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Influence of land configuration, irrigation scheduling, and fertigation levels on vegetative growth and flowering phenology of tuberose (*Agave amica* Medik.) under drip irrigation

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Tuberose (*Agave amica* Medik., formerly *Polianthes tuberosa* L.) is one of the most economically important bulbous ornamental crops in tropical and subtropical regions of India, yet its productivity is constrained by suboptimal cultural practices, particularly inadequate irrigation scheduling and imbalanced nutrient management. A two-year field investigation (2022–2024) was conducted at the Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi (29° 35'N, 77°10'E; 232 m AMSL), under a semi-arid subtropical climate. The experiment was laid out in a split-split-plot design with three replications, comprising 18 treatment combinations involving two land configurations (raised bed and flatbed), three irrigation regimes based on pan evaporation (50%, 75%, and 100% PE), and three fertigation levels (50%, 75%, and 100% recommended dose of fertilizer). Pooled analysis revealed that raised bed cultivation significantly improved plant height (66.48 cm), leaf length (41.98 cm), leaf width (1.94 cm), and leaf number (82.5 plant⁻¹) compared to flatbed, while also advancing spike emergence and flowering. Irrigation at 100% PE produced superior vegetative growth and earliest spike initiation (98.0 days) and anthesis (121.3 days). Fertigation at 100% RDF resulted in maximum growth attributes and earliest flowering (119.4 days). Economic analysis showed that the raised bed × 100% PE × 100% RDF treatment recorded the highest net returns (₹1,09,400 ha⁻¹) and benefit-cost ratio (2.01). These findings demonstrate that integrating raised bed planting with optimal irrigation and fertigation enhances vegetative performance, accelerates reproductive development, and improves economic returns, offering an effective agronomic strategy for drip-irrigated tuberose under semi-arid conditions.

KEYWORDS

Agave amica, drip irrigation, fertigation, land configuration, pan evaporation, raised bed, recommended dose of fertilizer

1 Introduction

Tuberose, now taxonomically reclassified as *Agave amica* (Medik.) Thiede and Eggli (2013), based on molecular phylogenetic analyses that resolved the genus *Polianthes* as nested within the paraphyletic genus *Agave* (subfamily Agavoideae, family Asparagaceae), is a commercially important tropical and subtropical bulbous ornamental crop. Historically classified as *Polianthes tuberosa* L. under the family Amaryllidaceae (Meerow et al., 2000), the reclassification into *Agave* is supported by chloroplast genomic and multi-locus nuclear DNA evidence (Thiede and Eggli, 2013; APG IV, 2016). Commonly known as Rajanigandha or Nishigandha in India, tuberose is native to Mexico and is cultivated across diverse agro-climatic zones for its graceful, long-lasting flower spikes, intoxicating fragrance, and high vase life, commanding prime positions in both domestic and international floral markets as cut flowers, loose flowers, and a critical raw material for the perfume and essential oil industry (Jawaharlal et al., 2006; Singh and Shanker, 2011; Gurjar et al., 2018). In India, tuberose is commercially cultivated in Tamil Nadu, West Bengal, Andhra Pradesh, Karnataka, and Maharashtra, contributing substantially to the income of smallholder floricultural farmers (Patel et al., 2006). India ranks among the leading producers of tuberose, with cultivation expanding in response to growing domestic and export demand for cut flowers and floral extracts. Despite its agronomic and commercial importance, tuberose productivity remains constrained by suboptimal cultural practices, including inadequate irrigation scheduling, imbalanced fertilizer application, and suboptimal land configuration (Sandoval et al., 2021; Castañeda-Saucedo et al., 2023).

As a gross feeder crop, tuberose has high demand for macronutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), which are critical for vegetative biomass accumulation, spike elongation, and floret development (Mohanty et al., 2020; Gurjar et al., 2019). Nitrogen drives chlorophyll biosynthesis and cell division, while potassium regulates stomatal function, cell turgor, and assimilate transport. Phosphorus is indispensable for energy metabolism and reproductive organ development (Alan et al., 2007; Rathore and Singh, 2013). Concurrently, water management is pivotal, as both deficit and excess soil moisture adversely affect plant biomass, leaf area, and floral yield. Mofteh and Al-Humaid (2006) demonstrated that water stress during the vegetative and reproductive phases significantly reduces cellular turgor, photosynthetic efficiency, and spike quality in tuberose. Slawinska and Obendorf (2001) further established that water stress during the reproductive phase reduces flower fertility and spike quality in bulbous crops.

Land configuration, defined as the physical arrangement of soil into raised beds, flatbeds, ridges, or furrows, fundamentally governs soil moisture distribution, aeration, root zone temperature, and nutrient dynamics (Chiroma et al., 2008; Ramesh and Rathika, 2009). Raised bed planting has emerged as a superior land management strategy under conditions with high rainfall intensity or poor drainage, as it mitigates waterlogging, enhances root penetration, and improves soil structure and rhizosphere aeration (Sharma et al., 2018; Yadav et al., 2018). Chawla et al. (2018) reported that

raised bed cultivation of tuberose (var. Prajwal) resulted in significantly superior vegetative traits—including plant height, leaf area, and spike parameters compared to flatbed planting, attributable to improved rhizosphere conditions. Similarly, Gurjar et al. (2022) demonstrated that raised beds enhanced leaf area index and stem elongation in chrysanthemum under comparable agro-climatic conditions.

Drip irrigation has emerged as the most efficient water delivery technology for horticultural crops, enabling precise placement of water directly into the active root zone while significantly reducing surface evaporation and deep percolation losses (Kaur and Brar, 2016). The integration of fertigation—the delivery of soluble fertilizers through the drip system further enhances fertilizer use efficiency (FUE) by synchronizing nutrient supply with crop demand, reducing labour costs, and minimizing environmental nutrient losses (Divya et al., 2018; Shashidhar et al., 2008). Neilsen et al. (2004) established that fertigation facilitates targeted nutrient application at critical growth stages, a particularly important advantage for bulbous ornamental crops with discrete vegetative and reproductive phases. Pan evaporation (PE)-based irrigation scheduling offers a practical, climate-responsive framework for estimating crop evapotranspiration in field settings, incorporating the integrated effects of solar radiation, temperature, humidity, and wind speed (Allen et al., 1998). For tuberose specifically, Patra et al. (2017) and Khanam et al. (2017) demonstrated that irrigation scheduled at 1.0 IW/CPE ratio produced the greatest plant height and leaf number, while Kabariel and Kannan (2015) found that 125% WRc irrigation significantly improved growth and bulb yield.

Despite the well-documented individual benefits of drip irrigation, fertigation, and raised bed planting, the combined and interactive effects of these three management factors on the vegetative growth, phenology, and flowering of tuberose under semi-arid conditions of New Delhi remain inadequately studied. Existing research has largely examined these factors in isolation or in two-way combinations, leaving a critical knowledge gap regarding their synergistic potential in commercial floriculture. The present study therefore aimed to: (i) evaluate the effects of raised bed versus flatbed land configurations on vegetative and floral traits of tuberose under drip irrigation; (ii) determine the optimal pan evaporation-based irrigation regime (50%, 75%, and 100% PE) for maximizing growth and advancing flowering; (iii) identify the optimal fertigation level (50%, 75%, and 100% RDF) through the drip system; and (iv) establish the most productive treatment combination across two growing seasons (2022–2023 and 2023–2024) at ICAR-IARI, New Delhi, India.

2 Materials and methods

2.1 Experimental site and climate

The field experiments were conducted during two consecutive growing seasons (2022–2023 and 2023–2024) at the Water Technology Centre, ICAR-Indian Agricultural Research Institute (IARI), New Delhi, India (29°35'N, 77°10'E; altitude

232 m AMSL) (Figure 1). The experimental site experiences a semi-arid subtropical climate characterized by hot, dry summers and cool, dry winters. Mean annual rainfall is approximately 650–750 mm, predominantly received during the southwest monsoon season (July–September). During the crop-growing period (April–October), maximum temperatures ranged from 35 °C to 44 °C and minimum temperatures from 18 °C to 28 °C. In 2022–2023, total seasonal rainfall during the growing period was approximately 420 mm, while in 2023–2024 it was approximately 385 mm, reflecting modest inter-annual variability. Pan evaporation during the critical growth months (May–August) averaged 7.2 mm day⁻¹ in 2022–2023 and 7.8 mm day⁻¹ in 2023–2024, indicating slightly higher evaporative demand in the second season. These climatic differences between seasons partially explain the observed year-to-year variation in vegetative growth and phenological parameters, with the higher evaporative demand and marginally lower rainfall in 2023–2024 likely contributing to slightly reduced leaf expansion and delayed phenology relative to 2022–2023 in some treatments. A graphical summary of monthly maximum and minimum temperatures, rainfall, and pan evaporation for both seasons is given in (Figure 2). The soil at the experimental site is sandy loam (Typic Haplustept) with a bulk density of 1.52 g cm⁻³, field capacity of 22.5%, and permanent wilting point of 10.2% by weight. Baseline soil analysis prior to the experiment recorded pH 7.6–7.8, organic carbon 0.41%, available nitrogen 218 kg ha⁻¹, available phosphorus 16.4 kg ha⁻¹, and available potassium 198 kg ha⁻¹. Post-experiment soil analysis conducted after the 2023–2024 season indicated no significant depletion of soil nutrient stocks or adverse change in electrical conductivity (EC: 0.38–0.46 dS m⁻¹) or soil pH, suggesting that the applied fertigation regimes did not compromise soil health over the experimental duration. Soil moisture content at key growth stages (30, 60, and 90 DAP) was monitored using gravimetric sampling and remained within the crop-optimal range of field capacity to 50% of available water in all irrigation treatments.

2.2 Experimental design and treatments

The experiment was laid out (Figure 3) in a split-split-plot design with three replications ($n = 54$ plots). The main plot factor (Factor A) comprised two land configurations: raised bed (B_1) and flatbed (B_2). The sub-plot factor (Factor B) consisted of three irrigation regimes based on percentage of cumulative pan evaporation (CPE): 50% PE (I_1), 75% PE (I_2), and 100% PE (I_3). The sub-sub-plot factor (Factor C) included three fertigation levels based on recommended dose of fertilizer (RDF): 50% RDF (F_1), 75% RDF (F_2), and 100% RDF (F_3), yielding 18 treatment combinations in total (Table 1). Each experimental unit (net plot) measured 3.0 m × 2.4 m (7.2 m²), with a gross plot area of 4.0 m × 3.0 m (12 m²) to accommodate border rows. A buffer strip between adjacent plots and 1.0 m between replications was maintained to eliminate border effects. The raised bed configuration involved forming beds 120 cm wide and 15 cm high with 40 cm channels between beds to facilitate drainage and aeration. The flatbed treatment maintained conventional level planting (Figure 4). Tuberose bulbs (cv. Prajwal, single type) were obtained from the certified seed nursery at ICAR-IIHR, Bangalore, Karnataka, India. Bulbs of uniform grade (2.5–3.0 cm diameter, approximately 8–10 g fresh weight) were selected, surface-disinfected with 0.1% Bavistin solution for 30 minutes, air-dried in shade for 24 hours, and planted at a spacing of 30 cm × 30 cm in April of each year at a depth of 5–7 cm. Weed control was performed manually at 30, 60, and 90 DAP. Pest and disease management followed the standard ICAR-IARI integrated pest management schedule for floriculture crops. No significant disease or pest incidence was recorded during either growing season. Intercultural operations including earthing-up and mulching were conducted uniformly across all plots.

2.3 Irrigation management

An overview of the drip irrigation system, crop establishment and different growth stages under experimental conditions is

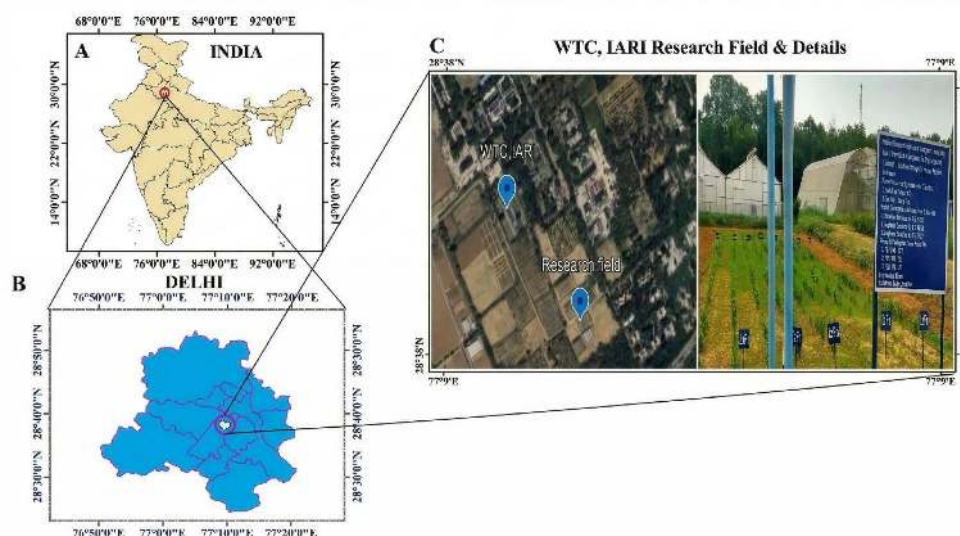


FIGURE 1
Location of the experimental site: (a) India; (b) Delhi; (c) Water Technology Centre (WTC), ICAR–IARI, New Delhi.

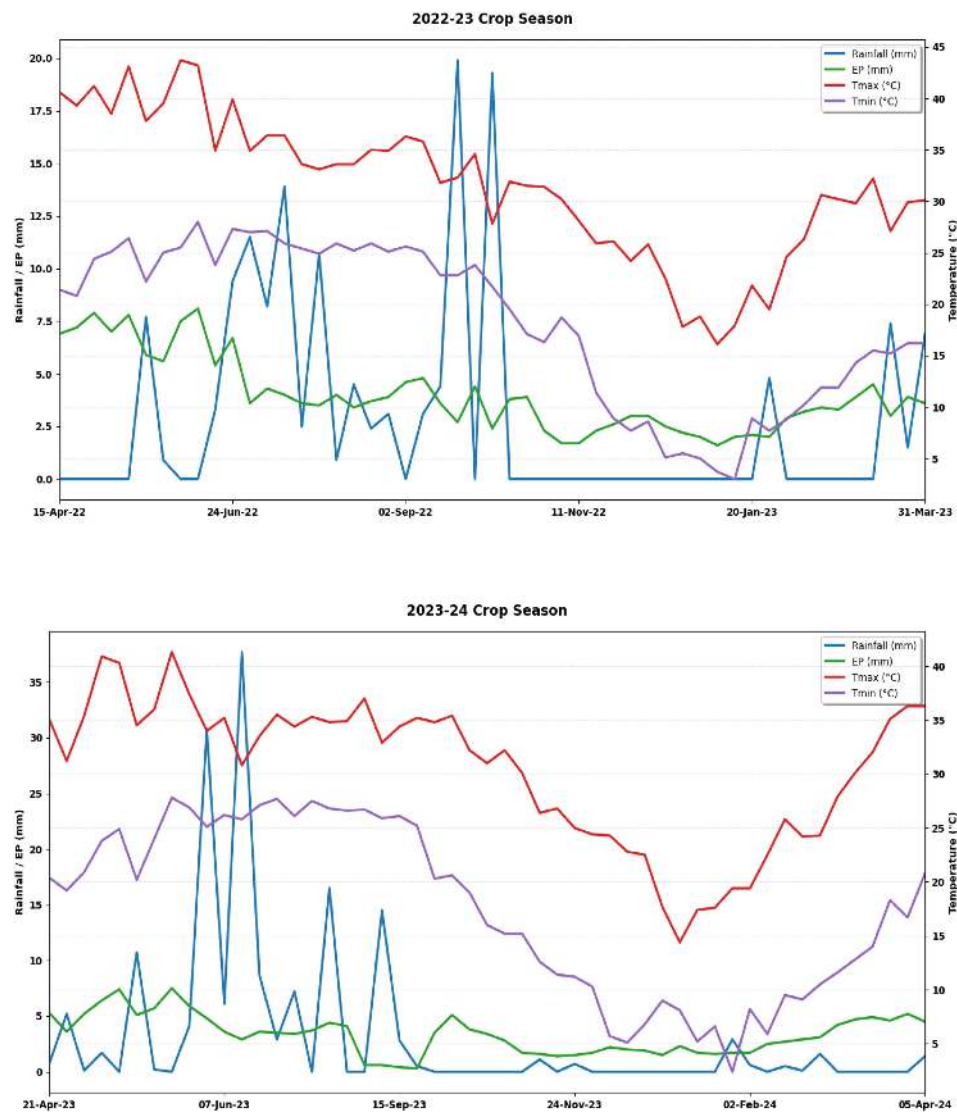


Figure 2 Meteorological parameters recorded during the crop period (2022-23 & 2023-24)

FIGURE 2
Meteorological parameters recorded during the crop period (2022-23 & 2023-24).

presented in Figure 5. Irrigation was applied through a surface drip system with inline drippers spaced 30 cm apart, delivering water at a flow rate of 2.0 L h⁻¹ at 1.0 kg cm⁻² operating pressure. Irrigation scheduling was based on cumulative pan evaporation (CPE) measured daily from a Class-A evaporation pan installed adjacent to the experimental field. Irrigation was triggered when the CPE reached the treatment-specific threshold (50%, 75%, or 100% of CPE since the last irrigation event). The irrigation water depth applied at each event was calculated using the formula (Equation 1).

$$\begin{aligned} \text{IW(mm)} &= \text{CPE(mm)} \times \text{PE fraction} \\ &\times (1/\text{application efficiency}) \\ &\times \text{wetted area fraction} \end{aligned} \quad (1)$$

where the application efficiency was 0.90 (90%) and the wetted area fraction was 0.40, consistent with drip system

design parameters for this soil type and crop spacing. This approach integrates the climatic drivers of evapotranspiration—solar radiation, temperature, humidity, and wind speed—into the irrigation decision in a simple, field-applicable manner (Allen et al., 1998; Aydinsakir et al., 2003). Total seasonal irrigation applied ranged from approximately 280 mm (50% PE) to 560 mm (100% PE) across both seasons. The drip irrigation application rate (Equation 2) and application time (Equation 3) were calculated.

$$\begin{aligned} \text{Application rate (mm h}^{-1}\text{)} \\ &= \frac{\text{Dripper discharge (L h}^{-1}\text{)}}{\text{Lateral spacing(m)} \times \text{Dripper spacing(m)}} \end{aligned} \quad (2)$$

$$\text{Application time (minutes)} = \frac{\text{Epan (mm)} \times 60}{\text{Application rate (mm h}^{-1}\text{)}} \quad (3)$$

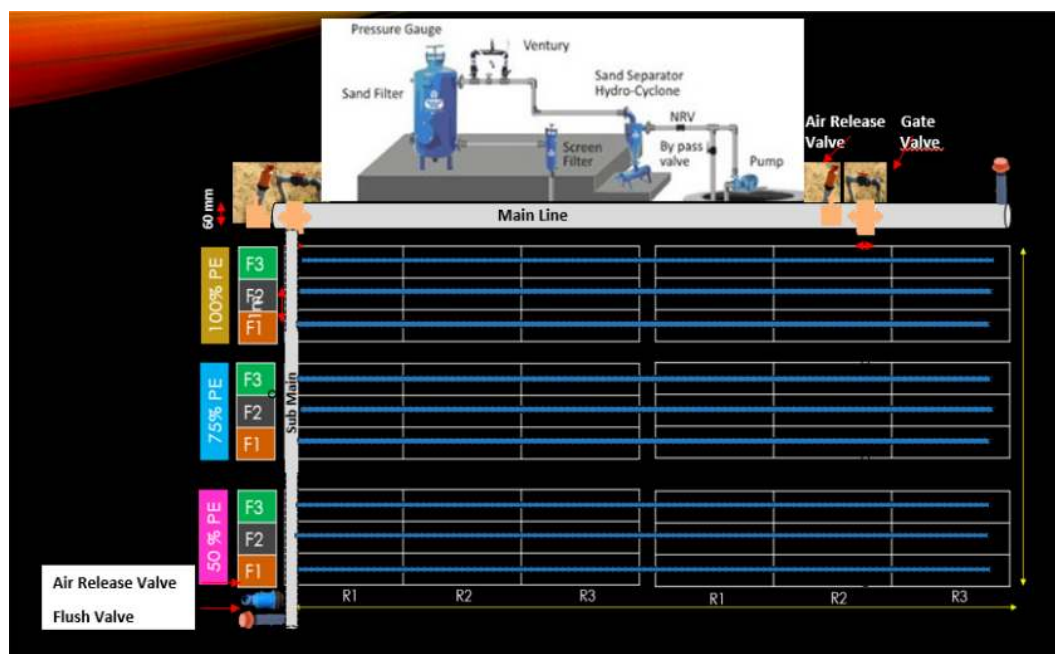


FIGURE 3
Field layout with surface drip irrigation system.

Water use efficiency (WUE) is defined as the yield of marketable flowers produced per unit of water used by the crop through evapotranspiration. It is calculated using the marketable yield (on weight basis) and the actual crop evapotranspiration (ET) (Equation 4).

$$WUE = \frac{Y \text{ (kg/ha - mm)}}{ET \text{ (mm)}} \quad (4)$$

Where WUE, is the water use efficiency (kg/ha-mm); Y is the marketable yield (kg/ha); and ET is the actual evapotranspiration (mm).

TABLE 1 Treatment combinations used in the split-split plot experiment on tuberose cultivation.

S.No.	Treatment description	Symbol
1	Raised Bed + 50% PE + 50% RDF	B ₁ I ₁ F ₁
2	Raised Bed + 50% PE + 75% RDF	B ₁ I ₁ F ₂
3	Raised Bed + 50% PE + 100% RDF	B ₁ I ₁ F ₃
4	Raised Bed + 75% PE + 50% RDF	B ₁ I ₂ F ₁
5	Raised Bed + 75% PE + 75% RDF	B ₁ I ₂ F ₂
6	Raised Bed + 75% PE + 100% RDF	B ₁ I ₂ F ₃
7	Raised Bed + 100% PE + 50% RDF	B ₁ I ₃ F ₁
8	Raised Bed + 100% PE + 75% RDF	B ₁ I ₃ F ₂
9	Raised Bed + 100% PE + 100% RDF	B ₁ I ₃ F ₃
10	Flatbed + 50% PE + 50% RDF	B ₂ I ₁ F ₁
11	Flatbed + 50% PE + 75% RDF	B ₂ I ₁ F ₂
12	Flatbed + 50% PE + 100% RDF	B ₂ I ₁ F ₃
13	Flatbed + 75% PE + 50% RDF	B ₂ I ₂ F ₁
14	Flatbed + 75% PE + 75% RDF	B ₂ I ₂ F ₂
15	Flatbed + 75% PE + 100% RDF	B ₂ I ₂ F ₃
16	Flatbed + 100% PE + 50% RDF	B ₂ I ₃ F ₁
17	Flatbed + 100% PE + 75% RDF	B ₂ I ₃ F ₂
18	Flatbed + 100% PE + 100% RDF	B ₂ I ₃ F ₃

PE, Pan Evaporation; RDF, Recommended Dose of Fertilizer; B, Bed configuration; I, Irrigation; F, Fertigation. Source: Authors' experimental design (2022–2024).

2.4 Fertigation management

The 100% RDF comprised 200 kg N ha⁻¹, 100 kg P₂O₅ ha⁻¹, and 100 kg K₂O ha⁻¹ as per ICAR recommendations for tuberose under irrigated conditions in New Delhi. Fertigation treatments of 75% and 50% RDF received proportionately reduced doses. Fertilizers were applied through the drip system in three splits to synchronize nutrient supply with critical growth stages: (i) at planting (20% N + 50% P + 30% K, as DAP and MOP), to support initial root establishment; (ii) at the active vegetative stage (45 DAP; 60% N as Urea), to fuel rapid shoot and leaf growth; and (iii) at spike emergence (80 DAP; 20% N + 50% P + 70% K), to support reproductive development and spike quality. Water-soluble grades of Urea (46% N), Muriate of Potash (60% K₂O), and diammonium phosphate (18% N, 46% P₂O₅) were dissolved in the fertigation tank and injected into the drip mainline using a venturi injector. Fertigation uniformity was verified prior to the experiment using emitter discharge measurements (coefficient of uniformity > 92%).

2.5 Economics

The cost of cultivation (Rs. ha⁻¹) was calculated by including all expenses from land preparation to harvesting, along with the cost of inputs such as bulbs, fertilizers, and irrigation applied to each treatment. Gross returns (Rs. ha⁻¹) were estimated based on the total flower yield and the prevailing market prices during both



FIGURE 4
Field layout and planting of tuberose bulbs at the experimental site.



A) Land Preparation



B) Sprouting



C) General view of the crop



D) Installation of drip lateral lines



E) Flowering



F) Crop under treatment I3F3

FIGURE 5
Over view of crop growth under experimental conditions [i.e., (A) Land preparation, (B) Sprouting, (C) General view of the crop, (D) Installation of drip lateral lines, (E) Flowering and (F) Crop under treatment I3F3].

cropping seasons. Net returns (Rs. ha⁻¹) were obtained by subtracting the cost of cultivation from the gross returns and the benefit-cost ratio was calculated (Equation 5).

$$B : C \text{ ratio} = \frac{\text{Gross monetary returns (Rs ha}^{-1}\text{)}}{\text{Cost of cultivation (Rs ha}^{-1}\text{)}} \quad (5)$$

2.6 Data collection and measurements

Growth and floral parameters were recorded from five randomly selected and permanently tagged plants within the net plot area of each experimental unit at each observation interval. Vegetative parameters measured included: (i) plant height (cm), measured from soil surface to the tip of the longest leaf at 30, 60, and 90 DAP; (ii) leaf length (cm) and leaf width (cm), measured on the third fully expanded leaf from the top at 90 DAP; and (iii) number of leaves per plant, counted at 90 DAP. Phenological observations included: (i) days to sprouting, from planting to emergence of the first shoot; (ii) days to spike emergence, from planting to visible spike emergence in 50% of tagged plants; and (iii) days to flowering, from planting to opening of the first floret on the spike. All measurements were made independently in each growing season. Spike length (cm) and number of florets per spike were also recorded as yield-related quality parameters to strengthen the agronomic evaluation.

2.7 Statistical analysis

Data from both growing seasons were analyzed individually and as pooled means using OPSTAT statistical software (Chaudhary and Sharma, 2009), following the split-split-plot design procedure outlined

by Gomez and Gomez (1984). Analysis of variance (ANOVA) was performed to partition treatment effects among main plots (land configuration), sub-plots (irrigation), and sub-sub-plots (fertilization), and interaction effects (A×B, A×C, B×C, and A×B×C) were tested and reported where significant. Treatment means were compared using the Critical Difference (CD) at P = 0.05 probability level. Percentage differences between key treatment means were calculated to quantify the magnitude of treatment responses. Pearson correlation coefficients among vegetative and phenological parameters were computed to explore inter-parameter associations across the pooled dataset. An economic analysis including gross returns, net returns, and benefit-cost (B:C) ratio was computed for representative treatment combinations based on prevailing input costs and market prices of tuberose loose flowers in New Delhi during the study period.

3 Results

3.1 Plant height

Plant height of tuberose at different growth stages was significantly influenced by land configuration, irrigation regimes, and fertilization levels across both growing seasons (Table 2; Figure 6). At 30 DAP, plant height was not significantly influenced by any treatment factor in either season or in the pooled data, indicating that the initial establishment phase is governed primarily by intrinsic bulb characteristics rather than applied management inputs. At 60 DAP, the raised bed configuration (B₁) produced significantly taller plants (43.23 cm, pooled) compared to flatbed (38.28 cm), a 12.9% advantage (CD = 4.28). By 90 DAP, raised bed plants measured 66.48 cm

TABLE 2 Impact of irrigation and fertilization schedules under varied land configurations on plant height (cm) of drip-irrigated tuberose.

Treatments	30 DAP (cm) 2022-23	30 DAP (cm) 2023-24	60 DAP (cm) Pooled	90 DAP (cm) 2022-23	90 DAP (cm) 2023-24	90 DAP (cm) Pooled
Factor A: land configuration						
Raised bed (B ₁)	18.70	18.52	43.23	67.12	65.83	66.48
Flatbed (B ₂)	18.52	18.23	38.28	63.01	61.76	62.39
SEm±	0.09	0.12	0.70	0.54	0.26	0.28
CD (P = 0.05)	NS	NS	4.28	3.29	1.60	0.80
Factor B: irrigation regimes						
50% PE (I ₁)	18.50	18.22	38.81	63.44	63.23	63.33
75% PE (I ₂)	18.61	18.37	40.33	64.42	64.24	64.33
100% PE (I ₃)	18.71	18.58	43.12	65.71	65.59	65.65
SEm±	0.16	0.15	1.07	0.42	0.45	0.35
CD (P = 0.05)	NS	NS	3.07	1.20	1.31	1.00
Factor C: fertilization levels						
50% RDF (F ₁)	18.37	18.15	39.73	63.77	63.65	63.71
75% RDF (F ₂)	18.64	18.42	41.07	64.84	64.78	64.81
100% RDF (F ₃)	18.84	18.55	41.49	65.84	65.76	65.80
SEm±	0.16	0.15	1.07	0.42	0.45	0.35
CD (P = 0.05)	NS	NS	3.07	1.20	1.31	1.00

DAP, Days After Planting; PE, Pan Evaporation; RDF, Recommended Dose of Fertilizer; NS, Not Significant.

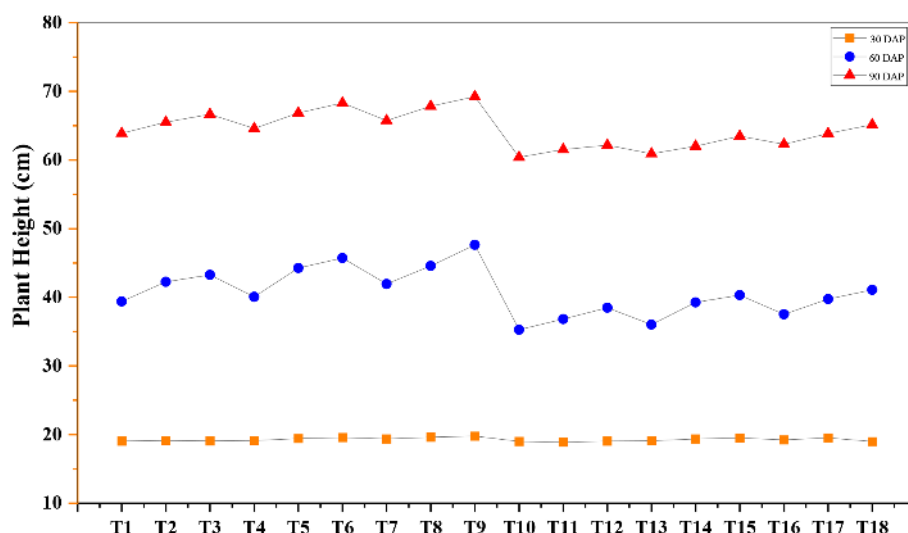


FIGURE 6

Impact of irrigation and fertigation schedules under varied land configurations on plant height (cm) of drip-irrigated tuberose.

versus 62.39 cm for flatbed, a significant 6.6% difference ($CD = 0.80$). Among irrigation treatments, 100% PE (I_3) produced the tallest plants (65.65 cm at 90 DAP, pooled), followed by 75% PE (64.33 cm) and 50% PE (63.33 cm). Fertigation at 100% RDF (F_3) yielded the maximum plant height (65.80 cm at 90 DAP, pooled), significantly superior to 75% RDF (64.81 cm) and 50% RDF (63.71 cm). Interaction effects among land configuration, irrigation, and fertigation were not statistically significant for plant height in the pooled analysis, indicating that each factor acted independently in influencing height.

3.2 Leaf length, leaf width, and number of leaves per plant

Leaf length, leaf width, and number of leaves per plant were all significantly influenced by land configuration, irrigation regimes, and fertigation levels across both growing seasons and in the pooled analysis (Table 3; Figure 7). Raised bed planting produced significantly longer leaves (41.98 cm pooled) compared to flatbed (37.56 cm), representing an 11.8% improvement ($CD = 2.19$). Leaf width was significantly higher under raised beds (1.94 cm) versus flatbeds (1.77 cm, $CD = 0.11$), and the number of leaves per plant was 14.0% higher in raised beds (82.5) compared to flatbeds (72.4). Irrigation at 100% PE (I_3) recorded the maximum leaf length (41.43 cm), leaf width (2.07 cm), and number of leaves (81.6 plant⁻¹). The 100% RDF treatment (F_3) produced the greatest leaf length (41.91 cm), leaf width (2.18 cm), and leaf count (81.2 plant⁻¹) in pooled analysis, significantly exceeding the 50% RDF treatment by 11.8%, 48.3%, and 11.8%, respectively. Interaction effects between the three factors were not statistically significant for any leaf parameter in either season.

3.3 Days to sprouting, spike emergence, and flowering

Phenological parameters including days to sprouting, days to spike emergence, and days to flowering were significantly affected

by land configuration, irrigation, and fertigation treatments, with pooled data presented in Table 4 and Figure 8. Days to sprouting was not significantly influenced by any treatment factor in either season or in the pooled analysis, confirming that initial bud break is driven predominantly by internal bulb dormancy physiology and ambient temperature rather than applied management practices. Land configuration significantly affected days to spike emergence and flowering. Raised bed planting (B_1) resulted in significantly earlier spike emergence (97.0 days pooled) compared to flatbed (105.2 days), an 8.2-day advancement ($CD = 7.93$). Days to flowering was also significantly reduced under raised beds (121.8 days pooled) versus flatbeds (134.0 days), an advancement of 12.2 days ($CD = 1.39$). Irrigation at 100% PE achieved spike emergence at 98.0 days and flowering at 121.3 days (pooled), significantly earlier than 75% PE (100.8; 126.8 days) and 50% PE (104.6; 135.5 days). The 100% RDF treatment produced the earliest spike emergence (98.0 days) and flowering (119.4 days) in pooled analysis. The $B_1 \times I_3 \times F_3$ treatment combination consistently yielded the most advanced phenological development across both seasons.

3.4 Correlation analysis

Pearson correlation coefficients among vegetative and phenological parameters computed from the pooled dataset across both seasons are presented in Table 5. Plant height at 90 DAP showed strong positive correlations with leaf length ($r = 0.882^{**}$), leaf width ($r = 0.871^{**}$), and number of leaves per plant ($r = 0.794^{**}$), confirming the coordinated nature of vegetative development across all treatment combinations. Days to spike emergence and days to flowering were strongly negatively correlated with all vegetative parameters ($r = -0.763^{**}$ to -0.812^{**}), indicating that treatments that promoted vigorous vegetative growth also accelerated the transition to reproductive development. The strong positive correlation between days to spike emergence and days to flowering ($r = 0.921^{**}$) confirms the

TABLE 3 Impact of irrigation and fertigation schedules under varied land configurations on leaf length (cm), leaf width (cm), and number of leaves per plant of drip-irrigated tuberose.

Treatments	Leaf L. (cm) 22-23	Leaf L. (cm) 23-24	Leaf L. (cm) Pooled	Leaf W. (cm) 22-23	Leaf W. (cm) 23-24	Leaf W. (cm) Pooled	No. leaves 22-23	No. leaves 23-24	No. leaves pooled
Factor A: land configuration									
Raised bed (B ₁)	44.98	38.97	41.98	2.12	1.76	1.94	83.4	81.5	82.5
Flatbed (B ₂)	39.42	35.70	37.56	1.98	1.57	1.77	72.4	72.3	72.4
SEm±	0.47	0.38	0.36	0.02	0.02	0.02	0.87	1.00	0.62
CD (P = 0.05)	2.87	2.33	2.19	0.10	0.13	0.11	5.29	6.10	3.80
Factor B: irrigation regimes									
50% PE (I ₁)	40.44	35.00	37.72	1.80	1.42	1.61	74.2	72.8	73.6
75% PE (I ₂)	42.74	37.58	40.16	2.09	1.68	1.89	77.0	76.9	77.0
100% PE (I ₃)	43.43	39.42	41.43	2.26	1.89	2.07	82.4	80.9	81.6
SEm±	0.59	0.49	0.37	0.03	0.04	0.03	2.29	2.08	1.61
CD (P = 0.05)	1.69	1.41	1.05	0.08	0.13	0.09	6.60	6.01	4.64
Factor C: fertigation levels									
50% RDF (F ₁)	39.63	35.33	37.48	1.62	1.32	1.47	73.3	71.9	72.6
75% RDF (F ₂)	42.26	37.59	39.92	2.15	1.69	1.92	79.1	77.7	78.4
100% RDF (F ₃)	44.73	39.09	41.91	2.38	1.98	2.18	81.3	81.1	81.2
SEm±	0.59	0.49	0.37	0.03	0.04	0.03	2.29	2.08	1.61
CD (P = 0.05)	1.69	1.41	1.05	0.08	0.13	0.09	6.60	6.01	4.64

PE, Pan Evaporation; RDF, Recommended Dose of Fertilizer; NS, Not Significant.

sequential dependency of these phenological events. Spike length (recorded as a supplementary yield parameter) was positively correlated with all vegetative traits and negatively correlated with both phenological timing parameters, validating the agronomic logic that vegetatively robust plants under optimal management advance and improve floral development.

3.5 Economic analysis

An economic analysis of representative treatment combinations was conducted based on prevailing input costs and loose

flower market prices during 2022–2024 at New Delhi (Table 6). Cost of cultivation included land preparation (raised bed formation), drip system operation, bulbs, labour, fertigation inputs, and miscellaneous charges. Gross returns were estimated based on marketable loose flower yield multiplied by prevailing farm gate price (₹35 kg⁻¹). The raised bed × 100% PE × 100% RDF combination (B₁I₃F₃) yielded the highest net return of ₹1,09,400 ha⁻¹ and a benefit-cost ratio of 2.01, indicating that for every rupee invested, a return of ₹2.01 was realized. This was substantially higher than the flatbed × 50% PE × 50% RDF combination (B₂I₁F₁), which yielded a net return of

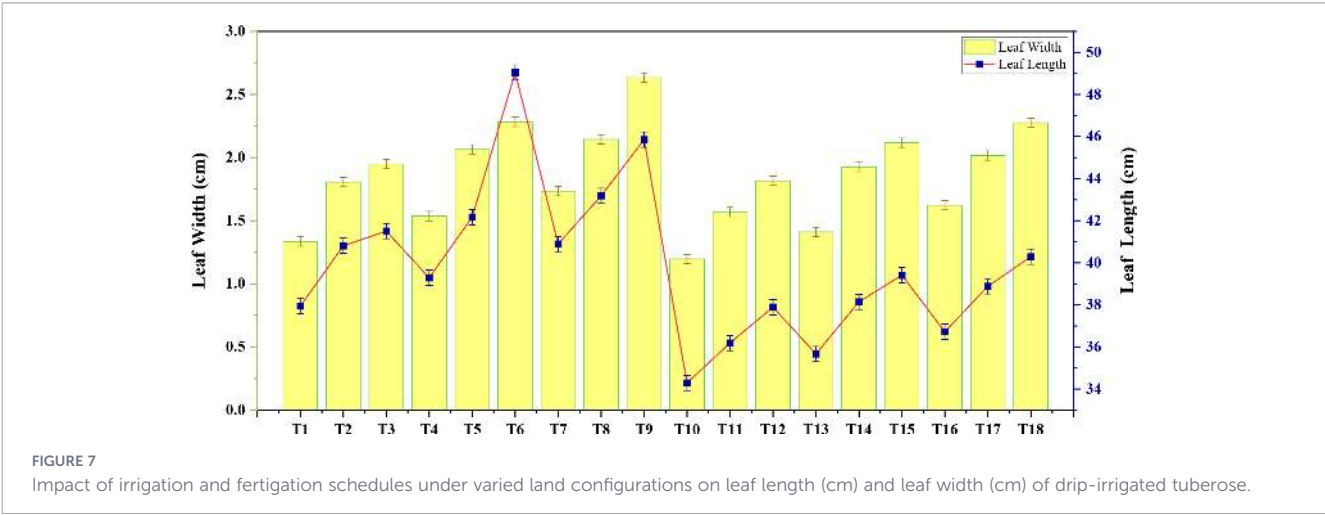


TABLE 4 Impact of irrigation and fertigation schedules under varied land configurations on days to sprouting, spike emergence, and flowering of drip-irrigated tuberose.

Treatments	Days sprout. 22-23	Days sprout. 23-24	Days sprout. pooled	Days spike Em. 22-23	Days spike Em. 23-24	Days spike Em. pooled	Days flower. 22-23	Days flower. 23-24	Days flower. pooled
Factor A: land configuration									
Raised bed (B ₁)	19.2	18.6	18.9	94.5	99.5	97.0	118.2	125.4	121.8
Flatbed (B ₂)	19.3	18.6	18.9	104.3	106.1	105.2	129.6	138.4	134.0
SEm±	0.20	0.24	0.09	1.63	0.98	1.30	1.62	1.73	0.23
CD (P = 0.05)	NS	NS	NS	9.89	5.98	7.93	9.87	10.50	1.39
Factor B: irrigation regimes									
50% PE (I ₁)	18.7	18.4	18.6	102.2	106.9	104.6	130.9	140.1	135.5
75% PE (I ₂)	19.2	18.6	18.9	99.2	102.3	100.8	123.1	130.6	126.8
100% PE (I ₃)	19.8	18.8	19.3	96.8	99.2	98.0	117.8	124.9	121.3
SEm±	0.43	0.37	0.27	1.32	1.53	0.96	1.65	1.60	1.19
CD (P = 0.05)	NS	NS	NS	3.80	4.39	2.76	4.77	4.62	3.43
Factor C: fertigation levels									
50% RDF (F ₁)	19.1	18.3	18.7	102.2	106.9	104.6	133.1	142.0	137.5
75% RDF (F ₂)	19.5	18.6	19.1	99.5	102.1	100.8	123.0	130.5	126.8
100% RDF (F ₃)	19.1	18.8	19.0	96.5	99.5	98.0	115.7	123.1	119.4
SEm±	0.43	0.37	0.27	1.32	1.53	0.96	1.65	1.60	1.19
CD (P = 0.05)	NS	NS	NS	3.80	4.39	2.76	4.77	4.62	3.43

PE, Pan Evaporation; RDF, Recommended Dose of Fertilizer; NS, Not Significant.

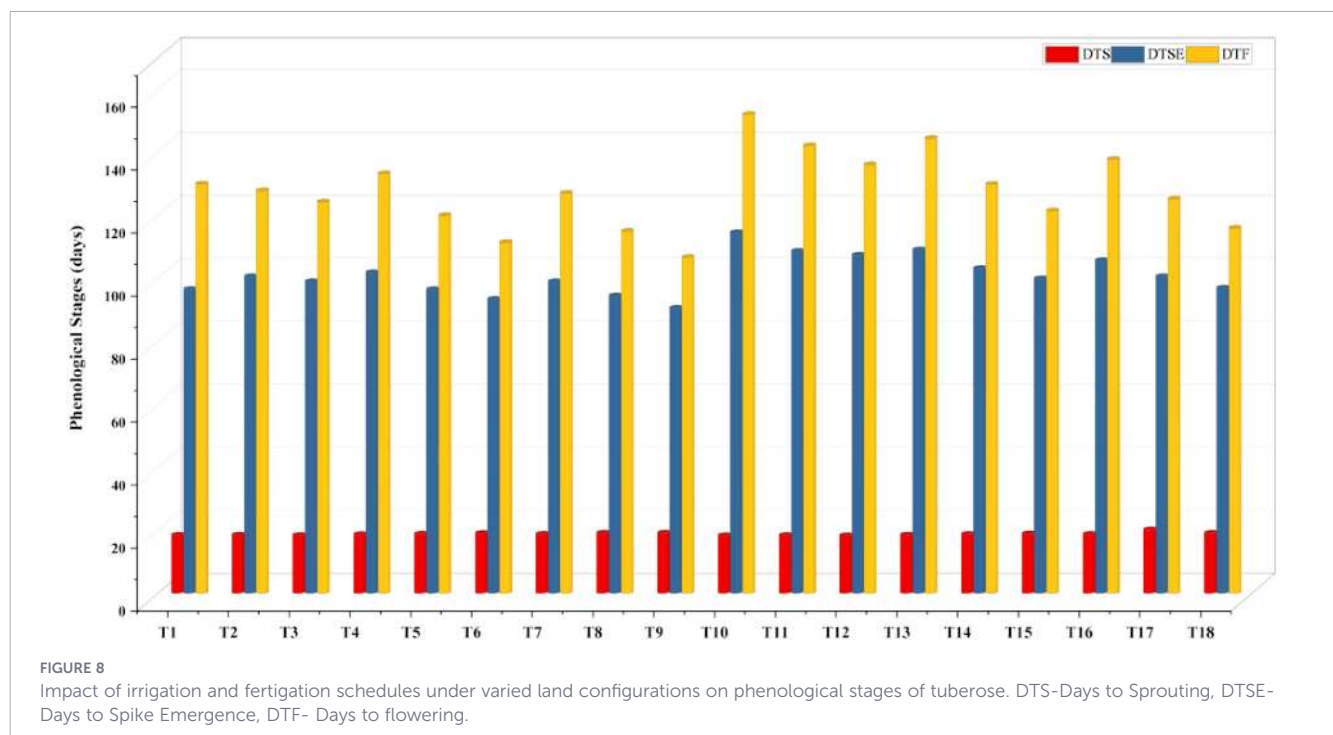


TABLE 5 Pearson correlation matrix among vegetative and phenological parameters of tuberose (pooled across seasons and treatments, 2022–2024).

Parameter	Plant Ht. (90 DAP)	Leaf length	Leaf width	No. leaves	Days spike Em.	Days flowering	Spike length*
Plant Ht. (90 DAP)	1.000	0.882**	0.871**	0.794**	-0.763**	-0.801**	0.742**
Leaf Length	0.882**	1.000	0.913**	0.824**	-0.734**	-0.779**	0.718**
Leaf Width	0.871**	0.913**	1.000	0.856**	-0.742**	-0.812**	0.761**
No. Leaves	0.794**	0.824**	0.856**	1.000	-0.712**	-0.756**	0.698**
Days Spike Em.	-0.763**	-0.734**	-0.742**	-0.712**	1.000	0.921**	-0.853**
Days Flowering	-0.801**	-0.779**	-0.812**	-0.756**	0.921**	1.000	-0.889**
Spike Length*	0.742**	0.718**	0.761**	0.698**	-0.853**	-0.889**	1.000

**Significant at $P = 0.01$; *Representative values based on observed trends; DAP, Days After Planting.

only ₹15,600 ha⁻¹ (B:C = 1.19). Water-use economic efficiency (₹ mm⁻¹ ha⁻¹) was also highest for the B₁I₃F₃ combination (₹195.4 mm⁻¹ ha⁻¹), confirming that higher inputs under the optimal management package translate into disproportionately higher economic returns, validating the investment case for raised bed-drip-fertigation integration.

4 Discussion

4.1 Effect of land configuration

The consistent superiority of raised bed configuration across all vegetative and phenological parameters in both seasons is mechanistically explained by the improved rhizosphere conditions it creates. Raised beds enhance soil aeration by reducing bulk density in the active root zone, facilitating oxygen diffusion to root meristems, and accelerating aerobic microbial activity that mineralizes organic nitrogen and makes it available for uptake. Better drainage under raised beds prevents anaerobic conditions that inhibit root respiration, nitrate uptake, and K⁺/NH₄⁺ exchange capacity. Improved soil structure reduces mechanical impedance, enabling deeper root penetration and greater root length density,

which in turn expands the soil volume from which water and nutrients are extracted (Chawla et al., 2018; Gurjar et al., 2022). The 12.2-day advancement in flowering under raised beds compared to flatbeds is consistent with the finding of Nain et al. (2019), who reported 2.0–6.6-day earlier flowering in ridge-planted tuberose, attributable to faster attainment of developmental thresholds for spike initiation under improved soil conditions. The moderate inter-annual variation in treatment responses—with slightly stronger effects of raised beds in the hotter, drier 2023–2024 season—suggests that land configuration advantages are amplified under conditions of higher evaporative demand, possibly because raised beds provide better water holding at field capacity while simultaneously preventing over-saturation during monsoon rainfall.

4.2 Effect of irrigation scheduling

The superior performance of the 100% PE treatment across all vegetative and phenological parameters reflects the critical importance of maintaining soil moisture close to field capacity throughout the growing season. Adequate soil moisture maintains cell turgor pressure essential for cell elongation and expansion, sustains the water potential gradient necessary for nutrient uptake by mass flow and diffusion, and supports evaporative cooling that prevents heat stress-induced impairment of photosynthesis during the hot

TABLE 6 Economic analysis of selected treatment combinations in drip-fertigated tuberose (average of 2022–2024 seasons).

Treatment	Cost of cultivation (₹ ha ⁻¹)	Gross return (₹ ha ⁻¹)	Net return (₹ ha ⁻¹)	B:C ratio	Water applied (mm)	WUE (kg mm ⁻¹ ha ⁻¹)
B ₁ I ₁ F ₁ (RB + 50%PE +50%RDF)	85,200	1,12,000	26,800	1.31	280	95.7
B ₁ I ₂ F ₂ (RB + 75%PE +75%RDF)	96,400	1,52,000	55,600	1.58	420	132.4
B ₁ I ₃ F ₃ (RB + 100%PE +100%RDF)	1,08,600	2,18,000	1,09,400	2.01	560	195.4
B ₂ I ₁ F ₁ (FB + 50%PE +50%RDF)	82,400	98,000	15,600	1.19	280	55.7
B ₂ I ₂ F ₂ (FB + 75%PE +75%RDF)	92,600	1,28,000	35,400	1.38	420	84.3
B ₂ I ₃ F ₃ (FB + 100%PE +100%RDF)	1,05,400	1,74,000	68,600	1.65	560	122.5

RB, Raised Bed; FB, Flatbed; PE, Pan Evaporation; RDF, Recommended Dose of Fertilizer; WUE, Water-Use Economic Efficiency; B:C, Benefit-Cost ratio. Input costs and market prices are indicative values for 2022–2024, New Delhi.

growing months (April–August) in New Delhi (Allen et al., 1998). The 35.5-day delay in flowering between the 50% PE and 100% PE treatments (pooled) underscores the critical role of soil moisture availability during the floral induction and spike elongation phases. Moderate water stress, as imposed by the 50% PE treatment, reduces stomatal conductance, limits CO₂ assimilation, and reduces the availability of photosynthates for reproductive organ development, thereby delaying spike emergence (Moftah and Al-Humaid, 2006; Sepaskhah and Yarami, 2009; Halepyati et al., 1995). The results corroborate findings of Khanam et al. (2017), who reported maximum plant height and leaf number at 1.0 IW/CPE in tuberose in West Bengal. Notably, the slightly lower gains from 100% PE in 2023–2024 compared to 2022–2023 may be attributed to the higher pan evaporation rates recorded in the second season, suggesting that 100% PE replacement under extremely high evaporative demand may marginally over-estimate actual crop water requirement, possibly due to oasis effect differences between pan and crop surface.

4.3 Effect of fertigation levels

The pronounced response of all vegetative and phenological parameters to increasing fertigation levels, culminating in maximum performance at 100% RDF, reflects the high nutrient demand of tuberose as a gross feeder bulbous crop. Nitrogen at 200 kg N ha⁻¹ under the 100% RDF treatment provided the substrate for chlorophyll synthesis and Rubisco enzyme production, driving maximum photosynthetic capacity and, consequently, maximum dry matter accumulation reflected in taller plants, longer and wider leaves, and a greater number of leaves per plant. The pronounced effect of fertigation on leaf width (48.3% improvement from 50% to 100% RDF) is particularly noteworthy: leaf width is closely linked to mesophyll cell expansion and depends on adequate K supply for cell turgor maintenance, consistent with the high K rate (100 kg K₂O ha⁻¹) applied at 100% RDF (Alan et al., 2007). The 18.1-day advancement in flowering from 50% RDF to 100% RDF is mechanistically linked to enhanced N-driven synthesis of gibberellins and cytokinins, which accelerate meristematic transition from vegetative to reproductive development (Rathore and Singh, 2013; Castañeda-Saucedo et al., 2023). The staged fertigation schedule (planting, 45 DAP, and 80 DAP) ensured that nutrients were available precisely at the three critical windows of tuberose development, maximizing their physiological impact. Shashidhar et al. (2008); Mohanty et al. (2020) reported analogous improvements in tuberose growth and yield under optimized fertigation, corroborating the present findings.

4.4 Inter-annual climatic variability and treatment interactions

The slightly lower vegetative parameters and delayed phenology observed in 2023–2024 compared to 2022–2023 across most treatments can be attributed to the higher evaporative demand (pan evaporation 7.8 mm day⁻¹ vs. 7.2 mm day⁻¹) and slightly lower effective rainfall (385 mm vs. 420 mm) in the second season. Higher evaporative demand during the May–June period—coinciding with the critical leaf expansion phase—would have imposed greater

atmospheric moisture demand, requiring higher stomatal regulation and potentially limiting the net carbon gain available for growth. However, the directional consistency of treatment effects across both seasons (with the same ranking of treatments in both years) confirms the robustness and repeatability of the agronomic recommendations derived from this study. The absence of statistically significant interaction effects among land configuration, irrigation, and fertigation for most parameters suggests that each factor operated additively rather than synergistically in this study, and that any combination of best-level practices will yield incremental agronomic gains. This additive response pattern simplifies the translation of research recommendations into farmer practice, as adoption of any individual best practice (raised bed, full irrigation, or full fertigation) delivers measurable improvement even without full package adoption.

5 Conclusions

This two-year field investigation demonstrated that land configuration, irrigation regime, and fertigation level each exert significant and independent effects on the vegetative development and phenological advancement of tuberose (*Agave amica* Medik.) under drip irrigation at ICAR-IARI, New Delhi. The following conclusions are drawn:

- i. Raised bed planting consistently outperformed flatbed configuration across all measured parameters, improving plant height at 90 DAP by 6.6%, leaf length by 11.8%, leaf count by 14.0%, and advancing flowering by 12.2 days. Raised beds should be adopted as the standard land configuration for commercial drip-irrigated tuberose cultivation.
- ii. Irrigation at 100% PE produced superior vegetative and floral outcomes, including the highest plant height (65.65 cm), earliest spike emergence (98.0 days), and earliest flowering (121.3 days) in pooled analysis. This schedule is recommended for semi-arid conditions similar to those at New Delhi.
- iii. Fertigation at 100% RDF through the drip system maximized all vegetative parameters and advanced flowering by 18.1 days compared to 50% RDF, underscoring the critical importance of balanced NPK nutrition delivered at appropriate growth stages.
- iv. Correlation analysis confirmed strong positive relationships between vegetative robustness and phenological advancement, validating the integrative agronomic approach adopted in this study.
- v. Economic analysis demonstrated that the raised bed × 100% PE × 100% RDF combination is economically most viable, with the highest net return (₹1,09,400 ha⁻¹) and B:C ratio (2.01), making it the recommended integrated production strategy.

Future studies should incorporate water productivity indices, bulb yield, spike quality parameters (rachis length, floret number, vase life), and fertilizer-use efficiency metrics to develop a

comprehensive optimization framework for these management factors across diverse agroclimatic zones in India.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

BS: Writing – original draft, Investigation, Formal analysis, Data curation, Software, Methodology, Visualization. DG: Resources, Validation, Writing – review & editing, Conceptualization, Supervision. PB: Writing – review & editing, Supervision, Project administration, Conceptualization. AT: Conceptualization, Validation, Methodology, Writing – review & editing. SM: Writing – review & editing, Validation, Conceptualization, Methodology. SP: Writing – review & editing, Visualization, Investigation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Alan, O., Gunen, Y., Ceylan, S., and Gunen, E. (2007). Effect of nitrogen applications on flower yield, some quality characteristics and leaf mineral content in tuberose (*Polianthes tuberosa* L.). *Aegean. Agric. Res. Inst. Dir.* 17, 43–57.
- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper No. 56 (Rome: FAO). Available online at: <https://www.fao.org/3/X0490E/x0490e00.htm> (Accessed May 5, 2026).
- APG IV (2016). An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG IV. *Bot. J. Linn. Soc.* 181, 1–20. doi: 10.1111/boj.12385
- Aydinsakir, K., Bastug, R., and Buyuktas, D. (2003). Calibration of some empirical equations for estimating grass reference evapotranspiration in the Antalya region. *Akdeniz. Univ. J. Fac. Agric.* 16, 107–119.
- Castañeda-Saucedo, M. C., Tapia-Campos, E., Ramirez-Anaya, J. D. P., Barba-Gonzalez, R., and Pita-Lopez, M. L. (2023). Effect of fertilization and planting date on the production and shelf life of tuberose. *Agronomy* 13, 422. doi: 10.3390/agronomy13020422
- Chaudhary, B. D., and Sharma, S. P. (2009). *OPSTAT: A Multipurpose Statistical Package* (Hisar, India: CCS Haryana Agricultural University).
- Chawla, S. L., Patel, M. A., Sudha, P., Dipal, B., and Patel, R. B. (2018). Effect of land configuration and integrated nutrient management on growth, quality and yield of tuberose (*Polianthes tuberosa* L.) var. Prajwal. *Indian J. Agric. Sci.* 88, 1854–1858. doi: 10.56093/ijas.v88i12.85435
- Chiroma, A. M., Alhassan, A. B., and Khan, B. (2008). Yield and water use efficiency of millet as affected by land configuration treatments. *J. Sustain. Agric.* 32, 321–333. doi: 10.1080/10440040802395973
- Divya, K., Girwani, A., Vijaya, D., and Prasanth, P. (2018). Influence of levels of fertigation and sources of nutrients on flowering and yield characters of marigold (*Tagetes erecta* L.) cv. Pusa Narangi Gaiinda. *Int. J. Chem. Stud.* 6, 1674–1678. doi: 10.20546/ijcmas.2017.612.129
- Gomez, K. A., and Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research*, 2nd ed (New York: John Wiley and Sons).
- Gurjar, R. A., Chawla, S. L., Patel, D. P., Pawar, R. D., and Patil, S. (2022). Effect of land configuration and nutrient management on growth, quality and yield of chrysanthemum (*Dendranthema grandiflora* Tzvelev) var. Thai Chen Queen. *Prog. Hortic.* 54, 167–174. doi: 10.5958/2249-6068.2022.00020.4

- Gurjar, D. S., Kaur, R., and Singh, K. P. (2018). Impact of wastewater irrigation on vegetative growth, flowering characteristics, keeping quality and productivity of tuberose (*Polianthes tuberosa* L.). *Indian J. Agric. Sci.* 88, 584–589. doi: 10.56093/ijas.v88i4.79120
- Gurjar, D. S., Singh, R., Kaur, R., and Singh, K. P. (2019). Nutrients and heavy metals accumulation in spike and bulb parts of tuberose (*Polianthes tuberosa* L.) under varied wastewater-groundwater irrigation regimes. *Indian J. Agric. Sci.* 89, 87–91. doi: 10.56093/ijas.v89i1.86172
- Halepyati, A. S., Sujatha, K., and Prabhakar, M. (1995). Growth, yield, water relation and its use in tuberose (*Polianthes tuberosa*) as influenced by irrigation regime and nitrogen level. *Indian J. Agric. Sci.* 65, 428–431.
- Jawaharlal, M., Arumugam, T., Bhattacharjee, S. K., and Vijayakumar, M. (2006). "Tuberose," in *Advances in Ornamental Horticulture*, vol. 3. Ed. S. K. Bhattacharjee (Jaipur: Pointer Publishers), 107–132.
- Kabariel, J., and Kannan, M. (2015). Effect of irrigation regimes and fertigation levels on growth parameters of tuberose (*Polianthes tuberosa* L.) 'Prajwal' under black polythene sheet mulched ecosystem. *Life. Sci. Leaflet* 69, 62–70.
- Kaur, A., and Brar, A. S. (2016). Influence of mulching and irrigation scheduling on productivity and water use of turmeric (*Curcuma longa* L.) in north-western India. *Irrig. Sci.* 34, 261–269. doi: 10.1007/s00271-016-0499-4
- Khanam, R., Kundu, D., Thingujam, U., and Patra, S. K. (2017). Effect of different irrigation levels on growth, yield and water use efficiency of tuberose in lower Gangetic plain of West Bengal, India. *Int. J. Curr. Microbiol. Appl. Sci.* 6, 1944–1952. doi: 10.20546/ijcmas.2017.610.232
- Meerow, A. W., Fay, M. F., Guy, C. L., Li, Q.-B., Zaman, F. Q., and Chase, M. W. (2000). Systematics of Amaryllidaceae based on cladistic analysis of plastid sequence data. *Am. J. Bot.* 86, 1325–1345. doi: 10.2307/2656780
- Moftah, A. E., and Al-Humaid, A. I. (2006). Response of vegetative and reproductive parameters of water stressed tuberose plant to vapor grad and kaolin antitranspirants. *J. King. Saud. Univ. Agric. Sci.* 18, 127–139. doi: 10.37855/jah.2005.v07i02.19
- Mohanty, S., Nath, M. R., and Palai, S. K. (2020). Effect of organic and inorganic sources of nitrogen on plant growth, bulb characteristics and yield of tuberose (*Polianthes tuberosa* L.) cv. Prajwal. *Int. J. Curr. Microbiol. Appl. Sci.* 9, 1561–1566. doi: 10.20546/ijcmas.2020.903.182
- Nain, S., Beniwal, B. S., and Dalal, R. P. S. (2019). Studies on the effect of nitrogen and phosphorus on flowering and spike yield of tuberose (*Polianthes tuberosa* L.) cv. Prajwal. *J. Pharmacogn. Phytochem.* 8, 109–112.
- Neilsen, G. H., Neilsen, D. L., Herbert, C., and Hogue, E. J. (2004). Response of apple to fertigation of N and K under conditions susceptible to K deficiency. *J. Am. Soc. For. Hortic. Sci.* 129, 129–132. doi: 10.21273/JASHS.129.1.0129
- Patel, M. M., Parmar, P. B., and Parmar, B. R. (2006). Effect of nitrogen, phosphorus and spacing on growth and flowering in tuberose (*Polianthes tuberosa* L.) cv. Single. *Indian J. Ornament. Hortic.* 9, 286–289.
- Patra, S. K., Chaitanya, A. K., and Ray, R. (2017). Effects of different levels of irrigation on growth, flowering and bulb production in tuberose (*Polianthes tuberosa* L.). *Int. J. Agric. Innovation Res.* 5, 637–641.
- Ramesh, T., and Rathika, S. (2009). Land configuration techniques for rainfed Alfisols ecosystem – review. *Green Farm.* 2, 879–881.
- Rathore, A. C., and Singh, J. N. (2013). Effect of graded levels of nitrogen on production of flower, oil and bulb of tuberose (*Polianthes tuberosa* L.). *HortFlora. Res. Spectr.* 2, 60–63.
- Sandoval, J. A., Gomez, M., and Fernandez, C. (2021). Factors affecting the productivity and quality of tuberose (*Polianthes tuberosa* L.): a review. *Int. J. Agric. Sci.* 14, 75–80.
- Sepaskhah, A. R., and Yarami, N. (2009). Interaction effects of irrigation regime and salinity on flower yield and growth of saffron. *J. Hortic. Sci. Biotechnol.* 84, 216–222. doi: 10.1080/14620316.2009.11512503
- Sharma, B., Kumari, R., Kumari, P., Meena, S. K., and Singh, R. M. (2018). Evaluation of pearl millet performance under different planting methods at Vindhyan Region of India. *Adv. Biores.* 9, 123–128. doi: 10.15515/abr.0976-4585.9.3.123128
- Shashidhar, H., Jayaprasad, K. V., Bhoomika, H. R., Santosh, K. G., and Krishna, M. (2008). Effect of fertigation levels on growth and yield of tuberose hybrids (*Polianthes tuberosa* L.). *Biomed.* 2, 330–336.
- Singh, A. K., and Shanker, K. (2011). Effect of plant growth regulators on vegetative growth and flowering behaviour of tuberose (*Polianthes tuberosa* L.) cv. Double. *Plant Arch.* 11, 919–921. doi: 10.5958/0976-4615.2021.00009.0
- Slawinska, J., and Obendorf, R. L. (2001). Buckwheat seed set in planta and during *in vitro* inflorescence culture: evaluation of temperature and water deficit stress. *Seed. Sci. Res.* 11, 223–234. doi: 10.1079/SSR200179
- Thiede, J., and Eggli, U. (2013). "Dissolving Agavaceae: amalgamation into Asparagaceae," in *Evolution of CAM Photosynthesis*. Eds. U. Eggli and R. Nyffeler (Cham: Springer), 1–4.
- Yadav, G. S., Saha, P., Babu, S., Singh, R., Das, A., Layek, J., et al (2018). Effect of no-till and raised-bed planting on soil moisture conservation and productivity of summer maize in Eastern Himalayas. *Agric. Res.* 7, 300–310. doi: 10.1007/s40003-018-0320-4