Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Deficit Irrigation Combined with Jeevamrutha-Based Nutrient Management Enhances Rhizosphere Microbial Abundance, Agronomic Performance, and Economic Returns of African Marigold Under Semi-Arid Conditions

Aditya Machnoor

adimachnoor07@gmail.com

Indian Agricultural Research Institute

D S Gurjar

Indian Agricultural Research Institute

P S Brahmanand

Indian Agricultural Research Institute

Rosin K G

Indian Agricultural Research Institute

Minakshi Grover

Indian Agricultural Research Institute

A K Tiwari

Indian Agricultural Research Institute

S L Meena

Indian Agricultural Research Institute

Shiv Prasad

Indian Agricultural Research Institute

Research Article

Keywords: Deficit irrigation, Jeevamrutha, Marigold, Rhizosphere microbiology, Sustainable floriculture, Water productivity

Posted Date: November 11th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11173116/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Deficit Irrigation Combined with Jeevamrutha-Based Nutrient Management Enhances Rhizosphere Microbial Abundance, Agronomic Performance, and Economic Returns of African Marigold Under Semi-Arid Conditions

Aditya V. Machnoor[1]*, D. S. Gurjar[2], P. S. Brahmanand[3], Rosin K G[4], Minakshi Grover[5], A. K. Tiwari[6], S. L. Meena[7], Shiv Prasad[8]

1 PhD Scholar, Discipline of Water Science and Technology, Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Email: adimachnoor07@gmail.com

2 Principal Scientist, Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Email: dhara.gurjar@icar.gov.in

3 Project Director, Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Email: pothula.brahmanand@icar.gov.in

4 Scientist, Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Email: kgrosin@gmail.com

5 Principal Scientist, Division of Microbiology, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Email: G.minakshi@icar.gov.in

6 Principal Scientist, Division of Floriculture and Landscaping, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Email: ajay.tiwarri@icar.gov.in

7 Principal Scientist, Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Email: sl.meena@icar.gov.in

8 Principal Scientist, Division of Environmental Sciences, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Email: shiv_drprasad@yahoo.co.in

***Corresponding author: Aditya V. Machnoor (adimachnoor07@gmail.com)**

Abstract

Sustainable floriculture in semi-arid regions needs irrigation and nutrient management that conserve water and soil biological function, yet whether deficit irrigation and organic biostimulation act additively or interactively on rhizosphere microbiology remains untested. This two-season (2023–2025) split-plot trial grew African marigold (Tagetes erecta L.) under three irrigation levels (full, I_1, 1.0 ETc; mild deficit, I_2, 0.8 ETc; moderate deficit, I_3, 0.6 ETc) crossed with four nitrogen regimes: a fully chemical dose (N_1) and Jeevamrutha meeting 100% (N_2), 75% (N_3) or 50% (N_4) of crop nitrogen, with supplementary chemical P and K. Moderate deficit gave the highest rhizosphere bacterial, fungal and actinomycete counts (6.67×10^7, 3.99×10^5 and 2.92×10^6 cfu g^{-1}), 11.5–11.9% above full irrigation; full Jeevamrutha-N substitution raised these counts 26.9–27.8% above chemical fertiliser, with a significant irrigation × nutrient interaction. These responses accompanied improved performance: moderate deficit gave the tallest plants (67.72 cm), longest longevity (22.17 days) and highest yield (14.76 t ha^{-1}), while full Jeevamrutha-N gave the widest canopy (47.74 cm) and highest yield (14.98 t ha^{-1}). Their combination (I_3N_2) ranked highest overall (16,909 kg ha^{-1} yield, ₹3.38 lakh ha^{-1} gross and over ₹2.21 lakh ha^{-1} net returns, and a benefit–cost ratio of 1.90) while cutting seasonal irrigation by 38.6%. Deficit irrigation thus amplified, not merely coexisted with, the response to Jeevamrutha nutrition. By advancing water conservation (SDG 6), reduced synthetic-input use (SDG 12) and soil biological health (SDG 15), the approach offers a scalable pathway to sustainable, water- and input-efficient floriculture.

Keywords: Deficit irrigation; Jeevamrutha; Marigold; Rhizosphere microbiology; Sustainable floriculture; Water productivity

1. Introduction

Floriculture occupies a distinctive position in the sustainability of modern agri-food systems: it is high-value, labour-intensive and closely tied to rural livelihoods, yet also water- and input-intensive at a time when both freshwater and synthetic-fertiliser use are under increasing scrutiny [1]. In India, the sector has grown rapidly, with market value estimated at ₹292 billion in 2024 and projected to exceed ₹744 billion by 2033 [2], growth that depends on production systems able to reconcile yield and quality with water conservation and soil biological health. African marigold (*Tagetes erecta* L., Asteraceae) is one of the sector's most widely grown species, valued for cut- and loose-flower markets, natural pigment and essential-oil extraction, pharmaceutical use, and companion planting for soil-borne pest suppression [3-4]. Because it is grown intensively on relatively small holdings across the semi-arid Indo-Gangetic plains, marigold is also a useful lens on a broader question facing Indian floriculture and, more widely, irrigated horticulture worldwide: how to sustain yield and profitability while reducing water withdrawal and dependence on synthetic inputs, in line with Sustainable Development Goals on water (SDG 6), responsible production (SDG 12) and life on land (SDG 15). Identifying management that delivers on these three goals simultaneously rather than trading one against another is central to the sustainable intensification of ornamental production and frames the sustainability rationale for the present study.

Two pressures converge on ornamental production in semi-arid regions. The first is water scarcity: agriculture accounts for roughly 70% of global freshwater withdrawals, and ornamental crops, which sustain a high canopy water demand through a long reproductive phase, are particularly exposed to irrigation curtailment as competition for water intensifies [5]. Deficit irrigation (DI), the deliberate, managed application of water below full crop evapotranspiration (ETc), has become a widely tested response: when kept within a crop's physiological tolerance, mild-to-moderate soil-water deficit can trigger osmotic adjustment, partial stomatal closure and a shift of assimilate partitioning from vegetative to reproductive sinks, often improving harvest index and water productivity even as total biomass declines [6-9]. The second pressure is the decline in soil biological health associated with sustained reliance on synthetic fertiliser, which has renewed interest in fermented, microbially active organic amendments as partial or full substitutes for mineral nitrogen. Jeevamrutha (a traditional Indian preparation of cow dung, cow urine, jaggery, pulse flour and native soil, fermented aerobically for about seven days) is one of the most widely adopted such inputs under India's natural-farming programmes, with documented adoption gains for crop yield and farm income at national scale [3, 10-11]. Its value lies less in its modest direct nutrient content than in the microbial inoculum and readily available carbon it delivers: nitrogen-fixing, phosphorus-solubilising and biocontrol organisms together with organic-acid and phytohormone-like compounds that can stimulate rhizosphere activity, organic-matter turnover and root growth [12-16]. Crop-

level evidence supports this: Jeevamrutha-based nutrition has raised yield and quality in senna [17] and, specifically in marigold cv. Siracole, has increased cutting and flower yield by 14–18% relative to chemical fertiliser [18]. More broadly, fermented and plant-derived biostimulants are known to modulate physiological and biochemical pathways linked to vigour and abiotic-stress tolerance, which is consistent with their use alongside, rather than only instead of, mineral fertiliser [19].

Deficit irrigation and organic biostimulation are therefore each reasonably well characterised on their own, but their *combined* effect is not. This matters because the two practices could conceivably interact rather than act additively: the soil aeration and reduced leaching associated with moderate water deficit might favour establishment of the aerobic, substrate-responsive microbial community introduced by a biostimulant, while a more active rhizosphere microbiome might in turn buffer the crop against deficit-induced stress. Outside ornamentals, this interaction is only just beginning to attract attention; for example, a recent two-year field trial combining regulated deficit irrigation with biostimulation in table grape found that the two practices together improved root colonisation and water productivity beyond either practice alone, describing the interaction itself as "a new approach" for the crop system studied [20]. In floriculture, no comparable factorial evidence exists: earlier work has evaluated deficit irrigation or Jeevamrutha-type inputs separately, or has combined them without a design able to isolate irrigation × nutrient interaction effects on rhizosphere microbial abundance, agronomic performance and economic return simultaneously. Recent genome- and community-level work on Jeevamrit own microbiome [21] and on organic-input effects on other ornamentals' rhizosphere microbiome [22] further underlines that its field-level effects are still being actively mapped, but neither addresses how soil-moisture regime modulates that effect.

Marigold is a suitable system in which to close this gap. Its short crop cycle (about 80–90 days), well-characterised evapotranspiration response, and market sensitivity to flower size, weight and post-harvest longevity make water- and nutrient-management decisions directly and quickly visible in profitability, so that any irrigation × nutrient interaction should be detectable within a single growing season. Accordingly, this two-season field study tested the hypothesis that regulated deficit irrigation and Jeevamrutha-based nutrition interact, rather than act additively, on rhizosphere microbial abundance, and that this interaction propagates through to agronomic and economic outcomes. Using a split-plot factorial design crossing three irrigation levels (full irrigation, mild deficit and moderate deficit, expressed as fractions of ETc) with four nitrogen regimes (fully chemical, and 100%, 75% or 50% chemical-nitrogen substitution by Jeevamrutha), the specific objectives were to: (i) quantify the individual and interactive effects of irrigation regime and nutrient regime on rhizosphere microbial abundance, dehydrogenase activity and post-harvest soil fertility; (ii) determine their effects on vegetative growth, flowering

phenology and marketable flower yield; (iii) evaluate the economic returns of each treatment combination under semi-arid conditions, so as to identify a water- and input-efficient management option with a demonstrable path to farm-level adoption; and (iv) integrate these responses into a comprehensive treatment performance index to identify the treatment combination performing most consistently across all measured dimensions. Collectively, these objectives were framed to evaluate how coupling deficit irrigation with Jeevamrutha-based nitrogen can simultaneously advance responsible water use (SDG 6), lower-input production (SDG 12) and soil biological health (SDG 15) in sustainable semi-arid floriculture.

2. Materials and Methods

2.1 Experimental Site and Environmental Context

Two field experiments were conducted in successive Rabi (winter) seasons at the Water Technology Centre, ICAR–Indian Agricultural Research Institute (IARI), New Delhi, India (28°38′N, 77°09′E; 225 m above mean sea level). In both years the crop occupied a 79-day cycle, transplanted on 10 November and harvested by 28 January (Season 1: 2023–2024; Season 2: 2024–2025), the cool, post-monsoon window in which marigold is conventionally grown across the north-Indian plains. Daily reference evapotranspiration (ET_0) was computed with the FAO-56 Penman–Monteith equation [23] from records at the adjoining IARI meteorological observatory. Season 2 was warmer than Season 1 and included an extended dry spell between late November and mid-December, which raised its cumulative ET_0 (Fig. 1; Table 1). The soil was a sandy loam (71% sand, 14% silt, 15% clay; bulk density 1.52 g cm^{-3}; field capacity 21.96%; permanent wilting point 8.7%) with, before sowing, pH 7.65, EC 0.29 dS m^{-1}, organic carbon 0.32%, and available N, P and K of 128.7, 26.6 and 283.6 kg ha^{-1}, respectively. The underlying field trial, and part of the resulting agronomic and economic dataset, were reported previously with a narrower focus on soil microbial health and crop sustainability [24]; the present paper extends that dataset with the full factorial microbial, post-harvest available-nutrient, agronomic and economic analysis and interprets it against the wider sustainability literature.

2.2 Crop Establishment and Cultural Management

Seedlings of *T. erecta* cv. Pusa Narangi Gainda were nursery-raised under shade and transplanted at the 6–8 true-leaf stage (4–5 weeks old) on the dates above, after conventional ploughing, harrowing and levelling. Phosphorus (single superphosphate, SSP) and potassium (muriate of potash, MOP) were applied basally before transplanting; nitrogen was split equally across transplanting, 30 DAT and 60 DAT. Hand-weeding was carried out at 20, 40 and 60 DAT, shoots were pinched at 30 DAT to encourage lateral branching, and plants were protected with fortnightly neem-based sprays.

2.3 Jeevamrutha Preparation, Characterisation and Nutrient Accounting

Jeevamrutha was prepared following the standard zero-budget natural-farming protocol [25]: cow dung (10 kg), fresh cow urine (10 L), jaggery (2 kg), pulse flour (2 kg) and native topsoil (1 kg) were dissolved in 200 L of water and fermented aerobically for seven days with daily stirring. The finished preparation was characterised chemically and microbiologically (Table 1; values on a fresh-weight basis, solution density taken as 1.00 kg L^{-1}). At 0.05% N (w/v) (0.50 g N L^{-1}), a seasonal application volume of 200,000 L ha^{-1} (1,000 batches of 200 L, applied as six fortnightly doses of ≈33,333 L ha^{-1}) supplied 100 kg N ha^{-1}, 40 kg P ha^{-1} and 100 kg K ha^{-1}. Because Jeevamrutha alone could not meet crop demand during early establishment, basal SSP and MOP closed the gap to the recommended dose in all Jeevamrutha-based treatments. Scaled to the 6 m^2 plot, this amounted to 120 L $plot^{-1}$ $season^{-1}$, delivered as six fortnightly doses of 20 L $plot^{-1}$.

2.4 Irrigation Management and Scheduling

Water was applied through surface furrows. Daily crop evapotranspiration (ETc) was obtained by scaling ET_0 with growth-stage crop coefficients (Kc = 0.30–0.50 during establishment, 0–20 DAT; 0.60–0.80 during crop development, 21–40 DAT; 0.90–1.10 at mid-season, 41–60 DAT; 0.70–0.80 in the late stage, 61–79 DAT):

Eq. (1): $$\mathbf{ET_0 = [0.408\Delta(Rn - G) + \gamma(900/(T + 273))u_2(es - ea)] / [\Delta + \gamma(1 + 0.34u_2)]}$$ [23]

where ET_0 is reference evapotranspiration (mm day^{-1}), Rn is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature (°C), u_2 is wind speed at 2 m (m s^{-1}), es and ea are saturation and actual vapour pressure (kPa), Δ is the slope of the saturation vapour-pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}).

Eq. (2): $$\mathbf{ETc = ET_0 \times Kc}$$ [23]

Three irrigation regimes were imposed: full irrigation (I_1, 1.0 ETc), mild deficit (I_2, 0.8 ETc) and moderate deficit (I_3, 0.6 ETc), corresponding to seasonal totals of approximately 1,669, 1,335 and 1,002 L $plot^{-1}$ in Season 2 and 1,024, 819 and 614 L $plot^{-1}$ in Season 1, applied every 3–4 days between 0600 and 0800 h. The 0.8 and 0.6 ETc thresholds were selected from regional agronomic guidance and published deficit-irrigation work on ornamental and horticultural crops in semi-arid northern India, where they are widely regarded as the mild- and moderate-deficit points beyond which yield loss begins to outweigh the water saved [6, 26]; 1.0 ETc served as the fully irrigated reference. Because these thresholds were adopted from the literature rather than fixed through a site-specific pilot trial (a limitation acknowledged here), crop-specific deficit levels for marigold should ideally be confirmed in dedicated calibration studies before the recommendations below are transferred to other agro-climatic zones.

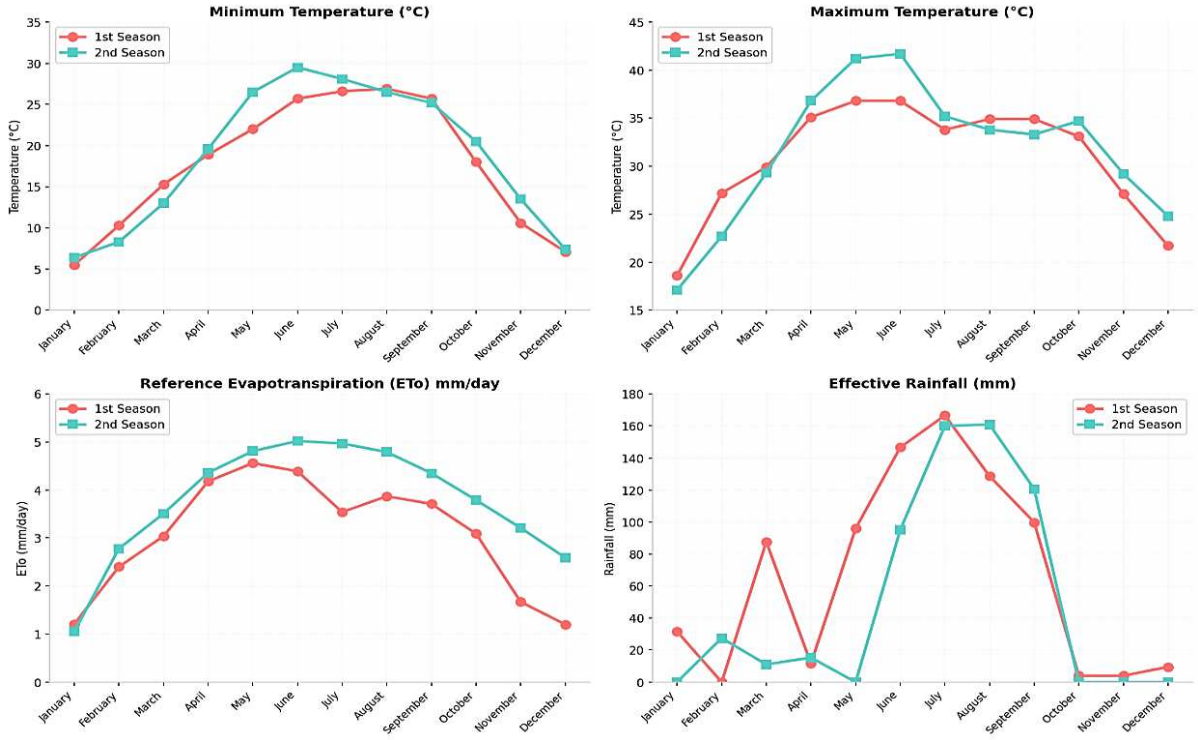


Fig. 1 Comparative trends of temperature, evapotranspiration, and rainfall during the two cropping seasons (2023–2024 and 2024–2025)

2.5 Experimental Design and Treatment Structure

Both seasons followed a split-plot design replicated three times, with irrigation regime (I_1–I_3) as the main-plot factor and nutrient regime (N_1–N_4) as the sub-plot factor nested within it; each plot measured 2 m × 3 m (6 m²). This gave 12 irrigation × nutrient combinations × 3 replicates = 36 plots per season (72 plots over the two seasons). The four nutrient regimes were: N_1, fully chemical recommended dose (urea 130.43 g, SSP 281.25 g, MOP 75 g plot^{-1}); N_2, 100% of crop nitrogen from Jeevamrutha with chemical P and K; N_3, 75% of crop nitrogen from Jeevamrutha with chemical P and K; and N_4, 50% of crop nitrogen from Jeevamrutha with chemical P and K, with supplementary chemical nitrogen added in N_3 and N_4 to bring total N to the recommended dose.

2.6 Observations and Measurements

Plant height, canopy spread and primary branch number were recorded at 30, 60 and 90 DAT on five representative plants per plot. Days to bud initiation and to 50% open flowers were recorded, and post-harvest longevity was assessed on ten cut flowers per plot held under standardised indoor conditions. Mean single-flower weight was determined from ten fully open flowers chosen at random, and flower yield was summed over all pickings and expressed per hectare. At final harvest, rhizosphere soil (0–15 cm; three composite sub-samples per plot) was serially diluted (10^{-1} to 10^{-7}; three plates per dilution) and

plated on nutrient agar for bacteria (37 °C, 48 h), potato dextrose agar for fungi (28 °C, 72 h) and Kuster's agar for actinomycetes (28 °C, 96 h); only plates with 30–300 colonies were counted and converted to cfu g^{-1} oven-dry soil. Un-inoculated blanks accompanied every plating run and reference strains were streaked periodically to confirm medium selectivity, giving a practical detection floor of ≈10^2 cfu g^{-1} soil. Counts were $\log_{10}$-transformed before ANOVA to stabilise variance and satisfy normality (confirmed by the Shapiro–Wilk test); back-transformed geometric means are reported in Table 2. These plate counts capture only the culturable fraction of the community on the selective media used; sequencing-based work shows that culturable and total (sequence-detected) taxa can diverge and that cultivability itself varies with growth conditions [27], so the counts here should be read as an index of the responsive, readily culturable community rather than of total microbial diversity, a point returned to in Section 3.1. Soil dehydrogenase activity was determined by the triphenyl tetrazolium chloride (TTC) reduction method (colorimetric reading of triphenyl formazan at ≈485 nm) and expressed as µg TPF g^{-1} soil h^{-1}. Post-harvest available soil N, P and K were measured by the alkaline permanganate, Olsen and flame-photometric procedures, respectively. Economic assessment used a mean study-period farm-gate price of ₹20 kg^{-1} for fresh flowers (Azadpur Mandi, Delhi) together with treatment-wise input costs and common overheads (detailed in Section 3.4). Complete plating protocols, including media recipes and full replicate-level data, are available from the corresponding author on reasonable request.

2.7 Statistical Analysis

Data were subjected to split-plot ANOVA, with irrigation (main-plot) effects tested over the block × irrigation error term and nutrient (sub-plot) and interaction effects tested over the residual sub-plot error, following the model:

$$\text{Eq. (3): } Y_{ijk} = \mu + \alpha_i + \delta_{ik} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}$$

Season (year) entered the model as an additional fixed factor, and season × treatment interactions were tested before any pooling; data were combined across seasons only where these interactions were non-significant ($P > 0.05$) and treatment rankings were consistent between years. Normality was checked with the Shapiro–Wilk test and homogeneity of variance with Levene's test; treatment means were separated by Tukey's Honestly Significant Difference (HSD) test at $P \leq 0.05$. All analyses used R v.4.3.1 with the agricolae package. Exact F and P values for every main effect and interaction discussed in Section 3, together with partial η^2 effect sizes, are given in Supplementary Table S1; the season × treatment F and P values underpinning the pooling decision are given in Supplementary Table S2.

2.8 Integrated Assessment of Treatment Performance

To synthesise the multidimensional treatment response, a Comprehensive Treatment Performance Index (CTPI) was computed for the 12 irrigation × nutrient combinations from pooled two-season means. Nine benefit-type indicators were grouped into four equally weighted domains: soil biological health (bacterial, fungal and actinomycete counts and dehydrogenase activity), soil fertility (post-harvest available N, P and K), crop productivity (flower yield) and economic performance (net return). Each indicator was rescaled to 0–1 by min–max normalisation, $(X - Xmin)/(Xmax - Xmin)$, where Xmin and Xmax are the lowest and highest treatment means for that indicator; the normalised indicators were averaged within each domain, and the CTPI was taken as the unweighted mean of the four domain scores. Domain-level averaging prevented the four-indicator biological domain from dominating, and equal weighting kept the index transparent. The CTPI is a descriptive synthesis that complements, and does not replace, the ANOVA of the individual variables, and is bounded to the treatment range examined.

Table 1. Composition of the Jeevamrutha soil drench (chemical constituents and microbial counts) prepared during the 2023–2024 and 2024–2025 Rabi seasons.

Parameter	Unit	Value
Nutrient composition		
Nitrogen (N)	%	0.05
Phosphorus (P)	%	0.02
Potassium (K)	%	0.05
Calcium (Ca)	%	0.04
Magnesium (Mg)	%	0.02
Zinc (Zn)	mg kg^{-1}	1.5
Manganese (Mn)	mg kg^{-1}	1.6
Copper (Cu)	mg kg^{-1}	1.3
Iron (Fe)	mg kg^{-1}	38.4
Microbial populations		
Total bacteria	cfu mL^{-1}	145×10^6
Fungi	cfu mL^{-1}	14.5×10^4
Actinomycetes	cfu mL^{-1}	2.0×10^3
Nitrogen-fixing bacteria	cfu mL^{-1}	7.5×10^4
P-solubilizing bacteria	cfu mL^{-1}	11.5×10^4
K-solubilizing bacteria	cfu mL^{-1}	2.5×10^4
Pseudomonas fluorescens	cfu mL^{-1}	5.5×10^4
Trichoderma spp.	cfu mL^{-1}	3.5×10^4
Total coliforms (post-fermentation)	cfu mL^{-1}	~3.8×10^5

Note Concentrations on a fresh-weight basis; solution density assumed 1.00 kg L^{-1}. cfu, colony-forming units. Faecal coliform counts declined from ~5.5×10^5 to ~1.7×10^5 cfu mL^{-1} within 24 h of fermentation, indicating progressive pathogen suppression.

3. Results and Discussion

3.1 Rhizosphere Microbial Abundance: Irrigation and Nutrient Effects

The Jeevamrutha used in this study carried bacteria, fungi and actinomycetes together with functional groups such as nitrogen fixers and phosphorus solubilisers (Table 1), providing the biological basis for the rhizosphere responses examined here. Both irrigation regime and nutrient treatment had significant ($P < 0.001$) independent effects

on rhizosphere bacterial, fungal and actinomycete counts at final harvest (Supplementary Table S1). The irrigation × nutrient interaction was significant ($P < 0.05$) for bacteria and actinomycetes but not for fungi ($P = 0.07$), suggesting the fungal community responded predominantly to substrate supply from the organic amendment rather than to soil moisture. Season × treatment interactions were non-significant for all three groups ($P = 0.24–0.61$; Supplementary Table S2), so pooled two-season means are presented (Table 2). These counts represent the culturable fraction on standard selective media and do not measure community functional diversity, metabolic activity or overall microbial health, none of which were assessed directly here; as noted in Section 2.6, culturable and sequence-detected taxa can diverge [27], so the interpretation below is scoped to the responsive, readily culturable community.

Among irrigation treatments, moderate deficit (I_3, 0.6 ETc) gave the highest bacterial (6.67×10^7 cfu g^{-1}), fungal (3.99×10^5 cfu g^{-1}) and actinomycete (2.92×10^6 cfu g^{-1}) counts, with full irrigation (I_1) lowest and mild deficit (I_2) intermediate, a graded response across the 0.6–1.0 ETc range. The increases of I_3 over I_1 were closely similar in relative terms (11.7%, 11.9% and 11.5% for bacteria, fungi and actinomycetes, respectively), indicating a broadly uniform response of the culturable community to reduced soil matric potential over this range. A likely physical explanation is that, at 0.6 ETc, volumetric soil moisture in the 0–15 cm layer remained at 10–13%, above the permanent wilting point of 8.7%, imposing only mild plant water stress while increasing the air-filled pore fraction of this sandy loam and, with it, the oxygen available for aerobic microbial metabolism [12]. Lower percolation under I_3 would also have reduced downward transport of dissolved organic carbon and mineral nutrients, retaining microbial substrates in the rhizosphere [28], whereas under full irrigation transient anaerobic micropores and greater leaching of soluble substrates may have suppressed obligate aerobes such as actinomycetes [29]. These mechanisms are inferred from established soil-physical principles and the cited literature rather than measured directly; confirmation would require dissolved-oxygen and dissolved-organic-carbon measurements, which are recommended for future work.

Among nutrient treatments, full Jeevamrutha-N substitution (N_2) gave the highest counts for all three groups, exceeding the chemical-fertiliser control (N_1) by 27.8% for bacteria (6.99 vs. 5.48×10^7 cfu g^{-1}), 27.1% for fungi (4.18 vs. 3.29×10^5 cfu g^{-1}) and 26.9% for actinomycetes (3.07 vs. 2.42×10^6 cfu g^{-1}). The similarity of this proportional increase across taxonomically distinct groups is consistent with a broad biostimulatory effect rather than promotion of a single taxon, probably reflecting two mechanisms acting together: direct inoculation from the microbial load carried in each fortnightly Jeevamrutha application, including nitrogen fixers (7.5×10^4 cfu mL^{-1}), phosphorus solubilisers (11.5×10^4 cfu mL^{-1}) and biocontrol agents such as *Pseudomonas fluorescens* (5.5×10^4 cfu mL^{-1}) and *Trichoderma* spp. (3.5×10^4 cfu mL^{-1}), and the readily available carbon and nitrogen supplied by the jaggery and pulse-flour fractions, which can sustain microbial

growth in the period following each application [30-31]. These results agree with a three-year field study reporting 20–35% higher bacterial counts under organic amendment than chemical fertilisation in pigeon pea [32], and are consistent with recent metagenomic evidence that Jeevamrit itself carries a functionally stratified, cooperating microbial consortium capable of nutrient mobilisation and rhizosphere competence [21, 33], as well as with a comparable field trial in strawberry in which natural-farming inputs of this kind increased rhizosphere microbiome activity alongside fruiting response [22, 34]. Partial-substitution treatments (N_3, N_4) gave intermediate, progressively lower counts, indicating a positive dose–response between Jeevamrutha volume and microbial stimulation across the 50–100% substitution range, consistent with reports in cowpea, where jeevamrutha and panchagavya application likewise produced a graded growth response [35].

In the interaction analysis, I_3N_2 recorded the highest bacterial (7.41×10^7 cfu g^{-1}, pooled mean) and actinomycete counts among the 12 combinations, differing significantly from I_1N_1 by the HSD test, and exceeding the value predicted from the additive I_3 and N_2 main effects, consistent with the significant irrigation × nutrient interaction reported above and with documented water–organic-matter interactions in soil microbial ecology [36]. A parsimonious explanation is that the aerobic, substrate-enriched rhizosphere created under I_3 favours establishment of the culturable community introduced through Jeevamrutha, whereas under full irrigation this community may be constrained by intermittent anaerobiosis and leaching. Soil dehydrogenase activity, an integrated index of microbial metabolic activity, followed the same pattern: I_3 recorded the highest activity (2.09 µg TPF g^{-1} soil h^{-1}), significantly above I_1 (1.87) and I_2 (1.82, not different from I_1); N_2 gave the highest activity among nutrient treatments (2.16), significantly exceeding N_3 (1.93), N_4 (1.88) and N_1 (1.72); and I_3N_2 reached the overall maximum (2.44). This correspondence between dehydrogenase activity and culturable abundance indicates that the I_3N_2 combination enhanced both the size and the metabolic activity of the rhizosphere community, a pattern broadly consistent with recent evidence that long-term, well-matched nutrient management can raise soil microbial activity and its resilience under moisture stress [37] and with reviews linking mineral–organic fertiliser balance to soil microbial functioning more generally [38]. Taken together, the higher microbial abundance recorded under Jeevamrutha should not be attributed to the amendment in isolation; it more likely reflects the joint influence of soil moisture, carbon-substrate availability, root exudation and aeration, with regulated deficit irrigation amplifying the microbial response to Jeevamrutha beyond what either practice achieves alone. This interaction-based reading is the most parsimonious one consistent with the data and should be tested directly through measurement of dissolved oxygen, dissolved organic carbon and root-exudate profiles in future work.

3.2 Post-harvest Available Soil Nutrient Status: Mechanisms and Agronomic Interpretation

The higher rhizosphere microbial abundance and dehydrogenase activity described above were accompanied by differences in the post-harvest available soil nutrient pool. The irrigation × nutrient interaction was significant for post-harvest available N, P and K ($P = 0.0032$, < 0.0001 and < 0.0001, respectively; Table 3), so the treatment combinations are considered alongside the main effects. At the treatment-combination level, I_3N_2 (T10; 0.6 ETc with 100% Jeevamrutha-N and adjusted chemical P and K) showed the highest pooled available N, P and K among the twelve combinations (Fig. 4). Season × treatment interactions were non-significant for N but significant for P and K; the pooled P and K means are therefore presented descriptively, with season-specific means reserved for inferential statements. These pools represent soil-test available fractions after harvest rather than a complete fertiliser-N or fertiliser-K recovery balance, and are interpreted below in terms of nutrient mineralisation, retention, reduced losses and crop uptake.

Among irrigation regimes, post-harvest available N, P and K were each highest under moderate deficit (I_3). Available N increased from 134.84 kg ha^{-1} under I_1 and 137.20 under I_2 to 143.75 under I_3, the I_3 value exceeding both I_1 (by 6.6%) and I_2 (by 4.8%) by more than the HSD ($HSD_{0.05} = 5.66$), while I_1 and I_2 did not differ. Available K rose in the order I_1 (278.26) < I_2 (281.13) < I_3 (282.76 kg ha^{-1}), all pairwise differences significant ($HSD_{0.05} = 0.14$), and available P was marginally but significantly higher under I_3 (35.14 kg ha^{-1}) than under I_1 (34.69) and I_2 (34.62; $HSD_{0.05} = 0.26$). The consistent rise in post-harvest N, P and K under reduced irrigation may reflect lower cumulative percolation and reduced convective transport of NO_3^- and K^+ out of the root zone in this sandy loam, a pattern consistent with established water–fertiliser coupling [28]; the smaller response of P is in line with its largely diffusion-controlled transport. That the higher flower yields recorded under I_3 (Section 3.3) were not accompanied by any sign of nutrient limitation is consistent with this reading, although plant-tissue uptake data or ^{15}N tracing would be required to separate reduced leaching from reduced uptake [39].

Among nutrient treatments, N_2 (100% Jeevamrutha-N) gave the highest pooled available P (40.63 kg ha^{-1}) and K (286.67 kg ha^{-1}), each exceeding the other nutrient treatments by more than the HSD, and the numerically highest available N (141.82 kg ha^{-1}), although available N did not differ significantly among nutrient treatments ($HSD_{0.05} = 6.61$). The higher available P and K under N_2 could be associated with the gradual mineralisation of organically bound P and K supplied by Jeevamrutha and with the organic matter it adds, which may raise the cation-exchange capacity of this light-textured soil and retain exchangeable K more effectively than the fully soluble muriate of potash used in N_1 [30, 40]; the phosphorus-solubilising bacteria carried in Jeevamrutha (11.5×10^4 cfu mL^{-1}) may likewise contribute to a larger Olsen-extractable P fraction persisting after harvest [41-42]. The partial-substitution treatments (N_3 and N_4) had the lowest available P (31.70 and 30.91 kg ha^{-1}) and K (277.32 and 274.76 kg ha^{-1}), below the chemical-fertiliser control, which suggests that at lower Jeevamrutha volumes the supplementary chemical

P and K, together with reduced organic-matter input, were insufficient to maintain the post-harvest available pool. This has a practical implication for extension: partial-substitution strategies may need proportionally higher chemical P and K support on light-textured, low-retention soils of this kind [43]. More broadly, the favourable post-harvest available-nutrient status under I_3N_2 is consistent with independent evidence that natural-farming-based nutrient management can improve soil fertility indices in other cropping systems [44].

Table 2. Rhizosphere microbial populations of marigold at harvest as influenced by deficit irrigation and Jeevamrutha-based nutrition (means pooled over the 2023–2024 and 2024–2025 Rabi seasons).

Treatment	Bacterial count ($\times 10^7$ cfu g^{-1} soil)	Fungal count ($\times 10^5$ cfu g^{-1} soil)	Actinomycetes count ($\times 10^6$ cfu g^{-1} soil)	Dehydrogenase activity (µg TPF g^{-1} soil h^{-1})
Main plot – Irrigation regimes				
I_1 (1.0 ETc)	5.97[b]	3.56[b]	2.62[b]	1.87[b]
I_2 (0.8 ETc)	5.85[b]	3.48[b]	2.55[b]	1.82[b]
I_3 (0.6 ETc)	6.67[a]	3.99[a]	2.92[a]	2.09[a]
$HSD_{0.05}$	0.17	0.11	0.075	0.07
Sub-plot – Nutrient complex				
N_1 (100% RDF by CF)	5.475[c]	3.29[c]	2.42[c]	1.72[c]
N_2 (100% Jeevamrutha-N + PK by CF)	6.99[a]	4.18[a]	3.07[a]	2.16[a]
N_3 (75% Jeevamrutha-N + PK by CF)	6.165[b]	3.67[b]	2.68[b]	1.93[b]
N_4 (50% Jeevamrutha-N + PK by CF)	6.02[b]	3.57[b]	2.61[b]	1.88[b]
$HSD_{0.05}$	0.275	0.12	0.115	0.11

Note Each value is a mean of three replications; within a column and treatment factor, values not sharing a common superscript letter differ significantly (Tukey's HSD, P ≤ 0.05). ETc crop evapotranspiration; CF chemical fertilizer; RDF recommended dose of fertilizer; HSD honestly significant difference.

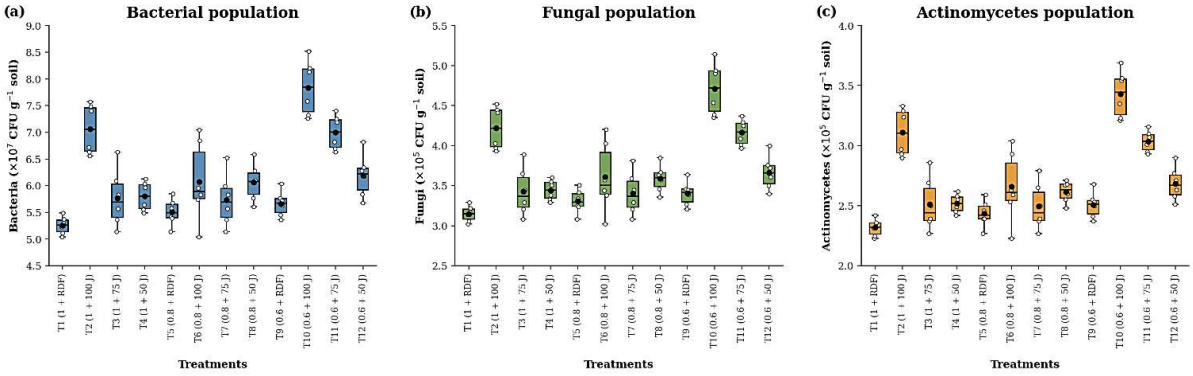


Fig. 2 Rhizosphere microbial populations (bacteria, fungi, and actinomycetes) under the 12 irrigation × nutrient treatment combinations at marigold harvest. Bars represent pooled two-season means; error bars denote ±1 standard error of the mean

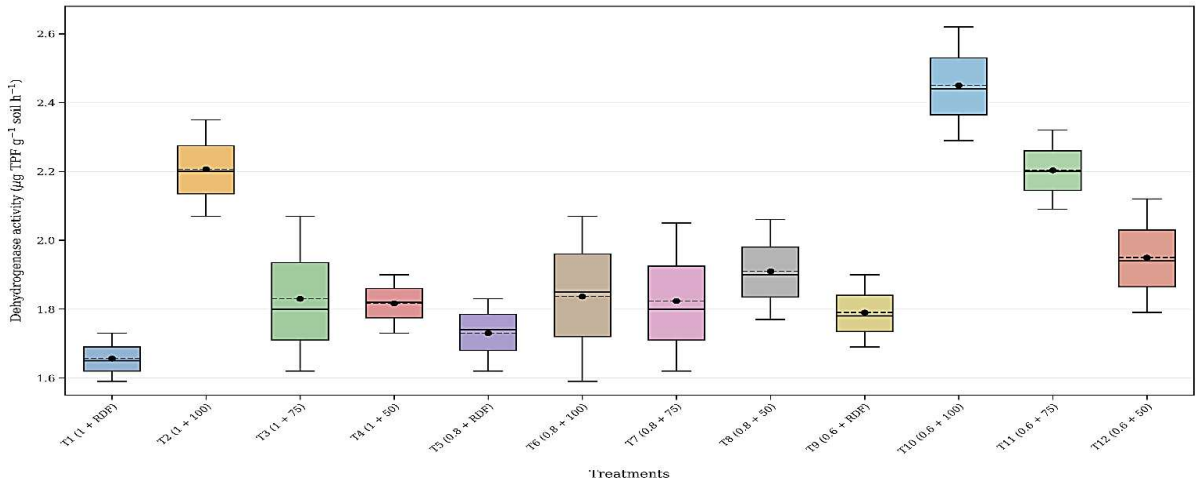


Fig. 3 Soil dehydrogenase activity under deficit irrigation and Jeevamrutha-based nutrition across the 12 treatment combinations. Bars represent pooled two-season means; error bars denote ±1 standard error of the mean

Table 3. Post-harvest available soil N, P and K after marigold harvest under deficit irrigation and Jeevamrutha-based nutrition (means pooled over the 2023–2024 and 2024–2025 Rabi seasons).

Treatment	Available N (kg ha⁻¹)	Available P (kg ha⁻¹)	Available K (kg ha⁻¹)
Main plot – Irrigation regimes			
I_1 (1.0 ETc)	134.84 ± 1.50	34.69 ± 1.78	278.26 ± 2.51
I_2 (0.8 ETc)	137.20 ± 2.10	34.62 ± 1.86	281.13 ± 2.47
I_3 (0.6 ETc)	143.75 ± 2.00	35.14 ± 1.90	282.76 ± 2.39
$HSD_{0·05}$	5.66	0.26	0.14
Sub-plot – Nutrient complex			
N_1 (100% RDF-CF)	137.28 ± 2.25	36.03 ± 1.88	284.12 ± 1.97
N_2 (100% Jeevamrutha-N + PK-CF)	141.82 ± 2.66	40.63 ± 2.37	286.67 ± 3.07
N_3 (75% Jeevamrutha-N + PK-CF)	137.99 ± 2.55	31.70 ± 1.72	277.32 ± 2.70
N_4 (50% Jeevamrutha-N + PK-CF)	137.28 ± 1.77	30.91 ± 1.68	274.76 ± 2.72
$HSD_{0·05}$	6.61	0.36	0.24

Note Values are means ± standard error (n = 6 per irrigation mean; n = 18 per nutrient mean, pooled over two seasons); $HSD_{0·05}$ values were computed from the split-plot error terms (Tukey's HSD). The irrigation × nutrient interaction was significant for available N, P and K (P = 0.0032, < 0.0001 and < 0.0001, respectively). Season × irrigation and season × nutrient interactions were non-significant for N but significant for P and K, so the pooled P and K means are presented descriptively and season-specific means are used for inferential statements. ETc crop evapotranspiration; RDF recommended dose of fertilizer; CF chemical fertilizer; PK-CF phosphorus and potassium as chemical fertilizer; HSD honestly significant difference.

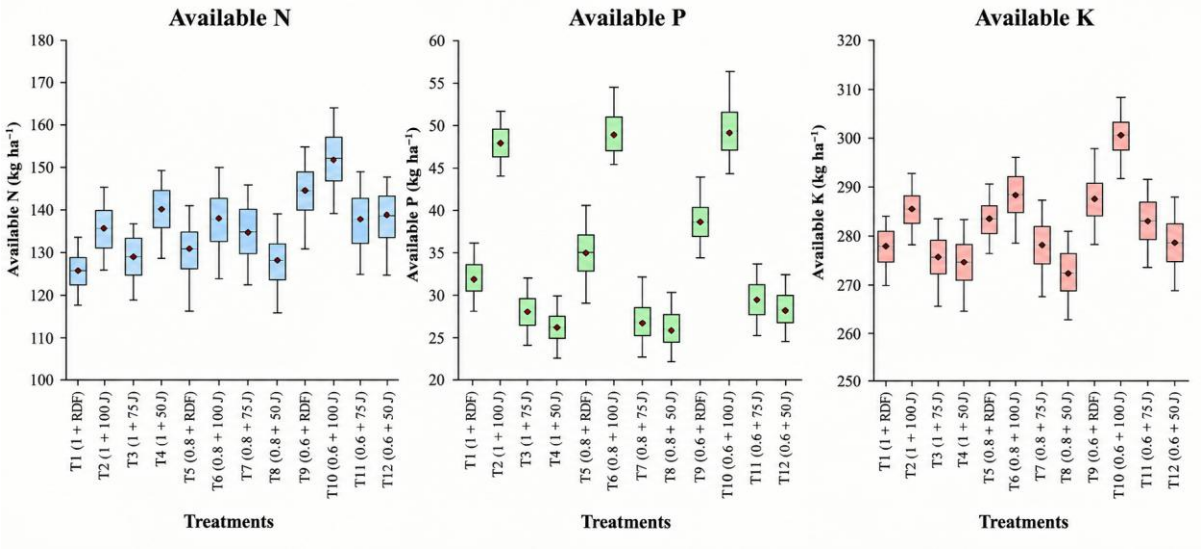


Fig. 4 post-harvest available soil N, P and K under the 12 irrigation × nutrient treatment combinations after marigold harvest. Boxes show the interquartile range, the central line the median and the diamond the mean; whiskers denote the range of the pooled two-season observations

3.3 Plant Growth, Flowering Phenology and Flower Yield

The changes in post-harvest available soil nutrient status described above were mirrored in crop growth, flowering and yield. Irrigation regime, nutrient treatment and their interaction each had significant effects ($P < 0.0001$ in almost all cases, the exceptions being irrigation effects on shoot number [$F = 7.09$, $P = 0.0042$] and days to 50% flowering [$F = 6.18$, $P = 0.0076$]) on the traits summarised in Table 4 and Fig. 5 (full ANOVA in Supplementary Table S1); season × treatment interactions were non-significant throughout ($P > 0.05$), supporting pooled presentation. Overall, I_3N_2 combined moderate vegetative branching with greater plant height, heavier and longer-lasting flowers, and the highest marketable yield, a profile well suited to the loose-flower market.

Plant height and canopy architecture. Moderate deficit (I_3) produced the tallest plants (67.72 cm), significantly above I_2 (65.79 cm) and I_1 (63.69 cm). This inverse relationship between water supply and plant height has also been reported in related ornamentals and attributed to reduced ethylene accumulation under aerobic soil conditions, since waterlogging under full irrigation can promote ethylene biosynthesis and restrict internode elongation via suppressed gibberellin signalling [45]; this mechanism is drawn from the cited literature and was not assessed directly here. Canopy spread was likewise largest under I_3 (47.96 cm) relative to I_1 (45.71 cm) and I_2 (45.91 cm), though the I_2–I_1 difference was small. Primary branch number showed the opposite pattern: highest under I_2 (6.06), lowest under I_3 (5.40), I_1 intermediate (5.80), suggesting that mild deficit maintains enough turgor for axillary bud break while reducing apical dominance, whereas moderate deficit limits bud release without a matching reduction in apical dominance; this hormonal interpretation remains tentative without cytokinin and auxin data. Among nutrient treatments, N_2 produced the tallest plants (68.72 cm), widest canopy (47.74 cm) and highest branch count (6.18), reasonably reflecting both the mineral-N released as the

organic-N fraction mineralises through the season and phytohormone-like compounds from the *Pseudomonas* and *Trichoderma* components of the inoculant [17]. N_1 gave the second-tallest plants (67.20 cm) but fewer branches (5.64) and a narrower canopy (47.29 cm), consistent with readily available mineral-N from urea favouring apical growth and internode elongation over lateral branching; lower Jeevamrutha volumes (N_3, N_4) gave progressively shorter plants and smaller canopies, again indicating a dose-dependent response.

Flowering phenology. Bud initiation was progressively delayed as irrigation decreased (I_3: 56.59 days vs. I_1: 53.59 days), a 3-day shift possibly reflecting temporary diversion of assimilate toward osmotic adjustment and root growth under water deficit, at the expense of carbon available to developing floral meristems. Once flowering began, however, I_3 flowers showed longer individual longevity (22.17 vs. 19.43 days for I_1), suggesting that the moderate stress experienced during vegetative growth favoured more durable floral tissue, possibly through stronger petal cell walls or higher petal carotenoid concentration, traits associated with extended vase life in *Tagetes* but not measured here [46]. Among nutrient treatments, N_2 reached 50% flowering latest (65.66 vs. 64.52 days for N_1), probably because slow-release nitrogen from Jeevamrutha extended vegetative development; this small delay did not translate into a yield penalty.

Individual flower weight and vase life. Individual flower weight increased with irrigation deficit (I_3: 13.06 g, 4.6% above I_2 and 16.1% above I_1), consistent with reduced water movement into petal vacuoles at lower turgor giving firmer, denser tissue with higher dry-matter content [18], and was accompanied by longer vase life under I_3 (22.17 vs. 19.43 days for I_1). Among nutrient treatments, N_1 gave the highest individual flower weight (13.70 g) and longest vase life (22.89 days), above N_2 (12.78 g; 21.07 days), possibly because the concentrated mineral-N pulses in N_1 promote rapid floral biomass accumulation compared with the more gradual carbohydrate loading under the slow-release Jeevamrutha-N profile. Despite this, N_2 produced higher total yield through a greater number of flowers per plant, so its advantage lies in productivity rather than per-flower quality.

Flower yield. Flower yield ranked I_3 (14.76 t ha^{-1}) > I_2 (13.14 t ha^{-1}) > I_1 (12.52 t ha^{-1}), all pairwise differences significant ($HSD_{0.05}$ = 0.17 t ha^{-1}). The I_3-over-I_1 advantage (+17.9%) exceeded the I_2-over-I_1 advantage (+4.9%), indicating a non-linear yield–water relationship over the 0.6–1.0 ETc range for marigold in this environment, in which a 38.6% reduction in seasonal irrigation was associated with a disproportionately larger yield gain. Although formal water-use-efficiency values were not calculated, this pattern of higher yield at lower water input is consistent with water-productivity gains reported for regulated deficit irrigation in other horticultural crops [6-7, 47]. Among nutrient treatments, N_2 (14.98 t ha^{-1}) significantly exceeded N_1 (13.03), N_3 (13.39) and N_4 (12.49 t ha^{-1}); the 15.0% yield advantage of N_2 over N_1 is consistent with the 14–18% gain reported for Jeevamrutha-based nutrition in marigold cv. Siracole [18, 48] and with comparable advantages of organic amendments over chemical fertiliser reported in pearl millet [49].

Interaction effects. I_3N_2 gave the highest pooled two-season flower yield (16,909 kg ha^{-1}; Table 5), significantly above every other combination (Tukey HSD, $P \leq 0.05$). That

I_3N_2 (16,909 kg ha^{-1}) exceeded I_3N_1 (14,471 kg ha^{-1}) by more than I_1N_2 (13,926 kg ha^{-1}) exceeded I_1N_1 shows that the yield gain from moderate deficit was largest when paired with full Jeevamrutha-N substitution; conversely, that the gap between I_1N_2 and I_3N_2 was larger than the gap between I_1N_1 and I_3N_1 shows that the response to Jeevamrutha was itself greater under the rhizosphere conditions created by moderate deficit. This mutual reinforcement is consistent with the significant microbial interaction described in Section 3.1, the elevated microbial abundance under I_3N_2 supported greater nutrient mineralisation, root-hair proliferation and phytohormone production, which in turn contributed to the higher yield, a pattern conceptually similar to the interaction recently reported between deficit irrigation and biostimulation in table grape, where the combination outperformed either practice alone [20].

Physiological basis of the deficit-irrigation growth and yield response. The higher growth and yield under I_3 is most likely explained by a set of coordinated physiological adjustments rather than a single mechanism. Mild-to-moderate water deficit is well documented to induce osmotic adjustment, in which cells accumulate compatible solutes to maintain turgor and sustain expansion at lower water potential, consistent with the taller plants and wider canopy recorded under I_3 despite lower water input. Partial stomatal closure under moderate deficit probably reduced transpirational water loss while maintaining adequate CO_2 assimilation, a response linked elsewhere to improved intrinsic water-use efficiency in horticultural species [6]; gas-exchange measurements were not made here, so this mechanism is inferred rather than confirmed. Deficit stress is also known to alter source–sink relationships and assimilate partitioning, directing photosynthate away from vegetative growth (reflected in the lower branch number under I_3) and toward reproductive sinks, consistent with the heavier flowers and higher yield recorded. Finer-root proliferation with a higher surface-area-to-volume ratio under moderate water limitation may have improved water and nutrient capture and contributed to the higher post-harvest available soil-nutrient pools discussed in Section 3.2. Confirming this set of mechanisms would require leaf water potential, stomatal conductance and root-architecture measurements, which were outside the scope of this study and are recommended as priorities for future work.

Table 4. Growth, flowering phenology and flower yield of marigold under deficit irrigation and Jeevamrutha-based nutrition (means pooled over the 2023–2024 and 2024–2025 Rabi seasons).

Treatment	Plant height (cm)	Canopy spread (cm)	No. of shoots	Bud initiation (days)	50% flowering (days)	Flower duration (days)	Flower weight (g)	Flower yield (t ha^{-1})
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

Note Each value is a mean of three replications; within a column and treatment factor, values not sharing a common superscript letter differ significantly (Tukey's HSD, P ≤ 0.05). ETc crop evapotranspiration; CF chemical fertilizer; RDF recommended dose of fertilizer; HSD honestly significant difference.

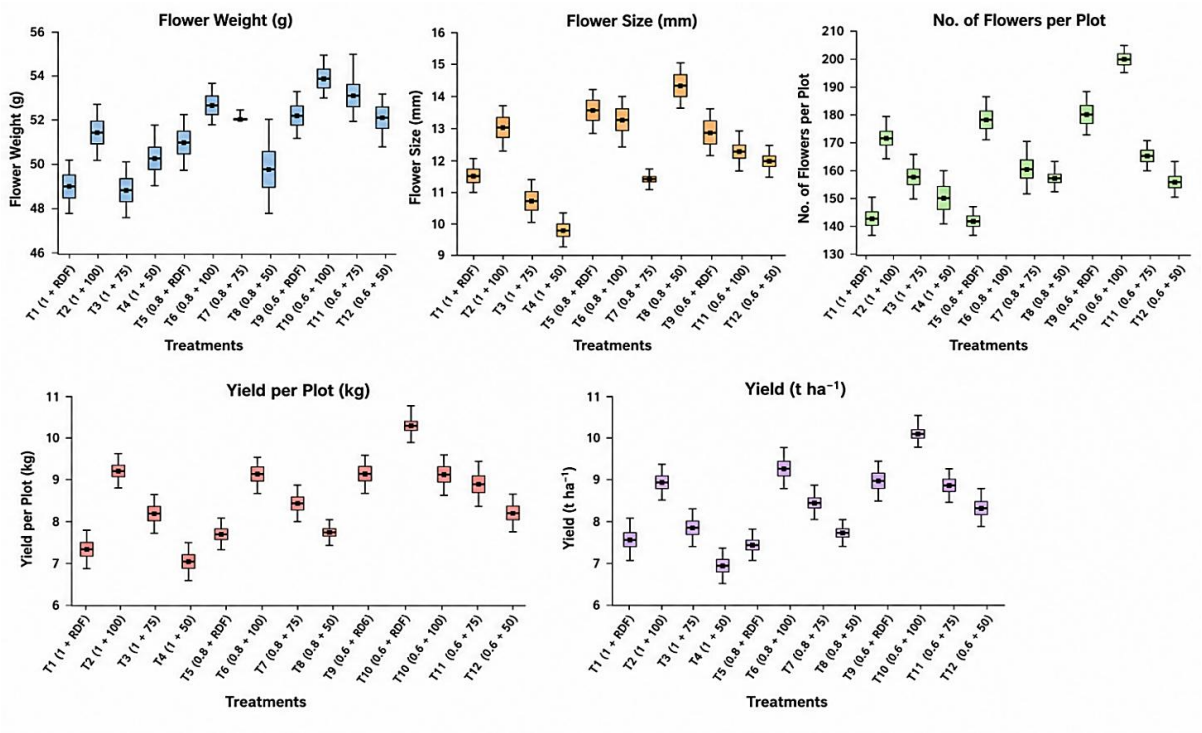


Fig. 5 Irrigation × nutrient interaction means for plant height, canopy spread, and flower yield across all 12 treatment combinations. Pooled two-season means with ±1 SE error bars

3.4 Economic Feasibility and Profitability Analysis

The agronomic responses above were assessed in economic terms to establish their practical value, using a reference fresh-flower price of ₹20 kg^{-1}, the mean wholesale rate at Delhi's Azadpur Mandi over the study period (November 2023–January 2025). Treatment-specific total production costs per hectare comprised seedling material (₹3,200, uniform), land preparation and transplanting labour (₹8,500, uniform), irrigation energy and operation (₹4,200 for I_3 to ₹4,800 for I_1), nutrient inputs (₹2,000 for chemical N_1 to ₹3,600 for full Jeevamrutha-N under N_2, including ingredient and preparation labour at ₹280 per 200-L batch), and harvest and post-harvest handling (₹8,200–10,500, proportional to yield); total costs ranged from ₹1,07,500 ha^{-1} (50% Jeevamrutha-N treatments) to ₹1,21,833 ha^{-1} (chemical-fertiliser controls). I_3N_2 gave the highest gross revenue (₹3,38,187 ha^{-1}), net returns (₹2,21,687 ha^{-1}) and benefit–cost ratio (1.90; Table 5, Fig. 6), 0.35 above the next-highest treatment (I_3N_3; B:C = 1.55), a gain from full rather

than partial Jeevamrutha-N substitution under moderate deficit. The lowest-ranked treatment (I_1N_1; B:C = 1.00) returned ₹1,22,250 ha^{-1} net, ₹99,437 ha^{-1} below I_3N_2, a difference of clear practical relevance for smallholders who depend on floriculture for income.

The profitability gradient $I_3 > I_2 > I_1$ held within every nutrient treatment, reflecting both the higher yield and the marginally lower irrigation energy cost (≈₹600 ha^{-1} relative to I_1) under moderate deficit. All N_2 treatments outperformed their N_1 counterparts at the same irrigation level despite a production cost about ₹5,333 ha^{-1} lower than the chemical-fertiliser control, so the economic advantage of Jeevamrutha-based nitrogen substitution arises from both lower input cost and higher yield simultaneously; because cost structure varied little across treatments, differences in profitability were driven mainly by yield. This cost profile suggests that adoption of Jeevamrutha at the N_2 level would likely remain economically favourable even if ingredient or labour costs rose moderately at commercial scale [43].

Several limitations qualify this analysis and should inform how the results are used. The reference price (₹20 kg^{-1}) is a study-period mean; Azadpur Mandi prices for fresh marigold range from ₹8 to ₹40 kg^{-1} across the season, and the I_3N_2-over-I_1N_1 advantage would narrow at the lower end of this range. Jeevamrutha preparation is most practical where households keep dairy cattle and can source low-cost dung and urine; farms without integrated livestock may face materially higher ingredient costs. The analysis is confined to one location, one soil type and two seasons, and does not capture year-to-year variation in price, rainfall or input cost; multi-year, multi-site economic studies incorporating price variability are needed before general extension or policy recommendations are made, and the long-term trajectory of the I_3N_2 system (including cumulative effects on soil organic carbon, microbial community composition and nutrient balance) warrants dedicated longer-term study. Practical feasibility at commercial scale also deserves comment. The seasonal Jeevamrutha volume used here (≈200,000 L ha^{-1}, prepared in 200-L batches, applied as six fortnightly doses) requires dedicated storage, a seven-day fermentation cycle with daily stirring, and an estimated 2–3 labour-hours per 200-L batch for assembly, mixing and application; these costs were included in the analysis (₹280 per batch) but may limit adoption where hired labour is scarce or costly. Reliable access to fresh cow dung and urine, and to consistent-quality jaggery and pulse flour, is a further constraint: for smallholders with integrated crop–livestock systems these inputs are typically low-cost, but input-purchasing or peri-urban producers could see reduced margins. Scaling Jeevamrutha preparation and application from plot to commercial area would also require mechanised mixing, storage and drenching infrastructure that was not evaluated here and represents a necessary next step before large-scale adoption is recommended.

Table 5. Economics of the deficit irrigation × Jeevamrutha-based nutrition treatment combinations in marigold (means pooled over the 2023–2024 and 2024–2025 Rabi seasons).

Treatment	Total cost (₹ ha⁻¹)	Yield (kg ha⁻¹)	Total revenue (₹ ha⁻¹)	Net margin (₹ ha⁻¹)	B:C ratio	Economic rank
I_1N_1 (1.0 ETc + 100% RDF by CF)	1,21,833	12,204.17^{d}	2,44,083.40	1,22,250.40^{e}	1.00^{e}	12
I_1N_2 (1.0 ETc + 100% N from Jeevamrutha + Adj. PK by CF)	1,16,500	13,925.67^{c}	2,78,513.40	1,62,013.40^{cd}	1.39^{cd}	5
I_1N_3 (1.0 ETc + 75% N from Jeevamrutha + Adj. PK by CF)	1,12,000	12,494.33^{d}	2,49,886.80	1,37,886.80^{de}	1.23^{de}	9
I_1N_4 (1.0 ETc + 50% N from Jeevamrutha + Adj. PK by CF)	1,07,500	11,433.12^{e}	2,28,662.40	1,21,162.40^{f}	1.13^{f}	10
I_2N_1 (0.8 ETc + 100% RDF by CF)	1,21,833	12,424.27^{d}	2,48,485.40	1,26,652.40^{de}	1.04^{e}	11
I_2N_2 (0.8 ETc + 100% N from Jeevamrutha + Adj. PK by CF)	1,16,500	14,093.51^{c}	2,81,870.20	1,65,370.20^{c}	1.42^{c}	4
I_2N_3 (0.8 ETc + 75% N from Jeevamrutha + Adj. PK by CF)	1,12,000	13,369.32^{cd}	2,67,386.40	1,55,386.40^{d}	1.39^{d}	6
I_2N_4 (0.8 ETc + 50% N from Jeevamrutha + Adj. PK by CF)	1,07,500	12,659.82^{d}	2,53,196.40	1,45,696.40^{de}	1.36^{de}	8
I_3N_1 (0.6 ETc + 100% RDF by CF)	1,21,833	14,471.02^{b}	2,89,420.40	1,67,587.40^{bc}	1.38^{bc}	7
I_3N_2 (0.6 ETc + 100% N from Jeevamrutha + Adj. PK by CF)	1,16,500	16,909.35^{a}	3,38,187.00	2,21,687.00^{a}	1.90^{a}	1
I_3N_3 (0.6 ETc + 75% N from Jeevamrutha + Adj. PK by CF)	1,12,000	14,293.52^{b}	2,85,870.60	1,73,870.60^{bc}	1.55^{bcd}	2
I_3N_4 (0.6 ETc + 50% N from Jeevamrutha + Adj. PK by CF)	1,07,500	13,373.16^{cd}	2,67,463.20	1,59,963.20^{d}	1.49^{d}	3

Note Each value is a mean of three replications; within a column, values not sharing a common superscript letter differ significantly (Tukey's HSD, P ≤ 0.05). ETc crop evapotranspiration; CF chemical fertilizer; RDF recommended dose of fertilizer; B:C benefit–cost ratio.

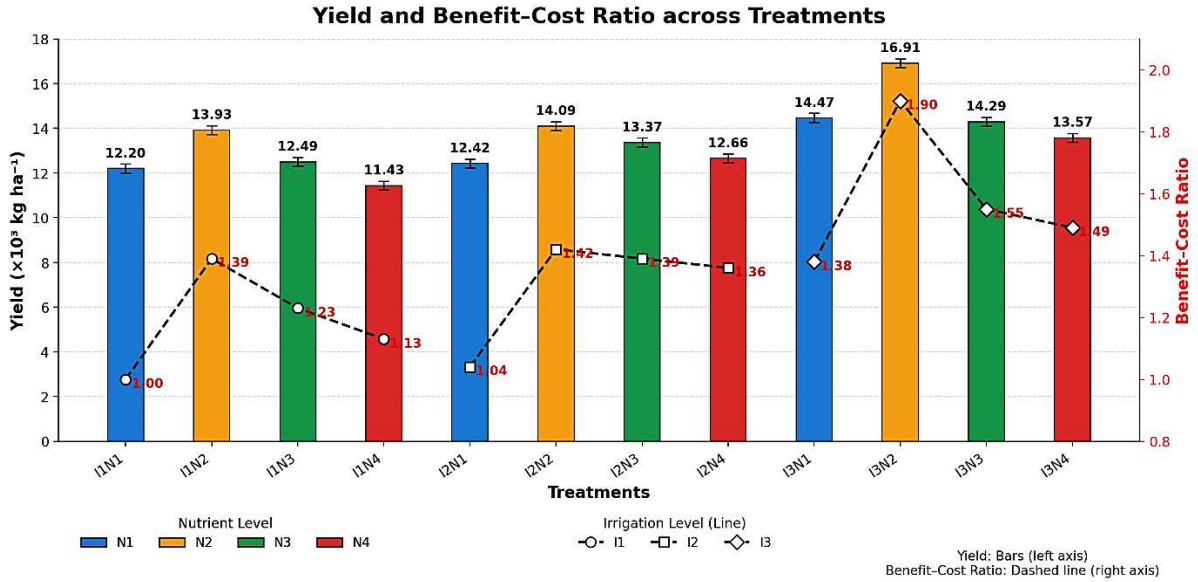


Fig. 6 Net returns (bar, left axis) and benefit–cost ratio (line with symbols, right axis) for all 12 irrigation × nutrient interaction treatments. Pooled two-season means; error bars represent ±1 SE

3.5 Integrated Treatment Performance

The CTPI integrated the biological, fertility, productivity and economic responses of the 12 treatment combinations (Fig. 7). I_3N_2 recorded the maximum index (CTPI = 1.000), scoring highest in all four domains, followed at a distance by I_1N_2 (0.515), I_3N_3 (0.505), I_2N_2 (0.468) and I_3N_1 (0.454); the lowest values were for I_1N_4 (0.088) and I_1N_1 (0.134). Across the matrix the index increased as irrigation decreased (irrigation-mean CTPI rising from 0.229 under full irrigation to 0.573 under moderate deficit) and peaked at full Jeevamrutha-N substitution (nutrient-mean CTPI 0.661), mirroring the individual-variable trends reported above. The stacked domain profile (Fig. 8a) shows that the high index of I_3N_2 arose from balanced strength across all four domains rather than a single dominant response, and the index was closely related to flower yield (r = 0.98) and net return (r = 0.97; Fig. 8b, c).

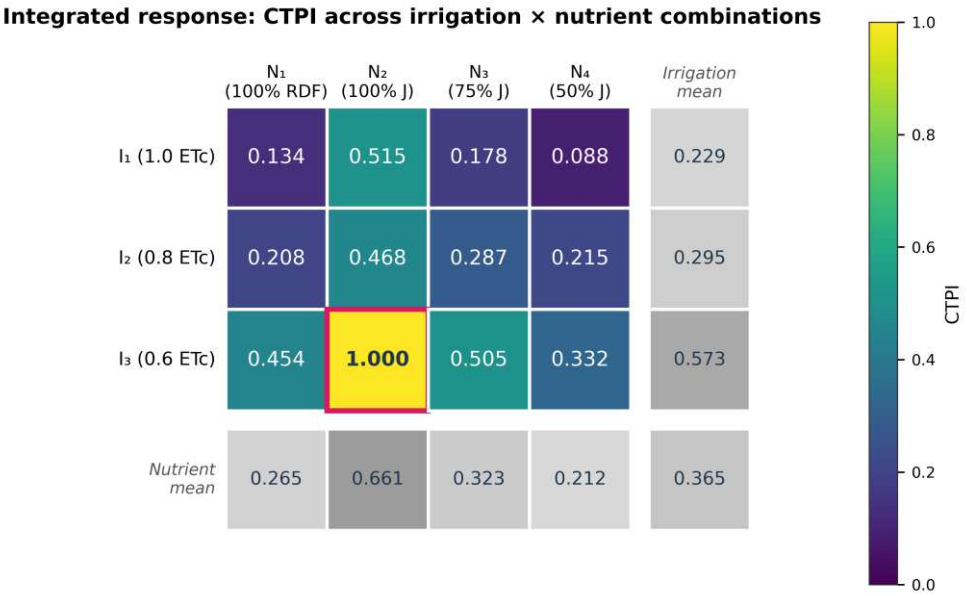


Fig. 7 Comprehensive Treatment Performance Index (CTPI) across the 12 irrigation × nutrient combinations, arranged as a 3 × 4 matrix of irrigation regime (rows) and nutrient regime (columns); grey margins give the irrigation and nutrient main-effect means. Higher values denote stronger integrated performance across the four domains

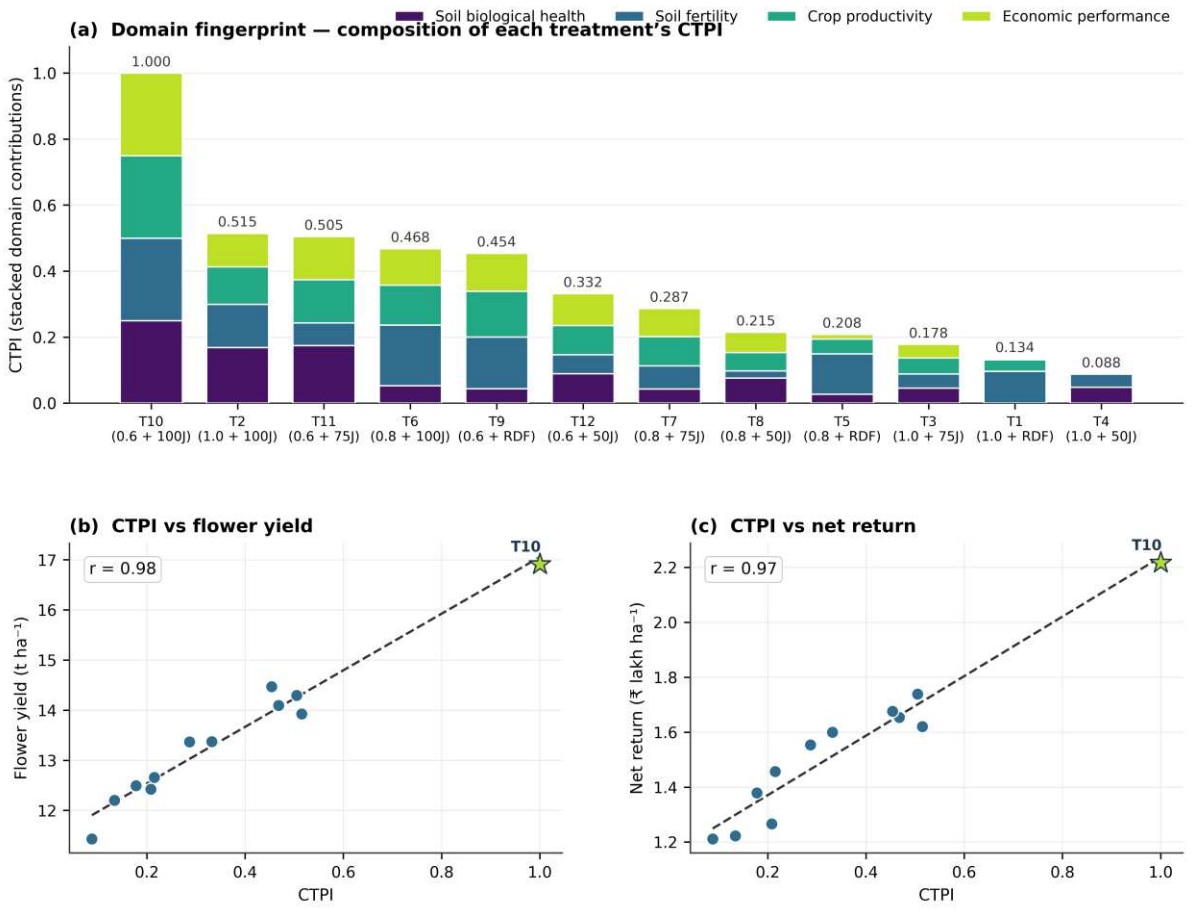


Fig. 8 (a) Domain composition of each treatment's CTPI, shown as the stacked contributions of the four equally weighted domains (soil biological health, soil fertility, crop productivity and economic performance); (b, c) relationship of CTPI with flower yield and net return. Values are pooled two-season means; T10 denotes I_3N_2

Because the index combines standardised soil, crop and economic indicators, this agreement across domains indicates that moderate deficit irrigation with full Jeevamrutha-N substitution performed consistently rather than trading one benefit for another. Comparable normalised multi-indicator frameworks have recently been used to rank water- and fertiliser-management treatments in horticultural systems [50-51]. A weight-sensitivity test, in which the four domain weights were varied across 5,000 random combinations, left I_3N_2 ranked first in every case (Supplementary Fig. S1), so its selection does not depend on the equal-weighting assumption. Because the CTPI–yield and CTPI–net-return correlations partly reflect the inclusion of yield and net return among the indicators, the index is interpreted here as a descriptive synthesis of overall performance rather than as an independent predictor of either outcome.

4. Conclusions

Over two Rabi seasons, moderate deficit irrigation (0.6 ETc, I_3) combined with full nitrogen substitution from Jeevamrutha plus supplementary chemical P and K (N_2) improved

rhizosphere microbial abundance, dehydrogenase activity, flower yield and economic returns in African marigold. Irrigation and nutrient management interacted rather than acting additively. Relative to full irrigation, moderate deficit raised bacterial, fungal and actinomycete counts by 11.7%, 11.9% and 11.5%, dehydrogenase activity by 11.8% and flower yield by 17.9%, while cutting seasonal irrigation water by 38.6%. Relative to the chemical-fertiliser control, full Jeevamrutha-N raised the same three microbial groups by 27.8%, 27.1% and 26.9%, dehydrogenase activity by 25.6% and yield by 15.0%. The I_3N_2 combination performed best overall. It gave the highest pooled yield (16,909 kg ha^{-1}), net return (₹2.21 lakh ha^{-1}; ₹99,437 ha^{-1} above the fully irrigated chemical-fertiliser treatment) and benefit–cost ratio (1.90). It also ranked first among the twelve treatment combinations in an integrated performance index, and this rank held across a wide range of indicator weightings. These results show that water conservation, reduced synthetic-input use and profitability need not trade off against one another in this system, directly advancing the Sustainable Development Goals on clean water and water-use efficiency (SDG 6), responsible production with reduced reliance on synthetic fertiliser (SDG 12), and healthy, biologically active soils that sustain life on land (SDG 15). For growers in similar semi-arid, sandy-loam settings, moderate (0.6 ETc) deficit irrigation with full Jeevamrutha-based nitrogen is therefore a practical, input-efficient package for marigold, contingent on access to livestock-based ingredients and the modest labour its preparation requires. Several limitations bound these conclusions. The findings come from one soil, one site, one cultivar (*Pusa Narangi Gainda*) and two seasons; the microbial counts reflect only the culturable fraction; and water-use efficiency, tissue nutrient uptake and the environmental co-benefits were inferred rather than measured directly. The interpretations offered here are therefore indicative rather than definitive. Future work should measure water-use efficiency and tissue nutrient partitioning directly, characterise rhizosphere function by metagenomics, trace nitrogen with ^{15}N, test sensor-based irrigation scheduling and include life-cycle carbon assessment, together with multi-site, multi-season and on-farm validation under real labour and input constraints. Such work would establish this deficit-irrigation and biostimulant strategy as a scalable option for water- and input-efficient floriculture in semi-arid regions.

Acknowledgments

The authors thank the Water Technology Centre and ICAR-Indian Agricultural Research Institute, New Delhi, for providing research facilities, and the technical staff of the Division of Agronomy, Division of Microbiology, and Division of Floriculture and Landscaping for assistance with the field experiments and laboratory analyses.

Author Contributions

Aditya V. Machnoor: conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft, writing – review and editing. D. S. Gurjar: methodology,

validation, writing – review and editing. P. S. Brahmanand: resources, validation, writing – review and editing. Rosin K G: validation. A. K. Tiwari: validation. S. L. Meena: validation. Minakshi Grover: validation. Shiv Prasad: validation. All authors read and approved the final manuscript.

Declarations

Competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Ethics approval: Not applicable. This study involved no research on humans or live vertebrates; all work concerned field-grown plants, soil samples and laboratory microbial assays.

Plant ethics declaration: The African marigold (Tagetes erecta L.) cultivar Pusa Narangi Gainda used in this study is a publicly released variety developed by the ICAR-Indian Agricultural Research Institute (ICAR-IARI), New Delhi; certified seed was obtained from the Institute and the crop was raised at the Institute's experimental research farm. The collection and use of this plant material complied with all relevant institutional, national and international guidelines and legislation. The species is neither endangered nor protected, and no specific permissions or licences were required for its cultivation or sampling.

Funding: This research received no external funding; it was carried out using institutional facilities of the ICAR-Indian Agricultural Research Institute.

Data availability: The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Consent to Participate declaration: not applicable.

Consent to publish: Informed consent to publish was obtained from all individuals appearing in the identifying photographs included in the graphical abstract.

Clinical trial number: not applicable.

References

1. Zhang P, Zhou J, He D, Yang Y, Lu Z, Yang C, et al. From flourish to nourish: cultivating soil health for sustainable floriculture. Plants. 2024;13(21):3055. https://doi.org/10.3390/plants13213055

2. IMARC Group. Indian floriculture market report by flower type, retail vs institutional, distribution channel, application and state, 2025-2033. New Delhi: IMARC Group; 2025. Available from: https://www.imarcgroup.com/floriculture-market-india

3. Kumar R, Kumar S, Yashavanth BS, Venu N, Meena PC, Dhandapani A, et al. Natural farming practices for chemical-free agriculture: implications for crop yield and profitability. Agriculture. 2023;13(3):647. https://doi.org/10.3390/agriculture13030647

4. Mahanta S, Talukdar MC, Nath S, Das P, Saikia R, Hazarika H, et al. Effect of addition of marigold petals in poultry feed to increase the carotenoid content in egg yolk and to enhance yolk color in laying hens. Ecol Environ Conserv. 2022;28(1):385-9.

5. Richter BD, Ao Y, Davis KF, Amaya M, Marston L, Wei D, et al. Alleviating water scarcity by optimizing crop mixes. Nat Water. 2023;1(12):1035-47. https://doi.org/10.1038/s44221-023-00155-9

6. Andreu-Coll L, Carbonell-Barrachina ÁA, Burló F, Galindo A, García-Brunton J, López-Lluch DB, et al. Regulated deficit irrigation perspectives for water efficiency in apricot cultivation: a review. Agronomy. 2024;14(6):1219. https://doi.org/10.3390/agronomy14061219

7. Ingrao C, Strippoli R, Lagioia G, Huisingh D. Water scarcity in agriculture: an overview of causes, impacts, and approaches for reducing the risks. Heliyon. 2023;9(8):e18507. https://doi.org/10.1016/j.heliyon.2023.e18507

8. Singh D, Badiyala A, Ranjha R. Organic methods of enhancing soil fertility. In: Organic production of vegetable crops. Palm Bay: Apple Academic Press; 2025. p. 139-67.

9. Yang B, Fu P, Lu J, Ma F, Sun X, Fang Y. Regulated deficit irrigation: an effective way to solve the shortage of agricultural water for horticulture. Stress Biol. 2022;2:28. https://doi.org/10.1007/s44154-022-00050-5

10. Kumar R, Kumar S, Yashavanth BS, Meena PC. Natural farming practices in India: its adoption and impact on crop yield and farmers' income. Indian J Agric Econ. 2019;74(3):420-32.

11. Kumar R, Kumar S, Yashavanth BS, Meena PC, Indoria AK, Kundu S, et al. Adoption of natural farming and its effect on crop yield and farmers' livelihood in India. Hyderabad: ICAR-National Academy of Agricultural Research Management; 2020.

12. Duraivadivel P, Kongkham B, Satya S, Hariprasad P. Untangling microbial diversity and functional properties of Jeevamrutha. J Clean Prod. 2022;369:133218. https://doi.org/10.1016/j.jclepro.2022.133218

13. Sagar S, Bala J, Singh A, Chauhan R, Bhatia RK, Walia A, et al. Insights into cow dung-based bioformulations for sustainable plant health and disease management in organic and natural farming systems: a review. J Soil Sci Plant Nutr. 2023;24(1):30-53. https://doi.org/10.1007/s42729-023-01566-y

14. Devvrat S. Natural farming and soil health: a review. Indian J Nat Farming. 2020;2(1):31-40.

15. Sugumaran MP, Akila S, Porkodi G. The potential of panchagavya and jeevamrutha for sustainable organic farming in India. J Eco-Friendly Agric. 2024;19(2):240-6.

16. Kongkham B, Kumar P, Prabakaran D, Hariprasad P. Prospects and application of traditional microbial formulation “Jeevamrutha” for sustainable climate-resilient agriculture. J Soil Sci Plant Nutr. 2026;26(3):8705-38. https://doi.org/10.1007/s42729-026-03429-9

17. Jnanesha AC, Venugopal S, Kumar SR, Kumar A, Bisht D, Chanotiya CS, et al. Optimization of a new organic approach to natural biostimulant (Jeevamrutha) for yield and quality management in senna (Cassia angustifolia Vahl.). Technol Hortic. 2024;4:e009. https://doi.org/10.48130/tihort-0024-0006

18. Kaushal N, Kashyap B, Dilta BS. Research on cutting and flower yield improvements in marigold cv. Siracole for sustainable production through the Jeevamruth application. Heliyon. 2024;10(23):e40567. https://doi.org/10.1016/j.heliyon.2024.e40567

19. Shawky BM, Hassan FA, Fetouh MI, El-Serafy RS, Hassan IF, Moussa MM, et al. Modulation of physiological and biochemical indices by Moringa oleifera aqueous leaf extract enhances salinity tolerance in Jatropha curcas L. Land Degrad Dev. 2026;37(8):3020-34.

20. Zapata-García S, Temnani A, Berríos P, Marín-Durán L, Espinosa PJ, Monllor C, et al. Combined effects of deficit irrigation and biostimulation on water productivity in table grapes. Plants. 2024;13(23):3424. https://doi.org/10.3390/plants13233424

21. Mukherjee S, Gupta A, Nandi R, Chakraborty A, Bhattacharjee A. Exploring the microbial community dynamics of Jeevamrit reveals the multifaceted roles of the Bacillus and Pseudomonas genera in nutrient availability and plant growth promotion in India's zero budget natural farming. J Soil Sci Plant Nutr. 2025;25:5836-52. https://doi.org/10.1007/s42729-025-02500-1

22. Kumar P, Chandel RS, Verma SC, Sharma N, Saini S, Bishist R, et al. Biostimulation through natural biological inputs on fruiting, nutrient availability and rhizosphere microbiome in legume intercropped 'Sweet Charlie' strawberry (Fragaria × ananassa Duch.). BMC Plant Biol. 2025;25:1-17. https://doi.org/10.1186/s12870-025-07017-4

23. Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome: Food and Agriculture Organization of the United Nations; 1998.

24. Machnoor AV, Gurjar DS, Brahmanand PS, Prajapati VK, Grover M, Tiwari AK, et al. Synergistic effects of deficit irrigation and jeevamrutha on soil microbial health and marigold (Tagetes erecta) sustainability. Indian J Agric Sci. 2026;96(3):380-7. https://doi.org/10.56093/ijas.v96i03.174425

25. Palekar S. Textbook on Shoonya Bandh Postulates. Amravati: Zero Budget Natural Farming; 2006.

26. Patel N, Sharma R, Singh R. Deficit irrigation and nutrient management effects on micronutrient uptake and yield in marigold. Agric Water Manag. 2023;283:108325. https://doi.org/10.1016/j.agwat.2023.108325

27. Zheng M, Wen L, He C, Chen X, Si L, Li H, et al. Sequencing-guided re-estimation and promotion of cultivability for environmental bacteria. Nat Commun. 2024;15. https://doi.org/10.1038/s41467-024-53446-4

28. Xing Y, Zhang X, Wang X. Enhancing soil health and crop yields through water-fertilizer coupling technology. Front Sustain Food Syst. 2024;8:1494819. https://doi.org/10.3389/fsufs.2024.1494819

29. Sharma R, Choudhary M, Singh R. Organic acids and microbial activity enhance micronutrient availability in organic farming systems. Ecol Indic. 2022;137:108736. https://doi.org/10.1016/j.ecolind.2022.108736

30. Sreenivasa MN, Naik SY, Bhat SN. Jeevamrutha: a bio-enhancer for soil and crop health. Int J Agric Sci. 2010;6(2):415-7.

31. Kaushal P, Ali N, Saini S, Pati PK, Maitra Pati A. Physiological and molecular insight of microbial biostimulants for sustainable agriculture. Front Plant Sci. 2023;14:1041413. https://doi.org/10.3389/fpls.2023.1041413

32. Shrivas VL, Sharma A, Choudhary AK, Rambia A, Hariprasad P, Shidture S, et al. Organic amendments modulate crop yield and rhizospheric bacterial community diversity: a three-year field study with Cajanus cajan (L.). Int Microbiol. 2023;27(2):477-90.

33. Alzate Zuluaga MY, Fattorini R, Cesco S, Pii Y. Plant-microbe interactions in the rhizosphere for smarter and more sustainable crop fertilization: the case of PGPR-based biofertilizers. Front Microbiol. 2024;15:1440978. https://doi.org/10.3389/fmicb.2024.1440978

34. Gajjar K, Chaudhary M, Patel S, Vasa N, Maniyar R, Agrawal D, et al. Natural farming as a sustainable agricultural approach enhances soil health and microbial diversity in wheat cultivation: a metagenomic perspective. Front Agron. 2026;8:1755662. https://doi.org/10.3389/fagro.2026.1755662

35. Sutar R, Sujith GM, Devakumar N. Growth and yield of cowpea (Vigna unguiculata (L.) Walp.) as influenced by jeevamrutha and panchagavya application. Legume Res. 2019;42(6):824-8.

36. Ismail SM, Almulhim N, Sedky A, El-Cossy SAN. Impact of soil ameliorants on soil chemical characteristics and nutrient availability under deficit irrigation. Sustainability. 2025;17(4):1513. https://doi.org/10.3390/su17041513

37. Vishwanath, Kumar S, Purakayastha TJ, Sinha SK, Mahapatra P, Rosin KG, et al. Five decades of nutrient management has enhanced soil microbial activity, resistance, and resilience against drought stress. Commun Soil Sci Plant Anal. 2025. https://doi.org/10.1080/00103624.2025.2494849

38. Xing Y, Xie Y, Wang X. Enhancing soil health through balanced fertilization: a pathway to sustainable agriculture and food security. Front Microbiol. 2025;16:1536524. https://doi.org/10.3389/fmicb.2025.1536524

39. Devau N, Le Cadre E, Hinsinger P, Gérard F. Soil phosphorus dynamics as affected by water regime and organic inputs. Plant Soil. 2011;348(1-2):203-21. https://doi.org/10.1007/s11104-011-0821-7

40. Beiküfner M, Kühling I, Vergara-Hernandez ME, Broll G, Trautz D. Impact of mechanical weed control on soil N dynamics, soil moisture, and crop yield in an organic cropping sequence. Nutr Cycl Agroecosyst. 2024;129(2):237-52. https://doi.org/10.1007/s10705-024-10370-9

41. Pandey J, Sharma IP, Bind S, Sharma S, Sharma AK. Impact of natural farming inputs and their microbes on the growth, yield, and nutrients of French bean (Phaseolus vulgaris L.) under controlled and field conditions. Org Agric. 2025. https://doi.org/10.1007/s13165-025-00492-x

42. Pang F, Li Q, Solanki MK, Wang Z, Xing YX, Dong DF. Soil phosphorus transformation and plant uptake driven by phosphate-solubilizing microorganisms. Front Microbiol. 2024;15:1383813. https://doi.org/10.3389/fmicb.2024.1383813

43. Khan MT, Aleinikovienė J, Butkevičienė L-M. Innovative organic fertilizers and cover crops: perspectives for sustainable agriculture in the era of climate change and organic agriculture. Agronomy. 2024;14(12):2871. https://doi.org/10.3390/agronomy14122871

44. Verma G, Dhaka AK, Singh B, Kumar A, Choudhary AK, Kumar S. Productivity, soil health, and carbon management index of soybean-wheat cropping system under double zero-tillage and natural-farming based organic nutrient management in north-Indian plains. Sci Total Environ. 2024;917:170418. https://doi.org/10.1016/j.scitotenv.2024.170418

45. Pan J, Sharif R, Xu X, Chen X. Mechanisms of waterlogging tolerance in plants: research progress and prospects. Front Plant Sci. 2021;11:627331. https://doi.org/10.3389/fpls.2020.627331

46. Veeranna HK, Shilpa HD, Shilpa ME, Adarsha SK, Deepa AG. Response of different levels of jeevamrutha and ghana jeevamrutha on pod yield and yield components of rainfed groundnut (Arachis hypogaea L.). Appl Ecol Environ Res. 2023;21(2):1595-1605.

47. Shoukat Hafiza B, Ishaque W, Ahmad S, Ali S, El-Sheikh MA. Optimizing wheat productivity and water productivity through deficit irrigation strategies in semi-arid environments. Sci Rep. 2025;15:20630. https://doi.org/10.1038/s41598-025-04618-9

48. Prakash S, Kumar D, Kumar A, Ram RM, Paul B, Kaur R, et al. Integrated nutrient management enhances growth, floral productivity, postharvest quality, and economic returns in African marigold (Tagetes erecta L.) cv. Pusa Narangi Gainda. J Adv Biol Biotechnol. 2026;29(9):149-59. https://doi.org/10.9734/jabb/2026/v29i94293

49. Patel SP, Malve SH, Chavda MH, Vala YB. Effect of Panchagavya and Jeevamrut on growth, yield attributes, and yield of summer pearl millet. Pharma Innov J. 2021;10(12):105-9.

50. Tian Y, Jiang W, Chen G, Wang X, Li T. Gypsum and organic materials improved soil quality and crop production in saline-alkali on the Loess Plateau of China. Front Environ Sci. 2024;12:1434147. https://doi.org/10.3389/fenvs.2024.1434147

51. Zhang J, Xiang L, Liu Y, Jing D, Zhang L, Liu Y, et al. Optimizing irrigation schedules of greenhouse tomato based on a comprehensive evaluation model. Agric Water Manag. 2024;295:108741. https://doi.org/10.1016/j.agwat.2024.108741

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterialNPK.docx
- Graphicalabstract.pdf