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Synergistic effects of deficit irrigation and *jeevamrutha* on soil microbial health and marigold (*Tagetes erecta*) sustainability

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ABSTRACT

Sustainable floriculture production under water-limited conditions necessitates integration of resource efficient irrigation strategies with biologically active nutrient management systems. The present study was carried out during winter (*rabi*) season from 2023–2025 at Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi to evaluate the interactive effects of regulated deficit irrigation and *jeevamrutha* based nutrition on rhizosphere microbial dynamics, agronomic performance, and economic viability of marigold (*Tagetes erecta* L. cv Pusa Narangi Gainda). The experimental design comprised of three irrigation regimes (I_1, 1.0 ETc; I_2, 0.8 ETc; I_3, 0.6 ETc) and four nutrient treatments (N_1, 100% recommended dose fertiliser; N_2, 100% nitrogen from *jeevamrutha* plus phosphorus-potassium from chemical fertiliser; N_3, 75% *jeevamrutha* nitrogen plus phosphorus-potassium; N_4, 50% *jeevamrutha* nitrogen plus phosphorus-potassium). Moderate deficit irrigation (I_3) significantly enhanced rhizosphere microbial populations, achieving bacterial counts of 6.67×10^7 cfu/g, fungi 8.165×10^5 cfu/g, and actinomycetes 2.915×10^6 cfu/g, surpassing full irrigation and mild deficit treatments. *Jeevamrutha*-based nutrition (N_2) complemented these effects, increasing microbial abundance by 27–29% over conventional fertilisation. Enhanced microbial activity translated into superior plant performance, with I_3 treatment producing tallest plants (67.72 cm), extended flower longevity (22.17 days), and maximum yield (14.76 t/ha). The N_2 module achieved optimal canopy development (47.74 cm) and yield (14.98 t/ha). The I_3N_2 combination consistently demonstrated superior performance, yielding 16,909 kg/ha with gross returns of ₹3.38 lakh/ha, net profits exceeding ₹2.15 lakh/ha, and benefit-cost ratio of 2.755. Results established that regulated deficit irrigation integrated with *jeevamrutha*-based nutrition enhances soil biological functioning, optimises resource partitioning toward reproductive development, and maximises economic returns, providing a scalable framework for water-efficient, biologically intensive ornamental production systems.

Keywords: Deficit irrigation, *Jeevamrutha*, Marigold, Rhizosphere microbiology

Marigold (*Tagetes* spp.), belonging to the Asteraceae family, represents a versatile ornamental crop with diverse applications spanning decorative, pharmaceutical industries, essential oil production, biological pest management, and natural pigment extraction (Mahanta *et al.* 2022, Kumar *et al.* 2023). In India, marigolds constitute a cornerstone of the loose-flower market, contributing substantially to the rapidly expanding floriculture sector. The national floriculture industry was valued at ₹292 billion in 2024, with projections indicating growth to exceed ₹744 billion by 2033, emphasising the critical need for sustainable and resource-efficient production systems (MoA&FW 2023). Contemporary floriculture production confronts unprecedented challenges related to freshwater availability and environmental sustainability. Agriculture currently accounts for approximately 70% of global freshwater consumption, necessitating the development of water-efficient cultivation strategies to ensure long-term sectoral viability (Richter *et al.* 2023). Ornamental crops, characterised by high water demands throughout their growth cycle, are particularly susceptible to water stress conditions. Research indicates that implementation of optimised irrigation management in rainfed agricultural systems could potentially benefit over 800 million people worldwide while simultaneously achieving significant water conservation objectives (Ingrao *et al.* 2023, Singh *et al.* 2025). Parallel to water scarcity concerns, intensive agricultural practices utilising synthetic inputs have contributed to widespread soil degradation, prompting renewed interest in nature-based farming systems. In India, organic/natural farming methodologies emphasise chemical-free production practices designed to restore soil biological activity and enhance ecosystem resilience

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(Palekar 2006, Patel *et al.* 2023). *Jeevamrutha*, a traditional fermented bioconcotion comprising cow dung, cow urine, jaggery, pulse flour, and indigenous soil microorganisms, has demonstrated significant potential for enhancing soil microbial diversity, optimising nutrient cycling processes, and improving plant drought tolerance (Sagar *et al.* 2023). Despite the reported individual benefits of deficit irrigation and organic bioconcoctions, their combined effects in floriculture systems remain poorly explored (Verma *et al.* 2024, Pandey *et al.* 2025). Deficit irrigation alters soil moisture, influencing nutrient mineralisation, diffusion, and cation exchange, while organic bioconcoctions enhance soil organic matter, microbial activity, and cation exchange capacity (Ismail *et al.* 2025) However, their interactive impacts on nutrient retention and overall soil fertility are still not well understood. The present study was designed to evaluate the integrated effects of deficit irrigation regimes and *jeevamrutha*-based nutrient management on soil microbial community dynamics, plant morphophysiological development, yield parameters, water use efficiency, and economic performance in marigold cultivation. The research aimed to provide scientific insights for developing sustainable ornamental crop production strategies that address contemporary challenges of water scarcity and soil health deterioration.

MATERIALS AND METHODS

Experimental site and environmental conditions: The present study was carried out during winter (*rabi*) season from 2023–2025 at Water Technology Centre, ICAR-Indian Agricultural Research Institute (28.35°N and 77.12°E; at an elevation of 228.6 m amsl), New Delhi. The site has deep alluvial sandy loam soils and a semi-arid subtropical climate, with an annual rainfall of ~710 mm. Maximum temperatures occurred in May–June, with the lowest values in winter. Season 2 had higher temperatures and dry spells, increasing reference evapotranspiration (ET_0) using the FAO Penman-Monteith method (Supplementary Fig. 1), whereas Season 1 received rainfall between June and September. The soil was sandy loam (71% sand, 14% silt, and 15% clay), with a bulk density of 1.52 g/cm^3, field capacity of 21.96%, and permanent wilting point of 8.7%. The initial properties included *p*H 7.65, EC 0.29 dS/m, organic carbon 0.32%, and available N, P, and K of 128.7, 26.6, and 283.6 kg/ha, respectively, with sufficient micronutrients.

Crop establishment and management practices: Marigold cultivar Pusa Narangi Gainda seedlings were raised in sterile medium under controlled nursery conditions. Transplantation was performed on November 10 in both years using 4–5-week-old uniform seedlings with 6–8 true leaves. The land was prepared by plowing, harrowing, and leveling to ensure uniform soil conditions. Basal doses of phosphorus (single super phosphate) and potassium (muriate of potash) were applied during the final land preparation. Nitrogen, either from synthetic fertilisers or *jeevamrutha*, was applied in three equal splits: at transplanting, and at 30 and 60 days after transplanting (DAT). Manual weeding was performed at 20, 40, and 60 DAT. Apical pinching was performed at 30 DAT to promote lateral branching. Pest control was achieved using neem-based sprays applied at two-week intervals.

Jeevamrutha *preparation, characterisation, and application*: *Jeevamrutha* was prepared following Palekar (2006) using cow dung (10 kg), cow urine (10 L), jaggery (2 kg), pulse flour (2 kg), and native soil (1 kg) in 200 L of water, and fermented aerobically for seven days with daily stirring. Chemical analysis showed 0.05% N, 0.02% P, 0.02% K, 0.04% Ca, 0.02% Mg, and micronutrients: Zn (1.5 mg/kg), Mn (1.6 mg/kg), Cu (1.3 mg/kg), and Fe (38.4 mg/kg). Microbial enumeration indicated high biological activity with bacteria (145 × 10^6 cfu/mL), fungi (14.5 × 10^4 cfu/mL), actinomycetes (2.0 × 10^3 cfu/mL), nitrogen fixers (7.5 × 10^4 cfu/mL), P and K solubilisers (11.5 × 10^4 and 2.5 × 10^4 cfu/mL, respectively), *Pseudomonas fluorescens* (5.5 × 10^4 cfu/mL), and *Trichoderma* spp. (3.5 × 10^4 cfu/mL) (Table 1). Coliform monitoring showed initial counts of ~1.2 × 10^6 cfu/mL (total) and ~5.5 × 10^5 cfu/mL (faecal), which reduced to ~3.8 × 10^5 and ~1.7 × 10^5 cfu/mL after 24 h of fermentation. At the field scale, 200,000 L/ha of *jeevamrutha* supplied 100 kg N, 40 kg P, and 100 kg K, fulfilling crop N requirements and partially substituting P and K, with the remainder balanced using single superphosphate (SSP) and muriate of potash (MOP). Substitution regimes (100%, 75%, and 50% N) were standardised by proportional *jeevamrutha* volumes and inorganic supplements. For experimental plots (6 m²), inputs were scaled as: 120 L *jeevamrutha* + 131.25 g SSP (100% N substitution) and 60 L *jeevamrutha* + 206.25 g SSP + 25 g MOP (50% N substitution). Applications were made as soil drenches (1.5–3 L/plot) at 15-day intervals

Tabel 1 Analysis of *jeevamrutha* applied as a soil drench over two growing seasons (2023–2024 to 2024–2025)

Chemical and microbial composition in *Jeevamrutha*	
Nitrogen	0.05%
Phosphorous	0.02%
Potassium	0.02%
Calcium	0.04%
Magnesium	0.02%
Zinc	1.5 mg/kg
Manganese	1.6 mg/kg
Copper	1.3 mg/kg
Iron	38.4 mg/kg
Bacteria	145 (cfu×10^6/mL)
Fungi	14.5 (cfu×10^4/mL)
Actinomycetes	2.00 (cfu×10^3/mL)
N-fixers	7.5 (cfu×10^4/mL)
Phosphorous solubilising microorganisms	11.5 (cfu×10^4/mL)
Potassium solubilising microorganisms	2.5 (cfu×10^4/mL)
Pseudomonas fluorescens	5.5 (cfu×10^4/mL)
Trichoderma	3.5 (cfu×10^4/mL)

during early morning hours to optimise microbial survival and infiltration.

Irrigation management: Irrigation was applied through the furrow method and scheduled based on crop evapotranspiration (ETc), computed in CROPWAT 8.0 using the FAO Penman-Monteith model (Allen *et al.* 1998). Reference evapotranspiration (ETo) was determined using Equation (1), and ETc was calculated with Equation (2) by applying stage-specific crop coefficients (Kc) for marigold: 0.30–0.50 (initial, 0–20 DAT), 0.60–0.80 (development, 21–40 DAT), 0.90–1.10 (mid-season flowering, 41–60 DAT), and 0.70–0.80 (senescence, 61–80 DAT). This approach was adopted to synchronise irrigation with physiological water demand, thereby improving water use efficiency, minimising nutrient losses, and enhancing flower quality under semi-arid conditions.

$$ETo = [0.408\Delta(Rn - G) + \gamma(900/(T + 273))u2(es - ea)]/[\Delta + \gamma(1 + 0.34u2)] \quad (1)$$

Where ETo, Reference evapotranspiration (mm/day); Rn, Net radiation at the crop surface (MJ/m^2/day); G, Soil heat flux density (MJ/m^2/day); T, Mean daily air temperature (°C); u2, Wind speed at 2 m height (m/s); es and ea are saturation and actual vapour pressure (kPa); Δ, Slope of the vapour pressure curve (kPa/°C); γ, Psychrometric constant (kPa/°C).

$$ETc = ETo \times Kc \quad (2)$$

Where ETc, Crop evapotranspiration (mm/day); ETo, Reference evapotranspiration (mm/day); Kc, Crop coefficient for specific growth stages.

Three irrigation levels [1.0 (I_1), 0.8 (I_2), and 0.6 (I_3) ETc] were imposed, corresponding to 1669.2, 1335.36, and 1001.52 L in 2024–25, and 1023.6, 818.88, and 614.16 L in 2023–24. Soil moisture in sandy loam (field capacity 22%) was maintained at 18–20%, with irrigation delivered every 3– 4 days in the early morning (06:00–08:00 h) to optimise infiltration and microbial activity. Nutrient management was integrated with irrigation. In the RDF control (N_1), urea (130.43 g), single superphosphate (SSP, 281.25 g), and muriate of potash (MOP, 75 g) were applied, with P and K as basal at transplanting and N in split doses. In natural farming treatments, nitrogen was replaced by *jeevamrutha* at 100%, (N_2) 75% (N_3), or 50% (N_4) levels, with proportional adjustments of SSP and MOP. All inputs were synchronised with irrigation to enhance nutrient-water interactions and uptake efficiency.

Data collection and measurement protocols: Growth, flowering, and yield parameters were recorded systematically under different irrigation regimes and nutrient complexes. Morphological observations included plant height (cm), plant spread (cm), and number of shoots/plant. Flowering attributes comprised days to bud initiation, days to 50% flowering, and duration of flowering (days). Yield parameters included individual flower weight (g) and total flower yield (t/ha). Plant height, plant spread, and number of shoots were measured at peak vegetative stage using tagged sample plants from each plot. Days to bud initiation and 50% flowering were recorded based on the number of days from transplanting to visible bud formation and when 50% of plants in a plot attained flowering, respectively. Flowering duration was calculated from the onset to the end of flowering in each treatment. Average flower weight was determined using a digital balance from randomly harvested flowers, and flower yield per hectare was computed by extrapolating plot yield to a hectare basis.

Economic analysis: An economic evaluation of the irrigation and nutrient management treatments was conducted to assess their financial viability. The analysis was performed using standard cost-return methodology based on treatment-wise yield and prevailing market prices during the experimental period.

Cost of cultivation: The total cost of cultivation (TC, ₹/ha) was calculated by summing all variable and fixed costs incurred in crop production:

$$TC = \sum \text{Variable costs} + \sum \text{Fixed costs}$$

Variable costs included expenses on planting material, chemical fertilisers (RDF), *Jeevamrutha* preparation and application, irrigation (water and energy charges), labour (land preparation, interculture, harvesting), and plant protection measures. Fixed costs comprised depreciation of farm implements, land revenue, interest on fixed capital, and rental value of land where applicable. Input prices and wage rates prevailing during the cropping season were uniformly applied across treatments.

Gross return: Gross return (GR, ₹/ha) was estimated based on marketable yield and the average farm-gate market price recorded during the harvest period:

$$GR = Y \times P$$

Where Y, Yield (kg/ha); and P, Market price (₹/kg).

Net return: Net return (NR, ₹/ha) was computed as:

$$NR = GR - TC$$

The parameter represents the actual economic gain from each treatment.

Benefit-cost ratio: The benefit-cost ratio (B:C) was calculated to evaluate economic efficiency:

$$B{:}C = GR/TC$$

B:C ratio greater than unity indicates economic feasibility of the selected crop production.

Statistical analysis: A split-plot design was adopted, with irrigation levels assigned to the main plots and nutrient treatments to the subplots, replicated thrice. Normality and variance homogeneity were checked using the Shapiro-Wilk and Levene tests. The data were subjected to two-way ANOVA using the following model:

$$Yijk = \mu + \alpha i + \beta j + (\alpha\beta)ij + \gamma k + \varepsilon ijk$$

Where μ, Overall mean; αi, Effect of irrigation; βj, Nutrient effect; (αβ)ij is their interaction; γk, Block effect; εijk, Random error. Significance was evaluated at $p \leq 0.05$, 0.01, and 0.001, and treatment means were compared using Tukey's HSD test.

RESULTS AND DISCUSSION

Soil microbial community response to deficit irrigation and organic nutrient management: The experimental findings revealed that moderate deficit irrigation at 60% crop evapotranspiration (0.6 ETc, designated as I_3) significantly enhanced microbial populations in the marigold rhizosphere compared to full irrigation (I_1) and mild deficit irrigation (I_2) treatments over two consecutive growing seasons (2023–2025). Quantitative microbiological analysis (Table 2, Supplemetary Fig. 2) demonstrated that I_3 treatment supported substantially higher colony-forming units of bacteria (6.67×10^7 cfu/g soil), fungi (8.165×10^5 cfu/g soil), and actinomycetes (2.915×10^6 cfu/g soil) relative to other irrigation regimes. This enhanced microbial proliferation under moderate water deficit can be attributed to improved soil aeration, reduced nutrient leaching losses, and the creation of optimal microenvironmental conditions favouring microbial colonisation and metabolic activity. The controlled water stress likely enhanced oxygen diffusion through soil pores while concentrating available nutrients in the rhizosphere, thereby promoting microbial growth and diversity (Duraivadivel *et al.* 2022). Organic nutrient management demonstrated complementary effects on soil microbial communities. The N_2 treatment, comprising 100% nitrogen from *jeevamrutha* biofertiliser supplemented with inorganic phosphorus and potassium, consistently exceeded the performance of conventional recommended dose of fertilisers (RDF, designated as N_1). Microbial populations under N_2 treatment were elevated by 27–29% across all microbial groups, demonstrating the bifunctional role of *jeevamrutha* as both a nutrient source and microbial inoculant. Statistical analysis revealed that the I_3N_2 interaction yielded the highest bacterial and actinomycetes counts, indicating synergistic effects between deficit irrigation and organic nutrient supplementation in establishing a functionally diverse rhizosphere microbiome (Sailaja *et al.* 2020, Sharma *et al.* 2024). The enhanced microbial activity under organic amendments corroborates previous studies (Kumar *et al.* 2019, Patel *et al.* 2021, Sharma *et al.* 2022, Vishwanath *et al.* 2025), while our findings extend this knowledge by demonstrating that regulated deficit irrigation amplifies these beneficial effects. The consistent microbial enhancement under *jeevamrutha* application validates its biostimulatory potential and suggests that organic amendments can mitigate adverse effects of water stress through biological soil enrichment, thereby improving the sustainability of ornamental crop production under water-limited conditions.

Soil nutrient availability: The pooled two-season data showed that both irrigation regime and nutrient management significantly influenced residual soil nutrients (Table 3, Supplemenatry Fig. 3). Under irrigation treatments, the lowest level (I_3= 0.6 ETc) registered the highest residual N (334.17 kg/ha) and K (416.54 kg/ha), with I_2 (0.8 ETc) intermediate and I_1 (1.0 ETc) lowest, while available P increased mildly with reduced water (60.46–60.88 kg/ha). These trends suggest that reduced irrigation limits leaching and conserves nutrient pools an effect consistent with water fertiliser coupling strategies that improve retention and minimise losses (Xing *et al.* 2024). For nutrient treatments, the 100% *jeevamrutha*-N + PK chemical (N_2) treatment sustained significantly higher residual fertility (332.83 kg N, 65.37 kg P, 440.75 kg K/ha) than the conventional RDF (N_1) or partial substitution (N_3, N_4). The stronger performance of N_2 likely arises from the combined action of organic N

Table 2 Effect of different irrigation practices and nutrient combinations on soil microflora following crop harvest (2023–2024 to 2024–2025)

Treatment	Bacterial count ($\times 10^7$ CFU/g soil)	Fungal count ($\times 10^5$ CFU/g soil)	Actinomycetes count ($\times 10^6$ CFU/g soil)
Main plot - Irrigation regimes			
I_1 (1.0 ETc)	5.97^b	3.56^b	2.615^b
I_2 (0.8 ETc)	5.85^b	3.48^b	2.55^b
I_3 (0.6 ETc)	6.67^a	8.165^a	2.915^a
$HSD_{0.05}$	0.17	0.11	0.075
Sub plot - Nutrient complex			
N_1 (100% RDF by CF)	5.475^c	7.205^d	2.42^c
N_2 (100% *jeevamrutha* N + PK by CF)	6.99^a	9.29^a	3.07^a
N_3 (75% *jeevamrutha* N + PK by CF)	6.165^b	8.04^b	2.68^b
N_4 (50% *jeevamrutha* N + PK by CF)	6.02^b	7.58^c	2.605^b
$HSD_{0.05}$	0.275	0.12	0.115

Values are the means of three replicates. Means followed by different letters within the same column and treatment factor are significantly different at $p \leq 0.05$, according to Tukey's HSD test. ETc, Crop evapotranspiration; CF, Chemical fertiliser; RDF, Recommended dose of fertiliser; HSD, Honestly significant difference.

supply, enhanced microbial activity, and improved nutrient cycling attributes widely documented in recent work on organic amendments and biofertilisers (Contreras *et al.* 2025, Singh *et al.* 2025). Partial substitution treatments (N_3, N_4) recorded lower P and K pools, indicating that aggressive reduction of chemical N without compensating mechanisms can impair nutrient balance. Notably, the elevated K under N_2 implies reduced leaching losses and better retention, perhaps via improved cation exchange capacity and lagged nutrient release from the organic matrix (Sreenivasa *et al.* 2010, Beikufner *et al.* 2024). However, higher residual pools under deficit irrigation may also reflect lower crop uptake under moisture stress rather than ideal efficiency, a caveat that must be interpreted in conjunction with yield and uptake data (Devau *et al.* 2011). Overall, integrating moderate water deficit (0.6 ETc) with full *jeevamrutha* substitution for N (with PK chemical supplementation) appears to enhance soil nutrient status, bolster microbial-mediated transformations, and sustain fertility under semi-arid conditions a result that aligns with recent findings on the role of organic amendments in strengthening soil health and nutrient availability.

Table 3 Effect of irrigation regimes and nutrient management on soil available NPK status in marigold (2023–2024 to 2024–2025)

Treatment	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)
Main plot: Irrigation regimes			
I_1 (1.0 ETc)	327.70 ± 1.78^c	60.46 ± 0.09^b	396.34 ± 0.10^c
I_2 (0.8 ETc)	329.21 ± 1.78^b	60.54 ± 0.09^b	410.60 ± 0.10^b
I_3(0.6 ETc)	334.17 ± 1.78^a	60.88 ± 0.09^a	416.54 ± 0.10^a
HSD$_{0.05}$	0.39	0.32	0.37
Sub-plot: Nutrient complex			
N_1 (100% RDF-CF)	329.71 ± 1.84^b	61.24 ± 0.05^b	412.10 ± 0.13^b
N_2 (100% *jeevamrutha*-N + PK-CF)	332.83 ± 1.84^a	65.37 ± 0.05^a	440.75 ± 0.13^a
N_3 (75% *jeevamrutha*-N + PK-CF)	329.42 ± 1.84^b	57.04 ± 0.05^c	394.00 ± 0.13^c
N_4 (50% *jeevamrutha*-N + PK-CF)	329.46 ± 1.84^b	56.45 ± 0.05^d	386.58 ± 0.13^d
HSD$_{0.05}$	0.34	0.28	0.39

Values are means ± standard error. Different letters within each column indicate significant differences according to Tukey's HSD test ($p \leq 0.05$). ETc, Crop evapotranspiration; RDF-CF, Recommended dose of fertiliser through chemical fertiliser; PK-CF, Phosphorus and potassium through chemical fertiliser; CV, Coefficient of variation; *** $p<0.001$; HSD, Honestly significant difference.

Plant growth parameters and reproductive performance: The enhanced rhizosphere microbial activity under I_3N_2 treatment directly translated into superior plant growth and flowering characteristics. Morphometric analysis (Table 4, Supplementary Fig. 4) revealed that deficit irrigation at 0.6 ETc produced the tallest plants (67.72 cm) and maximum flower yield (14.76 t/ha) compared to I_1 and I_2 treatments. While phenological development showed marginal delays in bud initiation (56.59 days) and 50% flowering (65.03 days), the I_3 treatment significantly increased individual flower weight (13.06 g) and post-harvest longevity (22.17 days). This physiological response indicated adaptive resource reallocation toward reproductive organs under moderate water stress, facilitated by enhanced microbial-mediated nutrient availability (Veeranna *et al.* 2023, Dutta *et al.* 2024). The observed improvement in flower quality parameters suggests that controlled water deficit, when combined with optimal soil microbial activity, promotes efficient assimilate partitioning into floral biomass. *Jeevamrutha*-based nutrition (N_2) resulted in maximum canopy diameter (47.74 cm) and flower yield (14.98 t/ha), significantly surpassing conventional fertilisation. These improvements are attributed to *jeevamrutha*'s capacity to stimulate beneficial rhizosphere microorganisms, enhance root system architecture, and improve nutrient uptake efficiency (Kaushal *et al.* 2024). The I_3N_2 combination consistently demonstrated superior performance across both experimental seasons, representing a paradigm shift toward quality-oriented floriculture production (Jnanesha *et al.* 2024). Although shoot proliferation was marginally reduced under deficit irrigation, the concurrent improvements in flower size, weight, and longevity align with commercial market preferences for premium ornamental products. These findings substantiate previous research on organic biostimulants' role in maintaining productivity under suboptimal water conditions (Sutar *et al.* 2018, Shrivas *et al.* 2023, Devvrat 2020) and establish an integrative approach where microbial enhancement and water-efficient management synergistically improve both yield quantity and flower quality.

Economic feasibility and profitability analysis: The biological improvements achieved through optimised irrigation-nutrition interactions translated into substantial economic benefits for marigold cultivation. Economic analysis (Table 5, Supplemenatry Fig. 5) demonstrated that the I_3N_2 treatment combination yielded the highest economic returns, with maximum flower production of 16,909 kg/ha generating gross returns of ₹338,187/ha. Given relatively uniform production costs across treatments (approximately ₹1.23 lakh/ha), the I_3N_2 treatment achieved net returns exceeding ₹2.15 lakh/ha with the highest benefit-cost ratio (2.755). The economic superiority of this treatment was consistently maintained across experimental seasons, positioning it as the most profitable strategy under resource-constrained conditions (Khan *et al.* 2024). *Jeevamrutha*-based nutrient modules (N_2 and N_3)

Table 4 Effect of different irrigation practices and nutrient combinations on the quality of marigold flowers and overall crop yield (2023–2024 to 2024–2025)

Treatments	Growth parameters			Flowering parameters		Yield parameters		
	Plant height (cm)	Plant spread (cm)	Number of shoots	Bud initiation (Days)	50% flowering (Days)	Duration of flower (Days)	Flower weight (g)	Flowers/ha (t/ha)
Main plot - Irrigation regimes								
I_1 (1.0 ETc)	63.69^{c}	45.71^{b}	5.80^{b}	53.59^{c}	63.13^{c}	19.43^{c}	11.25^{c}	12.52^{c}
I_2 (0.8 ETc)	65.79^{b}	45.91^{b}	6.06^{a}	54.39^{b}	63.99^{b}	21.05^{b}	12.48^{b}	13.14^{b}
I_3 (0.6 ETc)	67.72^{a}	47.96^{a}	5.40^{c}	56.59^{a}	65.03^{a}	22.17^{a}	13.06^{a}	14.76^{a}
$HSD_{(0.05)}$	0.07	0.11	0.06	0.09	0.17	0.32	0.13	0.17
Sub plot - Nutrient complex								
N_1 (100% RDF by CF)	67.20^{b}	47.29^{b}	5.64^{c}	57.49^{a}	64.52^{b}	22.89^{a}	13.70^{a}	13.03^{c}
N_2 (100% *Jeevamrutha* N + PK by CF)	68.72^{a}	47.74^{a}	6.18^{a}	55.07^{b}	65.66^{a}	21.07^{b}	12.78^{b}	14.98^{a}
N_3 (75% *Jeevamrutha* N + PK by CF)	64.92^{c}	45.56^{c}	5.84^{b}	53.73^{c}	63.77^{c}	20.19^{c}	11.61^{c}	13.39^{b}
N_4 (50% *Jeevamrutha* N + PK by CF)	62.09^{d}	44.10^{d}	5.35^{d}	53.12^{c}	62.25^{d}	19.37^{d}	10.95^{d}	12.49^{d}
$HSD_{(0.05)}$	0.14	0.11	0.05	0.08	0.13	0.19	0.14	0.14

Values are the means of three replicates. Means followed by different letters within the same column and treatment factor are significantly different at $p \leq 0.05$, according to Tukey's HSD test. ETc, Crop evapotranspiration; CF, Chemical fertiliser; RDF, Recommended dose of fertiliser; HSD, Honestly Significant Difference.

Tabel 5 Effect of different irrigation practices and nutrient combinations on the economic aspects of marigold cultivation (2023–2024 to 2024–2025)

Treatments	Total cost (₹/ha)	Yield (kg/ha)	Gross return (₹/ha)	Net profit (₹/ha)	B:C ratio	Economic rank
I_1N_1 (1 ETc + 100% RDF by CF)	121,833	12,204.17^{d}	244,086.60	122,253.6^{e}	2.005^{e}	11
I_1N_2 (1 ETc + 100% N from *jeevamrutha* + Adj. PK by CF)	122,833	13,925.67^{c}	278,513.40	155,680.4^{cd}	2.270^{cd}	05
I_1N_3 (1 ETc + 75% N from *jeevamrutha* + Adj. PK by CF) 9	122,583	12,494.33^{d}	249,886.70	127,303.7^{de}	2.040^{de}	09
I_1N_4 (1 ETc + 50% N from *jeevamrutha* + Adj. PK by CF)	122,333	11,433.12^{e}	228,662.40	106,329.4^{f}	1.865^{f}	12
I_2N_1 (0.8 ETc + 100% RDF by CF)	121,833	12,424.27^{d}	248,485.40	126,652.4^{de}	2.035^{e}	10
I_2N_2 (0.8 ETc + 100% N from *jeevamrutha* + Adj. PK by CF)	122,833	14,093.51^{c}	281,870.20	159,037.2^{c}	2.295^{c}	04
I_2N_3 (0.8 ETc + 75% N from *jeevamrutha* + Adj. PK by CF)	122,583	13,369.32^{cd}	267,386.40	144,803.4^{d}	2.185^{d}	06
I_2N_4 (0.8 ETc + 50% N from *jeevamrutha* + Adj. PK by CF)	122,333	12,659.82^{d}	253,196.40	130,863.4^{de}	2.070^{de}	08
I_3N_1 (0.6 ETc + 100% RDF by CF)	121,833	14,471.02^{b}	289,420.40	167,587.4^{bc}	2.375^{bc}	02
I_3N_2 (0.6 ETc + 100% N from *jeevamrutha* + Adj. PK by CF)	122,833	16,909.35^{a}	338,186.90	215,353.9^{a}	2.755^{a}	01
I_3N_3 (0.6 ETc + 75% N from *jeevamrutha* + Adj. PK by CF)	122,583	14,293.52^{b}	285,870.50	163,287.5^{bc}	2.330^{bcd}	03
I_3N_4 (0.6 ETc + 50% N from *jeevamrutha* + Adj. PK by CF)	122,333	13,373.16^{cd}	267,463.10	145,130.1^{d}	2.185^{d}	07

Values are the means of three replicates. Means followed by different letters within the same column and treatment factor are significantly different at $p \leq 0.05$, according to Tukey's HSD test. ETc, Crop evapotranspiration; CF, Chemical fertiliser; RDF, Recommended dose of fertiliser; HSD, Honestly Significant Difference.

consistently outperformed conventional RDF in profitability metrics, supporting the economic viability of organic farming systems. The profit differential of over ₹1 lakh/ha between the optimal I_3N_2 treatment and conventional I_1N_1 management highlights the substantial economic gains achievable through strategic integration of water and nutrient management. Since production costs remained stable across treatments, the observed economic advantages were primarily yield-driven, emphasising the biological efficiency of the integrated system. The economic benefits stem from *jeevamrutha*'s multifunctional effects: microbial consortium stimulation, root system enhancement, and improved nutrient bioavailability. This study demonstrates that moderate irrigation deficits, when strategically combined with organic inputs, can simultaneously enhance soil biological activity, optimise crop performance, and maximise economic returns (Sugumaran *et al.* 2024). The economic analysis validates the practical applicability of this integrated management strategy, offering producers a pathway to achieve higher profitability while maintaining environmental sustainability and resource conservation objectives.

This study demonstrates that moderate deficit irrigation at 60% crop evapotranspiration (I_3) combined with *jeevamrutha*-based nutrition (N_2) creates synergistic effects that enhance soil microbial activity, crop performance, and economic returns in marigold cultivation. The I_3N_2 treatment significantly increased rhizosphere microbial populations by 27–29% over conventional management, directly translating into superior flower yield (14.98 t/ha) with improved quality parameters. Economic analysis revealed net returns of ₹2.15 lakh/ha with the highest benefit-cost ratio (2.75), representing a profit advantage of over ₹1 lakh/ha compared to conventional practices. These findings challenge traditional irrigation paradigms by demonstrating that controlled water stress, when coupled with organic biostimulants, can enhance rather than compromise productivity. The integrated approach addresses critical sustainability challenges including water scarcity and soil health deterioration while maintaining economic viability. This research provides a scientifically validated pathway for resource-efficient ornamental horticulture that simultaneously achieves environmental conservation, economic profitability, and social sustainability through utilisation of locally available organic inputs. Future research should explore the mechanistic basis of plant-microbe-water interactions under deficit conditions and validate findings across diverse crops and agro-ecological zones to strengthen the evidence base for sustainable intensification of horticultural production systems.

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