Enhancing Water Productivity and Flower Yield of Tuberose through Drip Fertigation and Optimized Land Configurations in Semi-Arid Region

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The economic and agronomic impacts of drip fertigation techniques were evaluated on tuberose (*Polianthes tuberosa* L.) cultivation in a semi-arid region. Conducted over two growing seasons (2022-2024) at the ICAR-Indian Agricultural Research Institute in New Delhi, the field experiments utilized a split-split plot design with three factors: land configuration (raised bed and flatbed), irrigation schedules (50%, 75%, and 100% pan evaporation), and fertigation schedules (50%, 75%, and 100% recommended dose of fertilizers). Data were collected on flower yield, water productivity, and economic returns. The raised bed system consistently outperformed the flat bed system in water productivity and flower yield. Among the irrigation levels, the highest water productivity and flower yield were observed at 100% pan evaporation. Similarly, the highest fertigation level (100% RDF) resulted in the best outcomes in terms of both yield and economic returns. The economic analysis revealed that the raised bed configuration with higher fertigation and irrigation levels (BI3F3) was the most profitable, with the highest benefit-cost ratios. The study concludes that optimizing fertigation and irrigation practices, particularly using raised bed configurations with higher fertigation and irrigation levels, can significantly enhance tuberose cultivation's profitability and sustainability in water-scarce regions.

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INTRODUCTION

Tuberose (*Polianthes tuberosa* L.) is a prominent tropical ornamental bulbous flowering plant known for its long-lasting flower spikes and is popularly referred to as Rajanigandha or Nishigandha. This plant, belonging to the Amaryllidaceae family and native to Mexico, holds a prime position in both domestic and international markets due to its colour, elegance, and fragrance (Sood and Nagar 2005). In India, tuberose is commercially cultivated across diverse climatic conditions, notably in states such as Tamil Nadu, Andhra Pradesh, West Bengal, and Karnataka. Due to its great demand as a cut flower, loose flower, and essential ingredient in perfumes, tuberose production yields substantial profits (Singh and Shanker 2011).

However, the cultivation of tuberose faces several challenges, particularly in semi-arid regions where water scarcity and nutrient management are critical concerns. For proper irrigation management, the scheduling of water is essential, as stated by Tan (1981). Effective irrigation practices and optimal nutrient application are crucial to maintaining quality and maximizing profits. Despite significant advancements in crop improvement, the emphasis on irrigation management in tuberose cultivation remains limited. The total water applied through irrigation, supplemented by rainfall, needs to be meticulously managed to meet the crop's water requirements for optimum growth and yield (Allen *et al.* 1998). Evapotranspiration (ET) is a critical parameter in irrigation scheduling, representing the water loss from soil and plant surfaces. The use of pan evaporation methods to estimate ET provides a practical approach for adjusting irrigation schedules to account for climatic variables such as temperature, humidity, wind speed, and solar radiation. Pan evaporation methods have been identified as suitable for irrigation schemes, providing a reliable estimate of crop evapotranspiration (Aydinsakir *et al.* 2003).

The advent of modern irrigation techniques, such as drip irrigation, has revolutionized water management in horticultural crops. Drip irrigation provides precise water application directly to the root zone, significantly enhancing water use efficiency and minimizing wastage (Aydinsakir *et al.* 2003). Drip irrigation has been recognized as a transformative technique in horticulture, particularly for water-intensive crops such as tuberose. This method ensures precise water delivery to the root zone, significantly improving water use efficiency and reducing water loss through evaporation and runoff. For tuberose, characterized by its high-water demand and sensitivity to moisture stress, adopting drip irrigation systems can address the challenges posed by water scarcity, especially in semi-arid regions. Moreover, by providing a uniform water supply, drip irrigation minimizes the risks of over- or under-watering, fostering healthier growth and prolonged flowering periods. This technique aligns well with the need for sustainable water management practices in commercial floriculture, making it a cornerstone for profitable and efficient tuberose cultivation. Complementing drip irrigation, fertigation—the practice of applying fertilizers through the irrigation system—has emerged as an efficient method to provide timely and accurate crop nutrition. This method enhances fertilizer use efficiency, reduces wastage, and promotes better yield and quality of tuberose flowers. Studies have demonstrated that integrating drip irrigation with fertigation can optimize nutrient availability and uptake, leading to enhanced flower yield and quality (Deshmukh 2012). This study focuses on standardizing irrigation and fertigation schedules for tuberose cultivation, addressing field variability in semi-arid regions. By aligning water and nutrient application with the crop's dynamic needs—affected by climatic and soil conditions—it aims to enhance water productivity, flower yield, and economic returns.

Integrating drip fertigation with optimized land configurations, the research evaluates the combined effects of varying irrigation and fertigation levels on agronomic and economic outcomes. It provides insights into sustainable water and nutrient management, emphasizing profitability and resource efficiency. Additionally, the study investigates the cost-benefit ratio of these practices to support sustainable and profitable tuberose cultivation in water-scarce regions

EXPERIMENTAL

The field experiments were conducted during the 2022 to 2023 and 2023 to 2024 growing seasons at Water Technology Center, ICAR-Indian Agricultural Research Institute, New Delhi (29° 35' N and 77° 10' E, altitude of 232 meters AMSL). The experiment was laid out in split-split plot design and replicated thrice. The treatments comprised of three factors, with Factor A consisting of two land configurations (Raised bed and flatbed), Factor B of three irrigation schedules (50% PE, 75% PE and 100% PE) and Factor C of three fertigation schedules (50% RDF, 75% RDF and 100% RDF). The crop was planted in April and harvested at harvesting maturity.

The nitrogen fertilizer (200 kg ha^{-1}) was supplied through urea and DAP in three equal splits—at planting, at 30 days after planting (DAP), and during the spike emergence stage. Phosphorus (200 kg ha^{-1}) was provided entirely at planting *via* SSP, while potassium (200 kg ha^{-1}) was applied entirely at planting using MOP. The following Table 1 shows the details of the treatments.

The weather data for the experimental period were recorded at the IARI Meteorological Observatory, New Delhi, and summarized into standard meteorological weeks. In 2022 to 23, the mean maximum temperature ranged from 16.1 to 43.7 °C and the mean minimum temperature from 3.0 to 28.0 °C. For 2023 to 24, the mean maximum ranged from 14.4 to 41.3 °C, and the mean minimum from 2.4 to 27.8 °C. Total rainfall was 140.4 mm (33 rainy days) in 2022 to 23 and 144.5 mm (30 rainy days) in 2023 to 24. The Bright sunshine averaged 6.2 hours/day in 2022 to 23 and 6.0 hours/day in 2023 to 24. And the evaporation rates averaged 3.8 mm/day in 2022 to 23 and 3.3 mm/day in 2023 to 24. Biometric measurements of flower parameters were recorded for five selected plants in each plot, and the average values were reported. Flower yield was measured by multiplying the total number of spikes and flowers per spike and the average weight of a flower in each treatment plot was calculated. Water productivity (WP) is defined as the amount of yield produced per unit of water used, typically expressed in kilograms per cubic meter (kg m^{-3}). This measurement helps in assessing the efficiency of water use in crop production, providing insights into how effectively water resources are being utilized to achieve maximum crop yield.

Table 1. Details of the Treatments

Treatment No.	Treatment Detail	Label
T1	Raised Bed Planting + Irrigation Scheduled at 50% PE + 50% RDF	$B_1I_1F_1$
T2	Raised Bed Planting + Irrigation Scheduled at 50% PE+ 75% RDF	$B_1I_1F_2$
T3	Raised Bed Planting + Irrigation Scheduled at 50% PE + 100% RDF	$B_1I_1F_3$
T4	Raised Bed Planting + Irrigation Scheduled at 75% PE + 50% RDF	$B_1I_2F_1$
T5	Raised Bed Planting + Irrigation Scheduled at 75% PE + 75% RDF	$B_1I_2F_2$
T6	Raised Bed Planting + Irrigation Scheduled at 75% PE + 100% RDF	$B_1I_2F_3$
T7	Raised Bed Planting + Irrigation Scheduled at 100% PE + 50% RDF	$B_1I_3F_1$
T8	Raised Bed Planting + Irrigation Scheduled at 100% PE + 75% RDF	$B_1I_3F_2$
T9	Raised Bed Planting + Irrigation Scheduled at 100% PE + 100% RDF	$B_1I_3F_3$
T10	Flat Bed Planting + Irrigation Scheduled at 50% PE + 50% RDF	$B_2I_1F_1$

T11	Flat Bed Planting + Irrigation Scheduled at 50% PE+ 75% RDF	$B_2I_1F_2$
T12	Flat Bed Planting + Irrigation Scheduled at 50% PE + 100% RDF	$B_2I_1F_3$
T13	Flat Bed Planting + Irrigation Scheduled at 75% PE + 50% RDF	$B_2I_2F_1$
T14	Flat Bed Planting + Irrigation Scheduled at 75% PE + 75% RDF	$B_2I_2F_2$
T15	Flat Bed Planting + Irrigation Scheduled at 75% PE + 100% RDF	$B_2I_2F_3$
T16	Flat Bed Planting + Irrigation Scheduled at 100% PE+ 50% RDF	$B_2I_3F_1$
T17	Flat Bed Planting + Irrigation Scheduled at 100% PE+ 75% RDF	$B_2I_3F_2$
T18	Flat Bed Planting + Irrigation Scheduled at 100% PE+ 100% RDF	$B_2I_3F_3$

The economic analysis of tuberose cultivation for the 2022 to 23 and 2023 to 24 seasons considered both fixed and variable costs. Fixed costs included the cost of the drip irrigation system, calculated using the annual fixed cost (AFC) formula, as follows,

$$\text{AFC} = \text{CRF} \times \text{Present Value} \tag{1}$$

$$CRF = \frac{ir(1+ir)^y}{(1+ir)^y - 1} \tag{2}$$

where CRF = 0.1769. The annualized cost of the investment was 17.69% of the initial investment each year for the 10-year period. As the initial cost of drip is 400,000₹, then the annualized cost is calculated as, initial cost × CRF which is equal to 70,760₹. The government is providing a subsidy of 80%, one obtains 56,608₹ subsidy per year. Then, the annualized cost per year is 14,152₹.

Variable costs covered operational and maintenance expenses for the drip system and all cultivation activities, including land preparation, bulb costs, planting, plant protection, intercultural operations, fertilizer application, irrigation, and harvesting. The pumping cost was calculated based on the energy consumption of the pump, the hours of operation, and the cost of electricity. It was crucial to monitor and optimize the pumping schedule to minimize energy consumption while ensuring efficient water delivery to the crops.

The average market value of the flowers used in the experiment was used to determine gross returns (GRR). The net return (NER) was calculated by deducting the total cultivation cost (TCOC) from the gross return (GRR). Net returns to cultivation costs were compared to get the benefit-cost ratio (BCR), where all variables are represented in rupees per hectare (₹/ha). Everything from tillage to harvesting, including bulbs, fertilizers, and irrigation, was included in the cultivation cost for each treatment. The flower market prices that were prevalent during both crop seasons were used to compute the gross returns. To get the net returns, we took the gross monetary returns and subtracted the cultivation cost. The BCR was then calculated using Eq. 3.

$$\text{BCR} = \text{Net Return} / \text{Cost of Cultivation} \tag{3}$$

Data collected over a span of two years were then analyzed using the ‘Analysis of Variance’ (ANOVA) technique to assess statistical significance. The observed data on crops were subjected to analysis of variance procedures as outlined for split plot design (Gomez and Gomez 1984) to find out the treatment difference. Wherever the treatment difference was found significant, the critical differences were worked out at 5 per cent probability level. When the treatment difference was non-significant is denoted as NS.

RESULTS AND DISCUSSION

Irrigation Water Applied (mm) And Crop Water Requirement (mm)

Irrigation water was applied based on a percentage of pan evaporation (PE). PE measures the water evaporated from an open pan, which reflects the atmospheric demand for water. Different percentages (*e.g.*, 50, 75, or 100%) were used to determine the amount of irrigation water to apply, reflecting varying irrigation levels. For example, 100% PE aims to meet the full water demand of the crop, while lower percentages (*e.g.*, 50% and 75% PE) provide only part of the required water, potentially leading to water stress. The irrigation requirement (Table 2) was 397.2 mm for I1 (50% PE), 596.0 mm for I2 (75% PE), and 794.5 mm for I3 (100% PE). The crop water requirement represents the total amount of water needed by the crop for optimal growth, which includes evapotranspiration (ET) and soil moisture needs. It is influenced by various factors. Thus, the crop water requirement is typically higher than the irrigation water applied with values of 691.1 mm for I1, 892.9 mm for I2, and 1097.4 mm for I3.

Water Productivity

Water productivity varied significantly (Fig. 1) across treatments influenced by different land configurations, irrigation levels, and fertigation schedules. Among all treatments, T3 recorded the highest water productivity at 30.7 kg/m³, followed closely by T2 (30.6 kg/m³) and T1 (28.4 kg/m³). Conversely, the lowest water productivity was observed in T16 (13.2 kg/m³), T17 (14.3 kg/m³), and T18 (15.2 kg/m³).

Table 2. Pooled Data (2022-2024) of Irrigation Water Applied (mm) and Crop Water Requirement (mm) in Tuberose

Irrigation Requirement	**Pooled Data**
I_1: 50%PE	397.2
I_2: 75%PE	596.0
I_3: 100%PE	794.5
Crop Water Requirement	Pooled Data
I_1: 50%PE	691.1
I_2:75%PE	892.9
I_3:100%PE	1097.4

Note: PE, pan evaporation

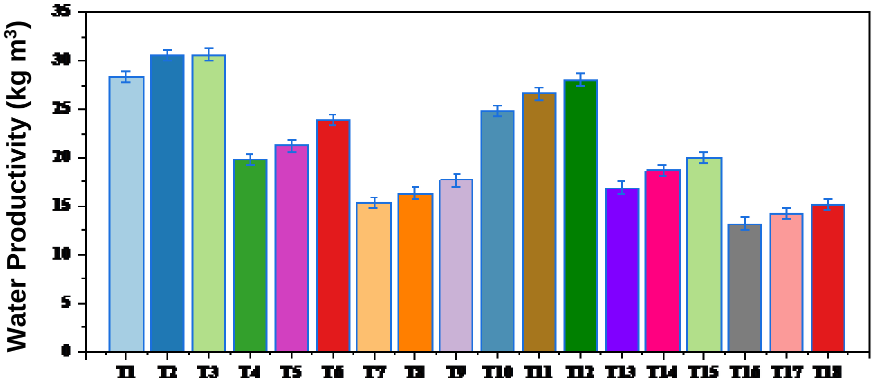

Fig. 1. Water productivity (kg/m³) as influenced by land configurations, irrigation levels, and fertigation levels (pooled data for 2022–2024 seasons)

The highest water productivity in T3 can be attributed to the optimal combination of land configuration, irrigation level, and fertigation scheduling, which likely maximized water use efficiency. The efficient use of water in T1 and T2 treatments also indicates favorable management practices, possibly reflecting a balance in moisture availability and nutrient uptake. In contrast, the lower water productivity in T16, T17, and T18 may be due to suboptimal water and nutrient management, leading to reduced water use efficiency. These treatments might have experienced moisture stress or inefficient nutrient uptake, resulting in lower productivity. These results agree with Khanam *et al.* (2017), who concluded in tuberose crop that higher water use efficiency occurred at lower levels of irrigation, emphasizing the importance of optimizing water application for crop yield. Similar results were also obtained by Banik *et al*. (2018) and Yadav *et al*. (2020).

Table 3. Flower Yield of Tuberose (t/ha) as Influenced by Land Configurations, Irrigation Levels and Fertigation Levels during 2022 to 2023, 2023 to 2024, and Pooled Data

Treatments	**Flower Yield (t/ha)**		
	2022 to 23	2023 to 24	Pooled
Factor A: Land configuration			
Raised bed (B1)	17.04	16.73	16.89
Flatbed (B2)	14.89	14.73	14.81
SEm±	0.18	0.18	0.18
CD (P=0.05)	1.12	1.07	1.09
Factor B: Irrigation Regimes			
50 % PE (I1)	14.91	15.22	15.06
75 % PE (I2)	16.48	15.74	16.11
100 % PE (I3)	16.50	16.23	16.37
SEm±	0.51	0.21	0.28
CD (P=0.05)	1.46	0.61	0.81
Factor C: Fertigation Regimes			
50 % RDF (F1)	14.43	15.03	14.73
75 % RDF (F2)	15.91	15.82	15.86
100 % RDF (F3)	17.55	16.34	16.94
SEm±	0.51	0.21	0.28
CD (P=0.05)	1.46	0.61	0.81

Flower Yield

The flower yield of tuberose (t/ha) was significantly influenced by land configuration, irrigation regimes, and fertigation levels across both the 2022 to 23 and 2023 to 24 seasons, as well as in the pooled data (Table 3). The treatment wise table is being presented in annexure. The raised bed configuration (B1) consistently produced higher flower yields in both years, with 17.04 t/ha in 2022 to 23 and 16.73 t/ha in 2023 to 24, resulting in a pooled yield of 16.89 t/ha. In contrast, the flatbed configuration (B2) yielded 14.89 t/ha in 2022 to 23 and 14.73 t/ha in 2023 to 24, with a pooled average of 14.81 t/ha. The higher flower yield in raised beds could be attributed to improved soil aeration, drainage, and root proliferation, enhancing the plant’s ability to absorb water and nutrients more effectively. Studies have reported that planting tuberose crops on ridges had higher flower yield when compared to the yield on flat beds (Nain *et al*. 2019). Similar results were also obtained by Bhatt *et al.* (2020) in gladiolus crops. Irrigation at 100% PE (I3) led to the highest flower yield across both years, with yields of 16.50 t/ha in 2022 to 23 and 16.23 t/ha in 2023 to 24, resulting in a pooled yield of 16.37 t/ha. This was closely followed by 75% PE (I2), which yielded 16.48 t/ha in 2022 to 23 and 15.74 t/ha in 2023 to 24, with a pooled average of 16.11 t/ha. The lowest yields were observed in 50% PE (I1), with 14.91 t/ha and 15.22 t/ha across the two years, resulting in a pooled yield of 15.06 t/ha. These results indicated that higher irrigation levels, especially at 100% PE, provided sufficient moisture for optimal crop growth and flower production. However, 75% and 100% PE are significantly on par and could also be a water-efficient regime while still maintaining high flower yields. Similarly, Patra *et al*. (2017) concluded that the highest flower yield was obtained when tuberose crop was irrigated at IW/CPE 1.0. This result was statistically similar to the moderate irrigation level at IW/CPE 0.8. The lowest values were significantly recorded when the irrigation level was at IW/CPE 0.4. The results obtained are consistent with Khanam *et al*. (2017), Kabariel (2015), and Pal *et al*. (2019).

Fertigation at 100% RDF (F3) consistently produced the highest flower yields, with 17.55 t/ha in 2022 to 23 and 16.34 t/ha in 2023 to 24, resulting in a pooled yield of 16.94 t/ha. Fertigation at 75% RDF (F2) showed moderate yields of 15.91 t/ha and 15.82 t/ha, with a pooled average of 15.86 t/ha. The lowest yields were recorded under 50% RDF (F1), with 14.43 t/ha in 2022 to 23 and 15.03 t/ha in 2023 to 24, giving a pooled yield of 14.73 t/ha. The increase in fertigation levels, particularly at 100% RDF, likely provided adequate nutrient availability, enhancing vegetative growth and flower production. This indicates that tuberose responds positively to higher fertigation levels, particularly when combined with optimal irrigation regimes. Saucedo *et al*. (2023) reported that the tuberose crop fertigation scheduled at N300-P200-K200 produced a statistically superior yield when compared to other treatments. Similar results were also obtained from Shashidhar *et al*. (2008), Kabariel (2015), and Sendhilnathan and Manivannan (2019).

Economics

The economic analysis of tuberose cultivation under various land configurations, irrigation regimes, and fertigation levels for the years 2022-23, 2023-24, and the pooled data is presented in Table 4 and Fig. 2. The cost of cultivation varied across treatments due to differences in land configurations, irrigation and fertigation levels. The lowest cost of cultivation was observed in the T10 treatment (flatbed configuration with 50%PE and 50% RDF), with pooled Cost of cultivation of ₹3,20,292.8/ha, while the highest cost of cultivation was recorded in T9 (raised bed with 100%PE and 100% RDF), with pooled COC of ₹4,09,486.0/ha. The higher Cost of cultivation in treatments with raised bed configurations and higher fertigation levels can be attributed to increased input costs for water and fertilizer.

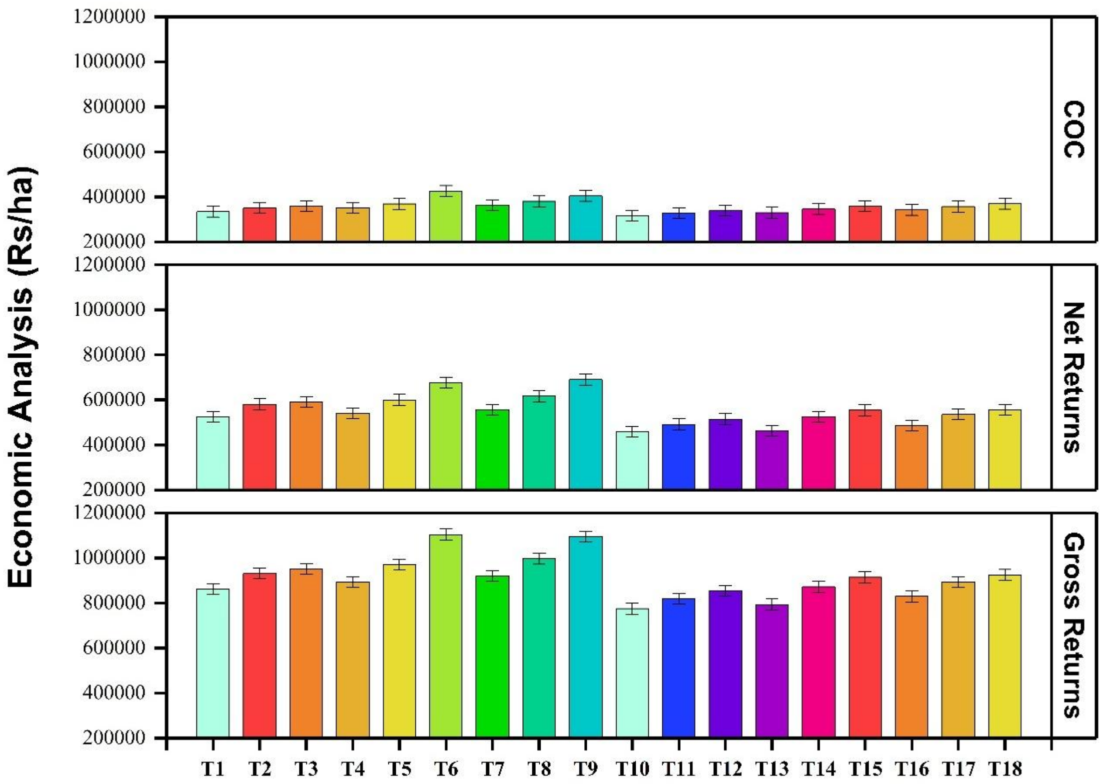

Fig. 2. Effect of irrigation and fertigation schedules on cost of cultivation (Rs/ha), net returns (Rs/ha), and gross returns (Rs/ha) in drip irrigated tuberose under varied land configuration

Table 4. Economic Analysis of Tuberose Cultivation Under Different Land, Irrigation, and Fertigation Regimes during 2022–2023, 2023–2024 and Pooled Data

Treatment	Label	Cost of Cultivation (₹/ha)			Gross Returns (₹/ha)			Net Returns (₹/ha)			B:C Ratio		
		2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T1	$B_1I_1F_1$	335143	343405	339274.4	801163	919797	860480.1	466020	576392	521205.8	2.4	2.7	2.5
T2	$B_1I_1F_2$	353758	357573	355665.5	880560	980968	930763.9	526802	623395	575098.4	2.5	2.7	2.6
T3	$B_1I_1F_3$	367211	363811	365511.0	913202	988771	950986.3	545992	624959	585475.3	2.5	2.7	2.6
T4	$B_1I_2F_1$	342494	357583	350038.3	834658	949013	891835.3	492164	591430	541797.0	2.4	2.7	2.5
T5	$B_1I_2F_2$	363146	370732	366938.6	930506	1007578	969041.8	567360	636846	602103.2	2.6	2.7	2.6
T6	$B_1I_2F_3$	393575	382300	387937.8	1063294	1042221	1052757.6	669719	659921	664819.9	2.7	2.7	2.7
T7	$B_1I_3F_1$	349870	371695	360782.2	868874	970732	919802.9	519004	599037	559020.8	2.5	2.6	2.6
T8	$B_1I_3F_2$	368583	386333	377457.9	959756	1033443	996599.5	591173	647110	619141.6	2.6	2.7	2.6
T9	$B_1I_3F_3$	410444	408528	409486.0	1165862	1127857	1146859.7	755418	719330	737373.7	2.9	2.8	2.8
T10	$B_2I_1F_1$	320400	320185	320292.8	729812	818388	774100.2	409412	498203	453807.4	2.3	2.6	2.4
T11	$B_2I_1F_2$	334150	330816	332482.8	781064	857498	819281.0	446914	526683	486798.2	2.3	2.6	2.5
T12	$B_2I_1F_3$	348213	340849	344531.0	818646	889723	854184.3	470434	548873	509653.4	2.4	2.6	2.5
T13	$B_2I_2F_1$	325414	331237	328325.4	750458	836241	793349.3	425044	505004	465023.8	2.3	2.5	2.4
T14	$B_2I_2F_2$	345211	344361	344785.6	840852	901642	871247.2	495642	557282	526461.6	2.4	2.6	2.5
T15	$B_2I_2F_3$	359327	356819	358073.3	886814	940615	913714.3	527487	583795	555641.0	2.5	2.6	2.6
T16	$B_2I_3F_1$	333704	345669	339686.5	790005	867687	828845.9	456301	522018	489159.4	2.4	2.5	2.4
T17	$B_2I_3F_2$	349879	358426	354152.8	859452	926123	892787.3	509573	567697	538634.6	2.5	2.6	2.5
T18	$B_2I_3F_3$	365128	367020	366073.9	914340	935095	924717.6	549212	568075	558643.7	2.5	2.5	2.5

Among the treatments, T9 (raised bed configuration with 100% PE and 100% RDF) consistently showed the highest gross returns, net returns, and profitability across both years and pooled data. In the 2022 to 23 season, the gross returns under T9 were ₹11,65,862/ha, which slightly declined to ₹11,27,857/ha in 2023-24, resulting in a pooled gross return of ₹11,46,859.7/ha. Net returns for the same treatment were ₹7,55,418/ha and ₹7,19,330/ha for the respective years, pooling to ₹7,37,373.7/ha, reflecting the overall best performance. The higher returns can be attributed to better growth and yield outcomes under the raised bed configuration with optimal fertigation and irrigation, enhancing flower quality and quantity. Similarly, T6 (raised bed configuration with 75% PE and 100% RDF fertigation) also exhibited robust economic performance, with pooled gross returns of ₹10,52,757.6/ha and pooled net returns of ₹6,64,819.9/ha. Although slightly lower than T9, this treatment still demonstrated substantial profitability due to efficient water and nutrient management, making a next best alternative after T9. In contrast, the treatments with lower irrigation levels and fertigation rates, such as T10 (flatbed configuration with 50%PE and 50% RDF), recorded the lowest returns. In 2022 to 23, the gross returns for T10 were ₹7,29,812/ha, which increased to ₹8,18,388/ha in 2023-24, yielding a pooled gross return of ₹7,74,100.2/ha. Due to lower flower yield and quality under least irrigation and fertigation, net returns for this treatment remained considerably lower, with pooled net returns of ₹4,53,807.4/ha.

In raised bed treatments, the highest pooled B:C ratio was observed in T9 (raised bed with 100%PE and 100% RDF), which recorded a ratio of 2.8. This high value reflects the combined benefits of increased water and nutrient availability along with raised bed configuration, leading to better yields and profitability. The strong performance of the T9 treatment highlights the importance of optimizing irrigation and fertigation levels for maximum returns. The treatment T6 also showed a strong pooled B:C ratio of 2.7 followed by T9. This treatment (raised bed with 75%PE and 100% RDF) was the second-best option, reinforcing the trend that higher input levels, when managed efficiently, lead to better profitability. On the other hand, treatments with lower input levels, particularly T10and T13, recorded the lowest B:C ratios, which had a pooled B:C ratio of 2.4, showing that these configurations was less profitable despite having lower costs of cultivation and these treatments resulted in lower returns compared to treatments with higher fertigation and irrigation inputs. Overall, the results indicate that raised bed configurations combined with higher irrigation levels (75% to 100% of pan evaporation) and fertigation rates (100%RDF) resulted in greater economic viability in tuberose cultivation. Treatments such as T9 and T6 provided the highest net returns due to the enhanced vegetative growth and flower yield, while flatbed configurations with lower inputs, like T10 were less profitable. The pooled data further confirms that the combination of raised bed planting, adequate irrigation, and higher fertigation levels is crucial for maximizing tuberose profitability. These findings align with previous studies stating that drip irrigation with 60% cumulative pan evaporation (CPE) water and 80% water solubilizing fertilizer (WSF) demonstrated superior results in gladiolus, with cost economics analysis of substantial net returns (Rs. 630260.72 per ha) and a favorable benefit-cost ratio (2.51) (Yadav *et al*. 2020). Treatments with lower fertigation and irrigation levels, particularly those using flatbed configurations, resulted in lower economic returns due to reduced yield. Conversely, economic analysis revealed that higher moisture regimes resulted in higher net returns but lower benefit-cost ratios. Despite higher moisture levels promoting certain growth aspects, the economic yield of tuberose was not optimal, leading to lower returns compared to lower moisture regimes (Khanam *et al*. 2017). Pal *et al.* (2019) reported similar findings in their studies on tuberose economics.

The findings emphasize the importance of optimizing both water and nutrient management through drip irrigation and fertigation to enhance the sustainability and profitability of tuberose cultivation, especially in water-scarce regions. This research provides a practical framework for farmers and policymakers to implement efficient irrigation and fertigation schedules, ultimately contributing to improved resource use and increased profitability in tuberose cultivation.

CONCLUSIONS

1. The study demonstrated that drip irrigation and fertigation, particularly with raised beds, significantly enhanced the growth, yield, water productivity, and economic returns of tuberose by improving soil aeration and moisture retention.
2. The combination of raised beds, irrigation at 100% pan evaporation (PE), and fertigation at 100% recommended dose of fertilizers (RDF) yielded the highest flower production, water productivity, and economic returns. However, irrigation at 75% PE was nearly on par with 100% PE, offering a more water-efficient option without compromising yield.
3. The combination of raised beds, 100% PE, and 100% RDF (T3) was the best treatment for maximizing yield and water productivity, while also delivering the highest net returns and benefit-cost ratio.

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APPENDIX

Table A1. Flower Yield of Tuberose (*Polianthes tuberosa* L.) Under Different Land Configurations, Irrigation, and Fertigation Regimes During 2022 to 2023, 2023 to 2024, and Pooled Data

Treatments	2022-23	2023-24	Pooled Data
T1	14.5	15.5	15.0
T2	16.0	16.5	16.2
T3	16.5	16.4	16.5
T4	15.1	16.1	15.6
T5	16.9	16.7	16.8
T6	19.3	18.8	19.1
T7	15.8	16.3	16.0
T8	17.3	17.1	17.2
T9	21.8	17.2	19.5
T10	13.2	13.7	13.5
T11	14.2	14.4	14.3
T12	15.0	14.8	14.9
T13	13.6	14.0	13.8
T14	15.3	14.9	15.1
T15	16.1	15.5	15.8
T16	14.4	14.6	14.5
T17	15.6	15.3	15.5
T18	16.5	15.3	15.9