced surface evaporation. The continuous supply of nutrients through fertigation may have supported sustained root development by maintaining nutrient availability near active root zones. Improved root architecture under sub-surface systems has been associated with enhanced soil moisture extraction and nutrient uptake efficiency, particularly under controlled environments (Guan et al. 2025; Zhao et al. 2024). Thus, the greater root development observed under sub-surface systems may have contributed to the improved crop performance observed in the present study, although nutrient uptake and physiological processes were not directly measured.

Flower quality parameters

Flower quality attributes were closely linked to nutrient synchronization and water availability within the root zone. Treatments with higher fertigation proportions under sub-surface drip irrigation produced superior flower size, weight (Camp, 1998; Guo et al. 2023; Koli et al. 2018), shelf life (Koli et al. 2018) and carotenoid content (Koli et al. 2018; Siddiqa et al. 2025). These improvements may reflect more favorable water and nutrient availability during crop development, although photosynthetic efficiency and assimilate partitioning were not directly measured in the present study. Continuous nutrient supply through fertigation could have contributed to improved crop growth and reproductive development by maintaining a more consistent nutrient supply (Chitra et al. 2023; Koli et al. 2018). Improved water and nutrient availability may also have contributed to better flower quality and post-harvest performance. These responses are consistent with studies showing that precise fertigation enhances nutrient-use efficiency and improves quality traits in horticultural crops by maintaining optimal physiological conditions throughout growth (Zhao et al. 2024). The results also indicate that quality improvement was more closely associated with the fertigation strategy than simply with the total fertilizer input. Vermiwash-based treatments did not consistently improve flower quality to the same extent as balanced NPK fertigation. Although vermiwash may contribute beneficial microbial metabolites and growth-promoting substances, its effects in the present study indicate that its effect remained supportive rather than substitutive. Thus, organic liquid supplements appear to be most effective when integrated within a precise mineral fertigation system rather than used as a partial nutritional replacement (Kumar et al. 2025; Koli et al. 2018).

Similar benefits of drip fertigation and sub-surface nutrient placement in enhancing yield, water use efficiecy, and nutrient-use efficiency in horticultural crops have been reported earlier (Camp, 1998; Li et al. 2021; Guo et al. 2023).

Marketable yield

Marketable yield was significantly enhanced under sub-surface drip fertigation, demonstrating the advantage of synchronized water–nutrient delivery over conventional practices. The superior performance of treatments with higher fertigation fractions indicates that continuous nutrient availability aligned with crop demand is more effective than basal-dominated fertilization. Sub-surface drip irrigation improves yield by maintaining uniform soil moisture distribution and reducing non-productive water losses, thereby enhancing nutrient uptake and

biomass accumulation (Mohanty et al. 2025; Yokamo et al. 2022). Global evidence confirms that sub-surface drip systems significantly increase crop yield compared to surface irrigation due to improved soil–water–nutrient interactions (Guo et al. 2023; Wang et al. 2022). The physiological basis for these yield differences is rooted in soil–plant water relations and microclimate modification. By placing emitters below the soil surface, SSDI maintains more stable moisture in the root zone which promotes uniform root growth and enhanced soil aeration, both of which support improved nutrient uptake and physiological functioning of plants. Reduced soil surface wetness also limits soil evaporation and restricts weed germination, indirectly allowing crops to access a larger proportion of water and nutrients for productive growth (Guo et al. 2023; Hashemi et al. 2024). In contrast, SDI systems can suffer from greater evaporative losses and uneven moisture distribution, particularly in coarse-textured soils or under high evaporative demand, which may reduce the effective water available to plants and constrain yield potential. In your plot, the higher median and upper quartile values for SSDI suggest that many trials experienced improved marketable output with sub-surface drip. At the same time, the wider spread and some high outliers under SSDI reflect how crop response to irrigation methods depends strongly on soil type, root architecture, irrigation scheduling, and management practices. For example, sub-surface irrigation systems buried too deeply or operated with inadequate soil capillarity may fail to supply sufficient moisture to shallow roots, potentially suppressing yields under certain conditions (Guo et al. 2023). Water savings from reduced evaporation and percolation under SSDI lead to greater fractions of applied irrigation being used directly for transpiration and growth. Increasing transpiration efficiency is often correlated with higher biomass accumulation and yield, especially in water-limited environments where drought stress constrains plant development (Umair et al. 2019). Similar yield advantages of sub-surface drip fertigation have been reported in high-value horticultural crops due to improved root proliferation and reduced nutrient losses (Camp 1998; Chitra et al. 2023; Li et al. 2021). These findings reinforce that yield improvement under protected cultivation is governed more by resource-use efficiency and input synchronization than by the absolute quantity of inputs applied.

Water use efficiency (WUE)

Water-use efficiency was generally higher under sub-surface drip irrigation, indicating more effective utilization of applied water for biomass production. The reduced irrigation levels combined with higher WUE demonstrate that sub-surface placement minimizes evaporation and deep percolation losses, thereby increasing the

fraction of water used in transpiration. Improved root growth and nutrient uptake further enhance transpiration efficiency, resulting in greater yield per unit of water applied (Koushal et al. 2024; Thiyagarajan et al. 2023).

Recent studies have shown that sub-surface drip irrigation can substantially improve water use efficiecy by optimizing soil moisture distribution and reducing non-productive losses (Guan et al. 2025; Wan et al. 2024). Several studies have demonstrated that sub-surface drip irrigation enhances WUE by 20–50 % compared to surface drip and conventional irrigation systems (Camp, 1998; Dass et al. 2025; Lamm et al. 2012). Furthermore, fertigation enhances nutrient uptake efficiency, leading to improved photosynthetic activity and biomass accumulation per unit water consumed.

These results highlight that WUE is a function of integrated soil–water–nutrient interactions rather than irrigation quantity alone, emphasizing the role of precision irrigation and fertigation in water-limited systems.

Sustainable yield index (SYI)

The sustainability index revealed that long-term system performance depends on both yield magnitude and inter-annual stability. While sub-surface drip fertigation treatments achieved higher productivity and WUE, variations in SYI indicate that maximum yield does not necessarily correspond to maximum stability. Treatments with relatively consistent performance across years exhibited higher SYI values, reflecting greater resilience to temporal variability. This aligns with the concept that sustainable intensification requires balancing productivity with stability under varying environmental conditions. Previous studies have also emphasized that efficient irrigation systems enhance sustainability by improving water use efficiecy and reducing resource losses over time (Gua et al. 2023). Therefore, integrated water–nutrient management under sub-surface drip systems contributes not only to higher yields but also to more stable and resource-efficient production systems under protected cultivation.

Conclusions

The present study demonstrated that the integrated irrigation–fertigation treatments substantially influenced root growth, flower quality, marketable yield and water-use efficiency of marigold under protected cultivation. Among the treatment combinations evaluated, T8, comprising 25% NPK applied basally and 75% NPK through fertigation under sub-surface drip irrigation at 0.6 PE, recorded the highest marketable yield, WUE, root growth and flower quality.

The three-year evaluation showed that high productivity and water-use efficiency were not necessarily accompanied by the highest yield stability. Integration of the Sustainable Yield Index with multivariate analysis therefore provided a broader assessment of treatment performance across years and highlighted the importance of considering both productivity and temporal stability when evaluating irrigation–fertigation strategies.

Because surface drip and sub-surface drip were evaluated at 0.8 PE and 0.6 PE, respectively, the differences between these systems represent the combined effects of irrigation method and irrigation level and cannot be attributed solely to irrigation placement. Within the treatment combinations evaluated in this study, sub-surface drip fertigation at 0.6 PE with 75% of NPK supplied through fertigation showed the most favourable overall performance and represents a promising resource-efficient strategy for marigold production under protected cultivation.

Author Contributions

R.J.: visualization, data curation, formal analysis, writing – original draft, writing – review and editing. S.K.S.: conceptualization, investigation, methodology, visualization , validation, software,. A.K.: visualization, investigation. D.R.: visualization, resources.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Data will be made available on request.

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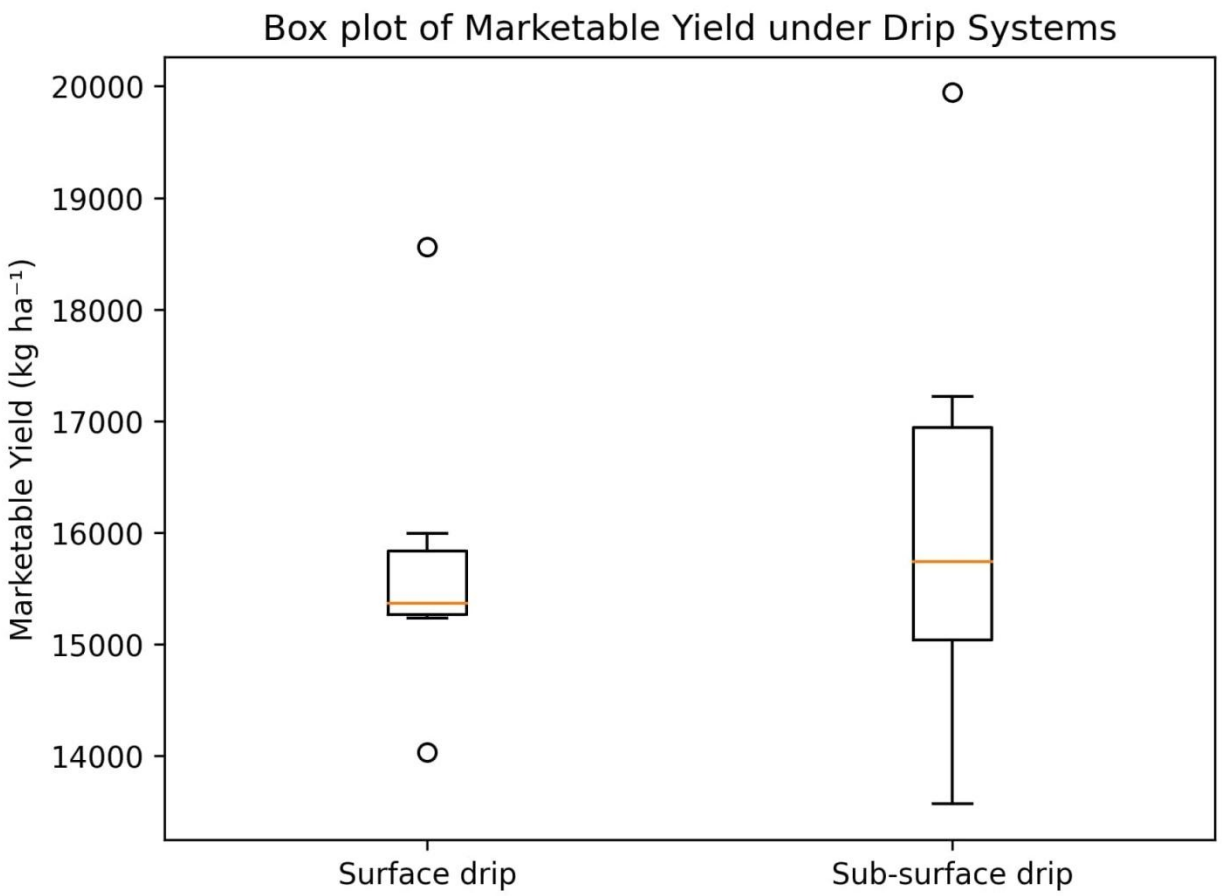
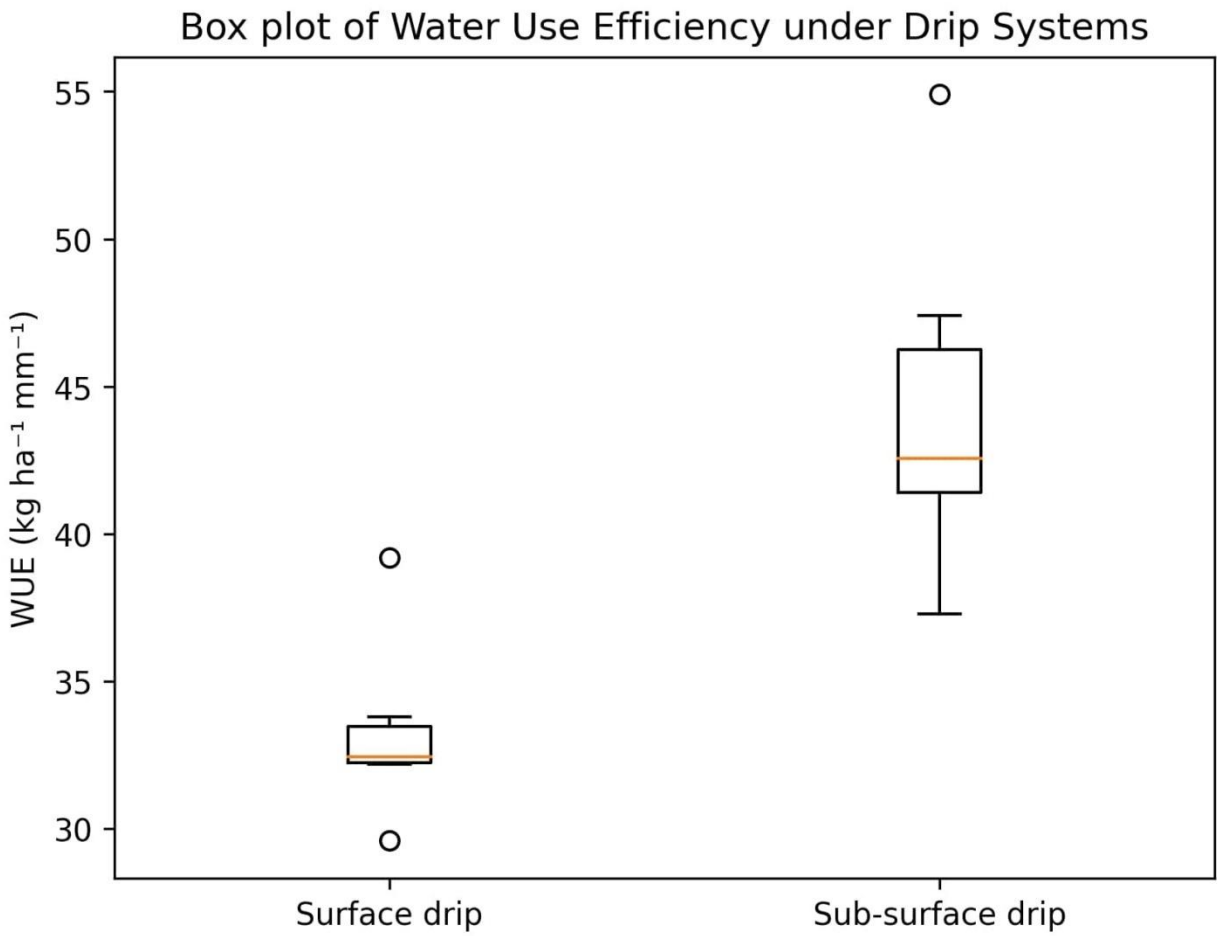


Fig. 1 Box plot showing marketable yield of marigold under surface drip irrigation (SDI) and subsurface drip irrigation (SSDI). The higher median and upper range under SSDI indicate a general yield advantage of subsurface placement over surface drip.



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664 **Fig. 2** Box plot showing water-use efficiency (WUE) of marigold under surface drip irrigation (SDI) and
665 subsurface drip irrigation (SSDI). Subsurface drip showed clearly higher WUE values, indicating better
666 conversion of applied water into marketable yield.

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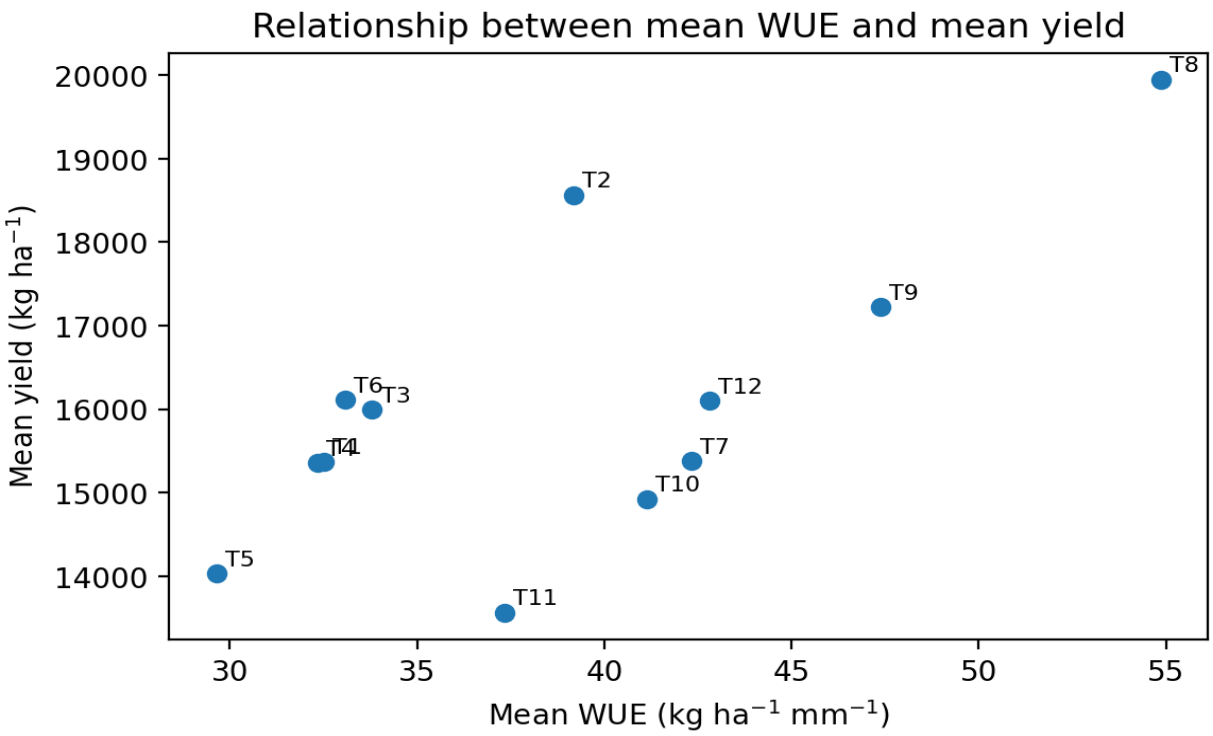

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670 **Fig. 3** Scatter plot showing the relationship between mean water-use efficiency and mean marketable
671 yield across treatments. Treatments positioned toward the upper right represent more productive and
672 water-efficient management combinations.

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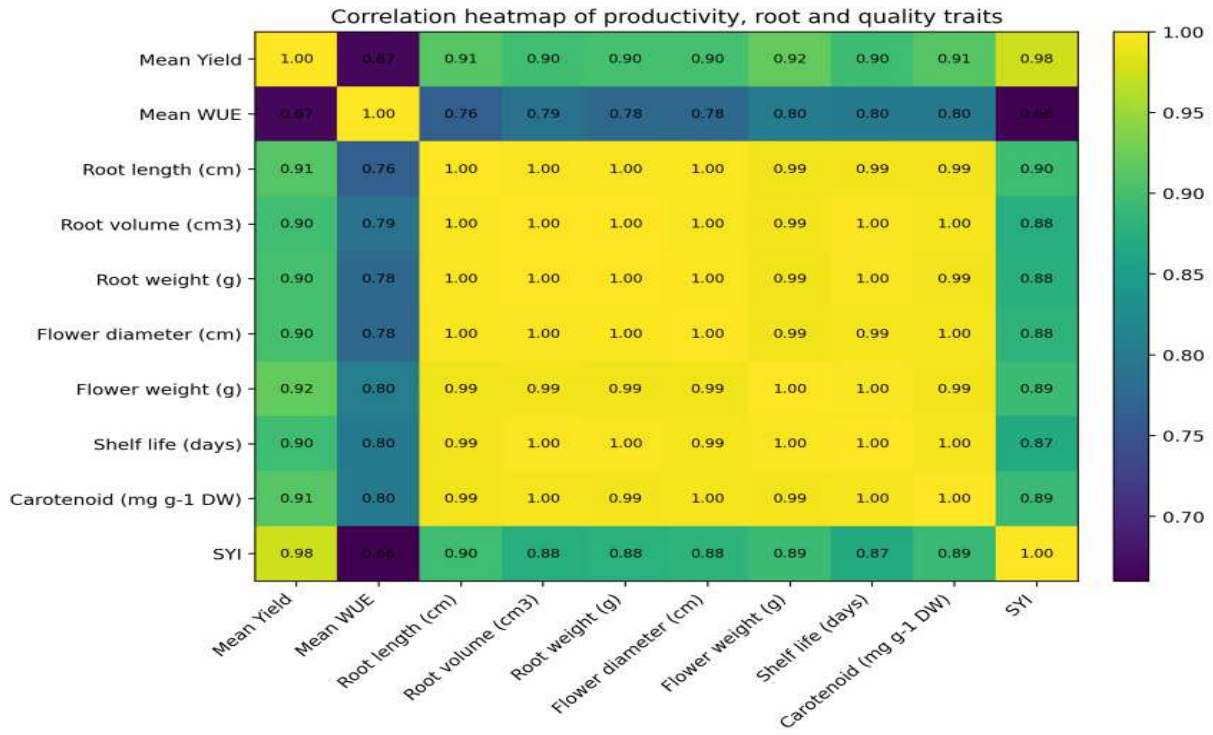

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675 Fig. 4 Correlation heatmap showing relationships among mean yield, mean WUE, root traits, flower
676 quality traits, and Sustainable Yield Index (SYI) in marigold.

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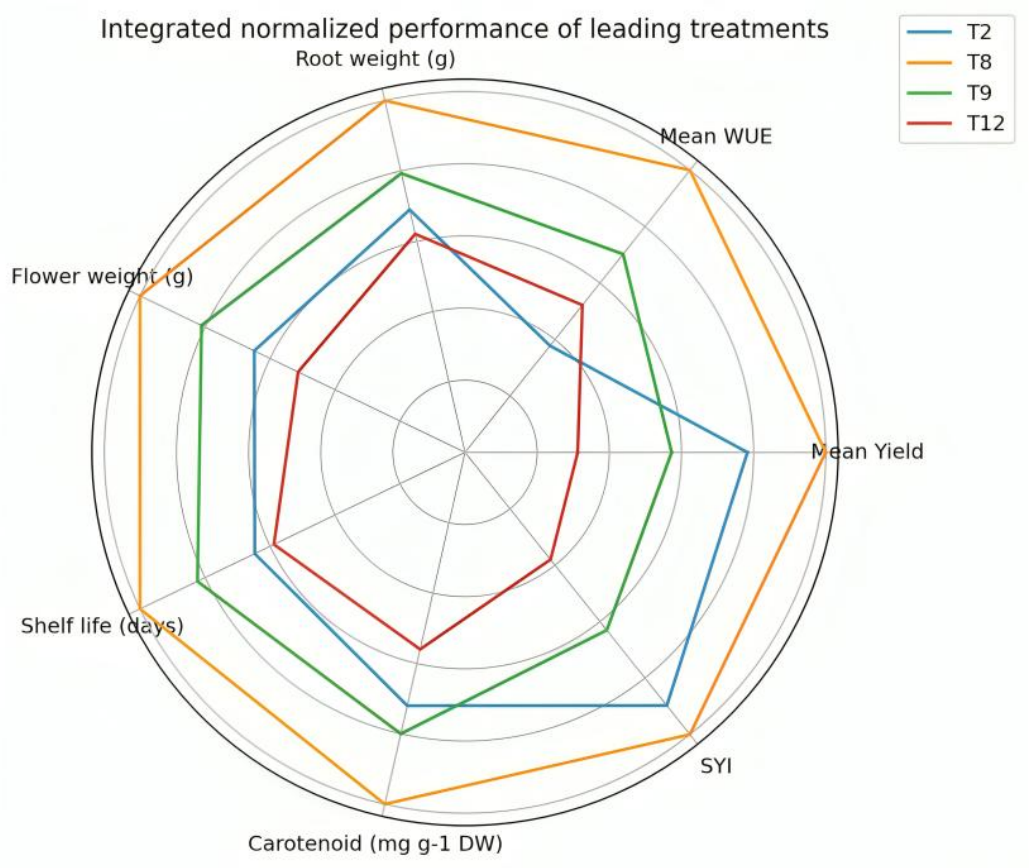

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681 Fig. 5 Integrated normalized radar plot comparing leading treatments for mean yield, mean WUE, root
682 weight, flower weight, shelf life, carotenoid content, and Sustainable Yield Index (SYI). Wider spread
683 indicates stronger overall treatment performance.

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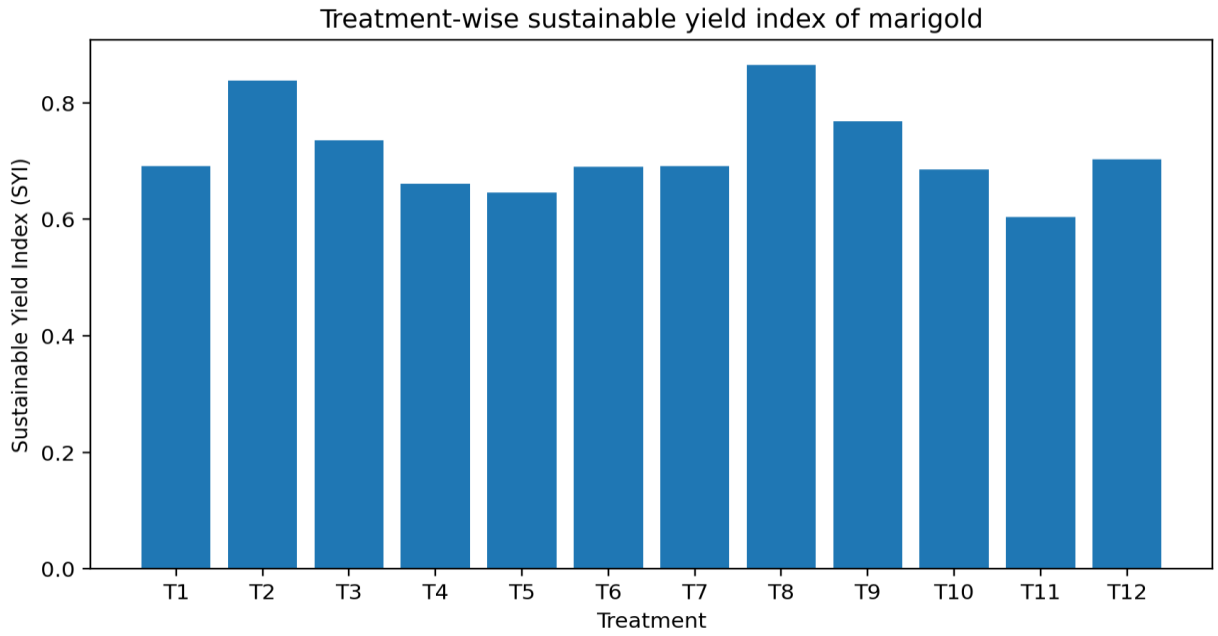

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687 **Fig. 6** Treatment-wise Sustainable Yield Index (SYI) of marigold. Higher SYI values indicate more stable
688 and sustainable yield performance across years.

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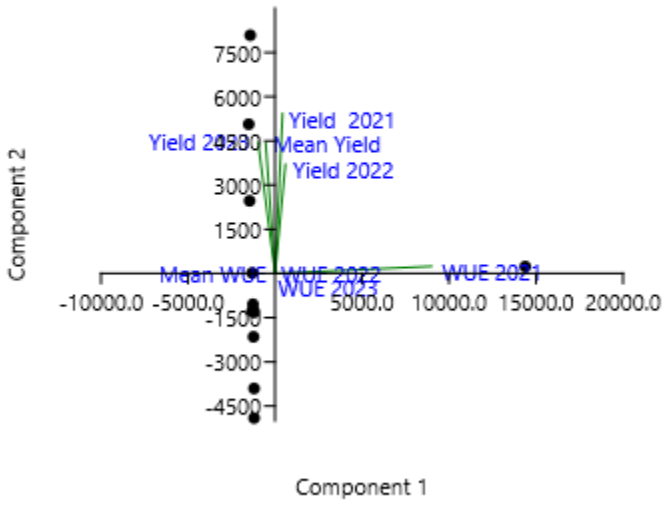

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692 **Fig: 7** Relationship among variables using PCA in marigold.

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