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Article

Integrated fertigation and foliar nutrient application for enhanced growth and flower yield of 'Pink Kakada' (*Jasminum multiflorum*)

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Abstract

'Pink Kakada' (*Jasminum multiflorum*) is a recently identified jasmine variety with potential for winter flower production when most commercial cultivars remain off-season. The present study was conducted to standardize nutrient management through fertigation and foliar nutrient application to enhance growth and flower yield. A field experiment was carried out in a randomized block design with eleven treatments and three replications, involving different levels of fertigation combined with foliar sprays. The results revealed that application of the recommended dose of water-soluble fertilizers through fertigation along with a foliar spray of 0.25% iron produced the most favorable overall response across growth, physiological, and flowering parameters. The highest plant height (89.38 cm), plant spread (87.05 cm North-South and 95.95 cm East–West), chlorophyll content (1.26 mg g^{-1}), and phenol content (9.92 mg g^{-1}) were recorded under this treatment. The treatment significantly increased flower yield (12.04 t ha^{-1}) and produced the highest values for the number of cymes per plant (247.85), 100-bud weight (11.19 g), flower bud length (3.74 cm), and corolla tube length (2.05 cm). Correlation and principal component analyses indicated that flower yield was strongly associated with dry matter production, number of cymes per plant, and specific leaf weight, identifying these as key determinants of productivity. Overall, the study demonstrates that integrated nutrient management through fertigation combined with foliar iron application enhances growth, physiological efficiency, and winter flower yield of 'Pink Kakada' jasmine, providing a practical strategy for improving commercial production during the off-season.

Keywords: fertigation; micronutrients; iron; jasmine; off-season flowering; nutrient use efficiency

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1 Introduction

Jasmine is one of the most important ornamental crops cultivated for its fragrant flowers, essential oil extraction, and commercial value in tropical and subtropical regions (Kumaresan et al., 2025). Among the cultivated species, *Jasminum multiflorum* is a perennial shrub known for its profuse flowering, attractive buds, and adaptability to diverse agro-climatic conditions (Kumaresan et al., 2019). The increasing demand for jasmine flowers in domestic and export markets has necessitated the development of improved production technologies to enhance yield and quality, particularly during the off-season when flowering is limited (Kumaresan et al., 2024).

Nutrient management plays a pivotal role in regulating plant growth, physiological processes, and flower productivity in horticultural crops. Nitrogen is a major constituent of chlorophyll, proteins, and nucleic acids, and significantly influences vegetative growth and photosynthetic activity (Nadhiya Devi et al., 2024). Phosphorus is essential for energy transfer, metabolic regulation, and root development, thereby enhancing flowering and yield (Khan et al., 2023). Potassium is involved in enzyme activation, osmotic regulation, and stress tolerance, contributing to improved flower quality and productivity (Rajaselvam et al., 2024). Balanced fertilization is essential for achieving optimum growth and yield in jasmine cultivation (Govindasamy et al., 2023).

Micronutrients are equally important in plant nutrition, as they regulate several biochemical and physiological processes (Saleem et al., 2022). Iron, in particular, plays a crucial role in chlorophyll synthesis, electron transport, and enzymatic activities, thereby influencing photosynthesis and plant metabolism (Hernández-Cánovas et al., 2025). Deficiency of micronutrients, especially iron, can lead to reduced growth and productivity in flowering crops (Iftikhar et al., 2024). Foliar application of micronutrients has been reported to enhance nutrient uptake efficiency and improve growth and yield attributes in various horticultural crops (Mohanty et al., 2021; Saleem et al., 2022).

Efficient nutrient delivery methods are essential to maximize fertilizer use efficiency and minimize nutrient losses. Fertigation, the application of water-soluble fertilizers through irrigation systems, is widely recognized as an effective technique for improving nutrient availability and uptake (Adamo et al., 2025). It ensures precise and timely nutrient supply to the root zone, resulting in improved growth, yield, and quality compared to conventional fertilizer application methods (Adamo et al., 2025).

The integration of fertigation with foliar nutrient application provides synergistic effects by supplying nutrients through both root and foliar pathways, thereby enhancing overall crop performance (Iftikhar et al., 2024).

Despite the importance of integrated nutrient management, limited information is available on the combined effect of fertigation and foliar micronutrient application in *J. multiflorum*, particularly in newly identified varieties suitable for off-season flowering. 'Pink Kakada' (JM-1) is a promising variety characterized by attractive flower buds, an extended flowering period, and suitability for winter production; however, standardized nutrient management practices for maximizing its growth and flower yield are yet to be established (Kumaresan et al., 2025).

Unlike previous studies that primarily focused on individual growth or yield responses, the present study integrates physiological, biochemical, and yield parameters to identify the key determinants of productivity. This approach provides a more mechanistic understanding of how nutrient management strategies influence flower production in jasmine. Therefore, the present study aimed to evaluate the effects of integrated nutrient management through fertigation and foliar iron application on the growth, physiological attributes, and flower yield of the emerging jasmine cultivar 'Pink Kakada' (*Jasminum multiflorum*) under winter conditions. The findings are expected to provide a scientific basis for improving off-season flower production and enhancing the commercial potential of this cultivar.

2 Materials and Methods

2.1 Study Site and Climatic Conditions

The field experiment was conducted at the Botanical Garden, Department of Floriculture and Landscape Architecture, Tamil Nadu Agricultural University, Coimbatore, India, during 2019-2020. The experimental site is located in a tropical agro-climatic zone. During the study period, the maximum temperature ranged from 25 to 35 °C with a mean of 30 °C, while the minimum temperature varied from 17 to 23.5 °C with a mean of 20 °C. The annual rainfall was approximately 750 mm, and the relative humidity ranged from 60% to 90%, with a mean of 75%.

2.2 Soil Characteristics and Field Preparation

The soil of the experimental field was sandy clay loam in texture with a pH of 6.5-7.5, electrical conductivity (EC) of 0.61 dS m^{-1}, and organic carbon content of 0.30%. The field was prepared by ploughing with a disc plough followed by cultivation and leveling using a rotavator. Pits were dug at a spacing of 1.25 × 1.25 m. At the time of planting, 75% of the total phosphorus dose, as per treatment, was applied as basal.

2.3 Experimental Design and Treatments

The experiment was laid out in a randomized block design with 11 treatments and three replications. The treatments consisted of different levels of recommended dose of fertilizers (RDF) applied as water-soluble fertilizers (WSF) and straight fertilizers (SF) in combination with foliar application of micronutrients.

The treatment details were as follows:

T_1: 125% RDF as WSF + 0.25% Fe
T_2: 125% RDF as WSF + 0.25% Zn
T_3: 100% RDF as WSF + 0.25% Fe
T_4: 100% RDF as WSF + 0.25% Zn
T_5: 75% RDF as WSF + 25% RDF as SF + 0.25% Fe
T_6: 75% RDF as WSF + 25% RDF as SF + 0.25% Zn
T_7: 50% RDF as WSF + 50% RDF as SF + 0.25% Fe
T_8: 50% RDF as WSF + 50% RDF as SF + 0.25% Zn
T_9: 25% RDF as WSF + 75% RDF as SF + 0.25% Fe
T_{10}: 25% RDF as WSF + 75% RDF as SF + 0.25% Zn
T_{11}: 100% RDF as SF (control)

Fertigation was applied at weekly intervals through a drip irrigation system to ensure continuous nutrient availability. Foliar applications of micronutrients (Fe and Zn at 0.25%) were carried out at 30, 60, and 90 days after planting during morning hours to maximize absorption efficiency.

2.4 Data Collection and Observations

Observations on vegetative growth parameters were recorded at 90, 180, 270, and 360 days after planting. Parameters included plant height, plant spread, and physiological traits. Flowering and yield parameters were recorded throughout the flowering period. Observations on flower quality parameters were taken during peak flowering and off-season stages. Standard procedures were followed for recording all observations.

2.5 Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a randomized block design (RBD), following the procedure described by Panse and Sukhatme (1985). The significance of treatment effects was tested at $p < 0.05$. Mean separation was carried out using Duncan's Multiple Range Test (DMRT) at $p < 0.05$. Treatment means are presented together with the standard error of difference (SEd) and critical difference (CD), where applicable. Pearson's correlation analysis was performed to evaluate relationships among growth, physiological, biochemical, and yield parameters. Principal component analysis (PCA) was conducted using standardized data to assess multivariate relationships and identify the major variables contributing to variation among treatments. All statistical analyses were performed using SPSS software.

3 Results

3.1 Effect of Fertigation and Foliar Application on Vegetative Parameters

Vegetative growth parameters were significantly influenced by different fertigation levels and foliar nutrient application (Figure 1; Table 1).

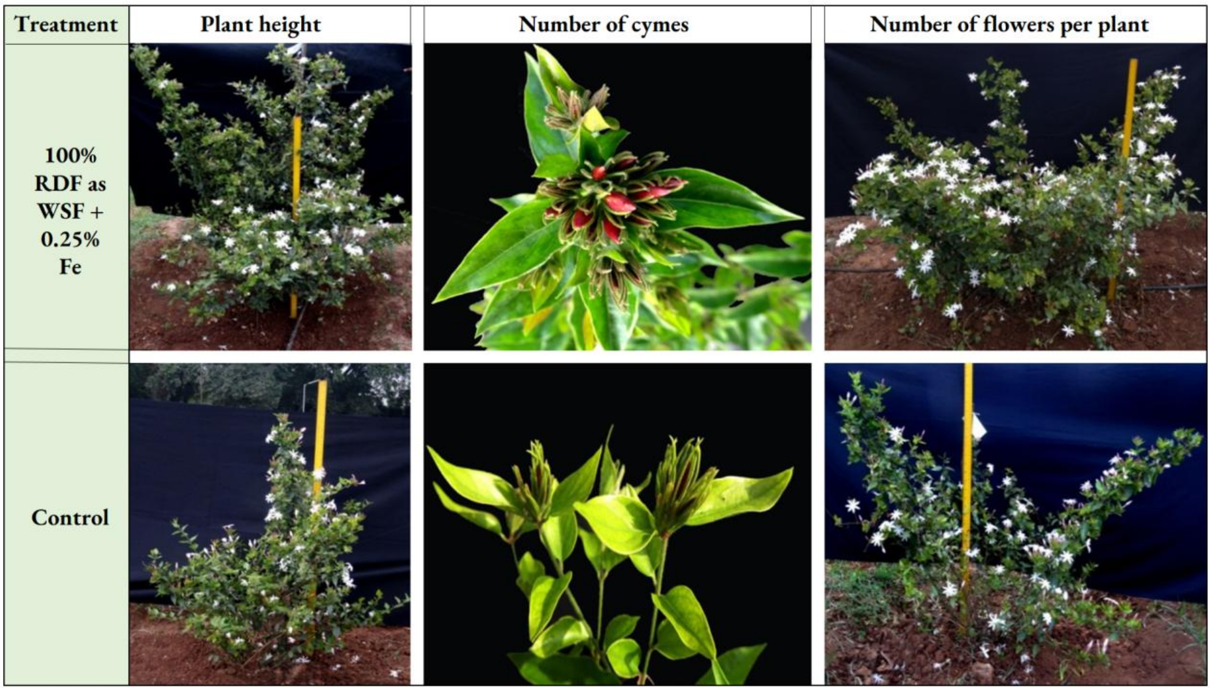

Figure 1. Effect of fertigation levels and foliar spray on growth and yield parameters of *Jasminum multiflorum* 'Pink Kakada'.

Among the treatments, T_3 consistently exhibited superior vegetative growth, recording significantly higher plant height, plant spread (both East–West and North–South), number of secondary branches, and leaf area compared to other treatments. Treatments T_4 and T_5 also showed comparable performance, though slightly lower than T_3. In contrast, T_{11} recorded the lowest values for most of the growth parameters. Plant spread followed a similar trend as plant height, with higher canopy expansion observed under optimized fertigation treatments. The number of secondary branches varied significantly among treatments, whereas the number of primary branches did not show significant differences. Leaf area was also markedly enhanced under higher fertigation levels, indicating improved vegetative development.

Table 1. Effect of fertigation levels and foliar spray on vegetative parameters.

Treatments	Plant height (cm)	Plant spread (E–W) (cm)	Plant spread (N–S) (cm)	Branches (no. plant^{-1})		Leaf area (cm^2)
				Primary	Secondary	
T_1	72.67^{cd}	76.88^{cd}	73.59^{c}	2.25	17.52^{b}	12.41^{b}
T_2	70.54^{d}	74.36^{d}	70.51^{cd}	2.11	17.07^{b}	11.56^{c}
T_3	89.38^{a}	95.95^{a}	87.05^{a}	2.71	19.69^{a}	13.48^{a}
T_4	83.68^{b}	90.85^{b}	79.79^{b}	2.35	16.97^{b}	12.65^{b}
T_5	79.97^{bc}	82.54^{c}	76.94^{bc}	2.25	15.03^{c}	11.86^{c}
T_6	74.82^{cd}	76.25^{cd}	74.59^{c}	2.25	14.22^{c}	11.76^{c}
T_7	76.28^{c}	73.02^{d}	73.50^{c}	2.11	12.47^{d}	11.59^{c}
T_8	70.51^{d}	72.94^{d}	70.24^{cd}	1.56	11.97^{d}	11.05^{c}
T_9	68.86^{d}	67.01^{e}	72.67^{c}	1.56	11.58^{d}	10.82^{c}
T_{10}	66.73^{de}	65.21^{e}	70.58^{cd}	1.56	11.34^{d}	10.50^{c}
T_{11}	65.87^{e}	61.34^{f}	69.28^{d}	1.18	8.40^{e}	10.25^{c}
SEd	2.13	2.00	1.25	0.61	1.02	1.59
CD	4.45	4.18	2.61	NS	2.13	3.32

Values represent mean of three replications. Means followed by different superscript letters within a column differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT). NS: not significant.

3.2 Effect on Physiological Parameters

The measured physiological and biochemical parameters responded differently to the treatments (Table 2). Chlorophyll content tended to be higher under the greater fertigation levels, with the highest numerical value recorded in T_3, although treatment differences were not statistically significant. In contrast, total phenol content, soluble protein content, IAA oxidase activity, and nitrate reductase activity varied significantly among treatments. Treatment T_3 recorded the highest values for phenol and protein contents, IAA oxidase activity, and nitrate reductase activity, followed generally by T_4, whereas the lowest values occurred in T_{11}. These responses indicate improved metabolic activity and nutrient assimilation under the optimized fertigation treatments.

Table 2. Effect of fertigation levels and foliar spray on physiological parameters.

Treatments	Chlorophyll (mg g^{-1})	Phenol (mg g^{-1})	Protein (mg g^{-1})	IAA oxidase (µg unoxidized auxin g^{-1} h^{-1})	Nitrate reductase (µg NO_2 g^{-1} h^{-1})
T_1	1.24	7.84^{c}	9.25^{c}	17.57^{b}	2.21^{c}
T_2	1.15	7.52^{c}	9.01^{c}	17.98^{b}	2.43^{b}
T_3	1.26	9.92^{a}	11.84^{a}	19.05^{a}	2.75^{a}
T_4	1.25	9.63^{a}	11.02^{ab}	18.82^{a}	2.68^{a}
T_5	1.23	8.42^{b}	10.22^{b}	18.56^{a}	2.34^{b}
T_6	1.22	8.22^{b}	9.84^{bc}	17.84^{b}	2.11^{c}
T_7	1.10	6.64^{d}	9.73^{c}	17.52^{b}	2.05^{c}
T_8	1.10	6.24^{d}	9.70^{c}	18.45^{a}	1.94^{c}
T_9	1.08	5.95^{d}	9.32^{c}	15.34^{c}	1.86^{c}
T_{10}	1.05	5.38^{e}	8.24^{d}	14.24^{c}	1.80^{c}
T_{11}	0.92	4.45^{f}	7.84^{d}	12.15^{d}	1.79^{c}
SEd	0.09	0.30	0.15	0.67	0.09
CD	NS	0.94	0.31	1.40	0.19

Values represent mean of three replications. Means followed by different superscript letters within a column differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT).

3.3 Effect on Flowering, Yield and Quality Parameters

Flowering and yield parameters were significantly affected by the treatments, while the response of floral quality traits was more limited (Tables 3 and 4). The number of cymes per plant and flower yield were markedly higher under optimized fertigation treatments, particularly T_3, followed by T_4 and T_5, whereas the lowest values were recorded in T_{11}. Flower yield ranged from 5.22 to 12.04 t ha^{-1}. Among the floral quality traits, bud diameter differed significantly among treatments and was highest under T_3 and T_4. Single bud weight, 100-bud weight, bud length, and corolla tube length reached their highest numerical values under T_3, but the treatment differences for these traits were not statistically significant.

Table 3. Effect of fertigation levels and foliar spray on yield and productivity parameters

Treatments	Specific leaf weight (g cm^{-2})	Dry matter production (kg ha^{-1})	Cymes (no. plant^{-1})	Flower yield (t ha^{-1})
T_1	0.253^{c}	675.25^{c}	215.24^{c}	8.53^{c}
T_2	0.237^{cd}	654.87^{cd}	210.58^{cd}	8.20^{c}
T_3	0.342^{a}	825.38^{a}	247.85^{a}	12.04^{a}
T_4	0.315^{b}	794.74^{ab}	239.30^{ab}	11.83^{a}
T_5	0.274^{c}	758.54^{b}	221.24^{b}	11.38^{ab}
T_6	0.251^{c}	735.42^{bc}	220.14^{b}	11.30^{ab}
T_7	0.245^{cd}	699.25^{c}	218.19^{c}	8.49^{c}
T_8	0.242^{cd}	664.54^{cd}	210.48^{cd}	8.32^{c}
T_9	0.231^{d}	658.41^{cd}	205.44^{cd}	8.15^{c}
T_{10}	0.223^{d}	612.54^{d}	200.45^{d}	8.02^{c}
T_{11}	0.198^{e}	594.97^{d}	176.04^{e}	5.22^{d}
SEd	0.009	14.85	6.92	0.42
CD	0.018	30.42	14.20	0.86

Values represent mean of three replications. Means followed by different superscript letters within a column differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT).

Table 4. Effect of fertigation levels and foliar spray on floral quality parameters

Treatments	Single bud weight (g)	100-bud weight (g)	Bud length (cm)	Corolla tube length (cm)	Bud diameter (cm)
T_1	0.1021	10.25	3.40	1.88	0.65^{b}
T_2	0.1013	10.00	3.35	1.79	0.62^{b}
T_3	0.1069	11.19	3.74	2.05	0.71^{a}
T_4	0.1047	10.74	3.56	1.97	0.67^{a}
T_5	0.1028	10.53	3.50	1.91	0.63^{b}
T_6	0.1022	10.48	3.48	1.90	0.62^{b}
T_7	0.1020	10.31	3.45	1.87	0.61^{b}
T_8	0.1013	10.30	3.30	1.85	0.59^{b}
T_9	0.1015	10.23	3.31	1.83	0.56^{c}
T_{10}	0.1010	10.10	3.28	1.80	0.51^{c}
T_{11}	0.1006	10.12	3.24	1.72	0.50^{c}
SEd	0.0018	0.35	0.11	0.07	0.03
CD	NS	NS	NS	NS	0.07

Values represent mean of three replications. Means followed by different superscript letters within a column differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT). NS: not significant.

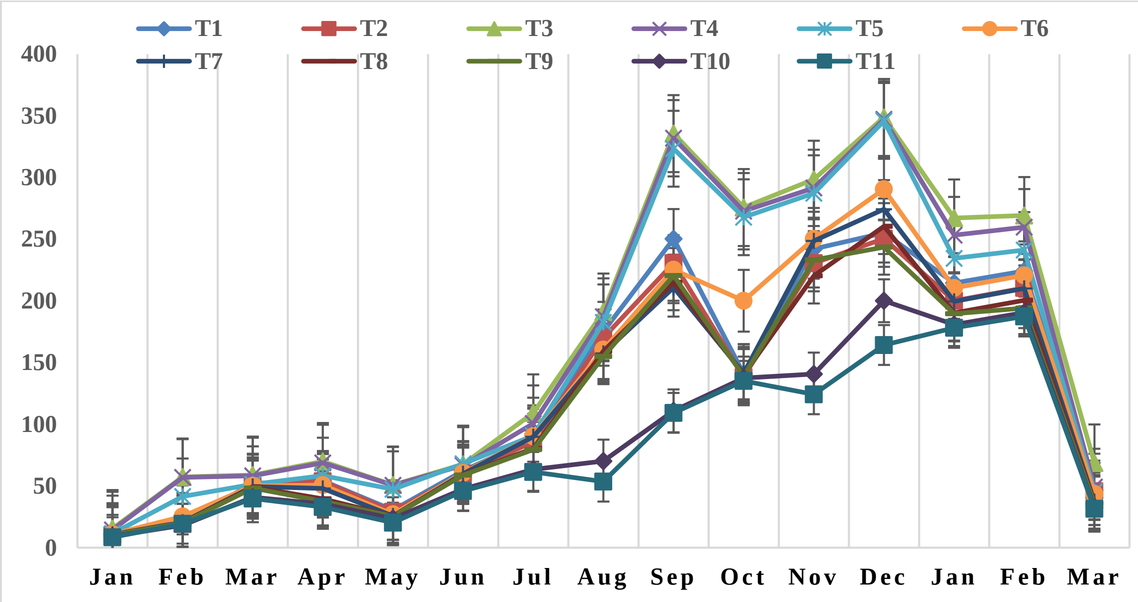

Figure 2. Effect of fertigation levels and foliar spray on monthly flower bud weight per plant (g) in *Jasminum multiflorum* 'Pink Kakada'. Values represent treatment means (n = 3).

3.4 Multivariate Analysis and Identification of Yield Determinants

To further explore the relationships among measured variables, Pearson correlation analysis was performed for growth, physiological, biochemical, and yield parameters (n = 33; Table 5), and principal component analysis was used to visualize multivariate relationships among treatments (Figure 3).

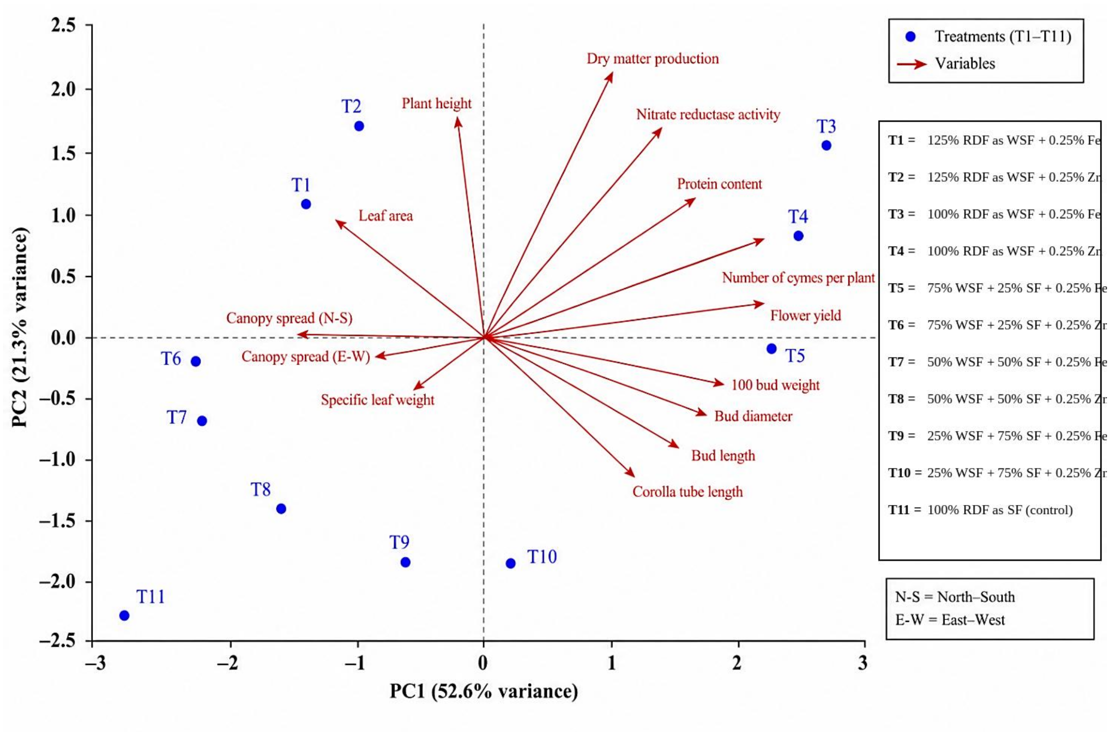

Figure 3. Principal component analysis (PCA) biplot showing relationships among growth, physiological, biochemical, and yield parameters under different fertigation treatments.

Pearson's correlation analysis (Table 5) revealed that flower yield exhibited strong positive correlations with dry matter production (r = 0.94), number of cymes per plant (r = 0.91), and specific leaf weight (r = 0.90), indicating that biomass accumulation and sink strength are the primary determinants of productivity. Nitrate reductase activity (r = 0.88) and protein content (r = 0.86) also showed significant positive associations with yield, highlighting the importance of nitrogen metabolism in supporting flowering. Among the variables, dry matter production and cyme number exhibited the strongest relationship with yield, suggesting that biomass accumulation and sink strength are primary determinants of productivity. Similarly, the positive association of nitrate reductase activity highlights the importance of nitrogen assimilation in supporting reproductive development. These findings demonstrate that yield improvement in *J. multiflorum* is governed by coordinated interactions among physiological and biochemical processes rather than individual traits.

Table 5. Pearson correlation coefficients among key variables influencing flower yield

Variables	PH	LA	SLW	DMP	Cymes	NR	Protein	Yield
PH	1.00							
LA	0.82**	1.00						
SLW	0.75**	0.79**	1.00					
DMP	0.84**	0.88**	0.91**	1.00				
Cymes	0.78**	0.81**	0.87**	0.92**	1.00			
NR	0.72**	0.76**	0.83**	0.89**	0.85**	1.00		
Protein	0.69**	0.74**	0.80**	0.85**	0.82**	0.88**	1.00	
Yield	0.80**	0.85**	0.90**	0.94**	0.91**	0.88**	0.86**	1.00

PH - Plant height; LA - Leaf area; SLW - Specific leaf weight; DMP - Dry matter production; NR - Nitrate reductase activity. ** Significant at $p < 0.01$

Principal component analysis (PCA) was performed to reduce the dimensionality of the dataset and to identify the key variables contributing to variability among treatments. The first two principal components (PC1 and PC2) together explained 73.9% of the total variance (PC1, 52.6%; PC2, 21.3%), indicating that the principal patterns of variation could be summarized effectively using these components. PC1 accounted for the largest share of total variation and was strongly associated with yield and its related physiological and biochemical traits, including dry matter production, specific leaf weight, number of cymes per plant, protein content, and nitrate reductase activity. The high positive loadings of these variables on PC1 indicate that they collectively represent the metabolic and assimilatory efficiency of the plant system, which plays a dominant role in determining flower yield. PC2, in contrast, was primarily associated with vegetative growth parameters such as plant height, canopy spread, and leaf area. This component reflects structural growth variation, which, although important, contributed less directly to yield formation compared to physiological efficiency. The PCA biplot revealed a clear separation of treatments along PC1, with treatments receiving higher proportions of water-soluble fertilizers and foliar iron application (notably T_3 and T_4) positioned on the positive side of PC1. This clustering indicates superior performance in terms of both metabolic activity and yield attributes, whereas treatments with lower nutrient inputs were grouped towards the negative side of PC1. The close association of yield with dry matter production, nitrate reductase activity, and cyme number in the PCA space further confirms that yield is primarily driven by coordinated regulation of biomass accumulation, nitrogen metabolism, and sink development. Overall, PCA indicates that yield improvement is governed by integrated physiological efficiency and sink strength rather than individual traits.

4 Discussion

The present study provides a comprehensive evaluation of the combined effects of fertigation and micronutrient application by integrating growth, physiological, biochemical, and yield parameters. Unlike earlier studies that focused on individual traits, this study highlights the coordinated role of metabolic efficiency and structural development in determining productivity.

4.1 Nutrient Availability and Vegetative Growth Mechanisms

Fertigation significantly enhanced vegetative growth, with treatments receiving water-soluble fertilizers (WSF) combined with micronutrient supplementation (particularly T_3) consistently outperforming conventional fertilizer application (T_{11}). This response indicates that nutrient form, delivery method, and micronutrient availability collectively regulate vegetative performance. The improved growth under fertigation can be attributed to enhanced nutrient use efficiency, as nutrients are supplied in synchrony with crop demand, leading to increased uptake and reduced losses (Liu et al., 2025). Enhanced nitrogen availability under fertigation promotes cell division and elongation, resulting in increased plant height, while potassium-mediated osmotic regulation improves turgor and cell expansion, contributing to greater canopy development (Shah et al., 2024). The higher number of secondary branches under optimized treatments suggests improved assimilate production and hormonal regulation, particularly cytokinin-mediated lateral bud development (Saleem et al., 2022). The absence of significant variation in primary branches indicates that secondary branching is a more sensitive indicator of nutrient-mediated responses. Micronutrient effects were clearly evident, with iron application showing a stronger influence on vegetative growth compared to zinc. Iron plays a critical role in chlorophyll biosynthesis, electron transport, and nitrogen metabolism, thereby enhancing photosynthetic efficiency and biomass accumulation (Li et al., 2021), whereas zinc primarily contributes to enzyme activation and auxin synthesis (Saleem et al., 2022). The superior performance of WSF-based treatments compared to straight fertilizers (SF) further emphasizes that nutrient availability and uptake efficiency, rather than total nutrient quantity, govern plant growth (Govindasamy et al., 2023).

4.2 Physiological and Biochemical Responses

Physiological and biochemical parameters were markedly enhanced under optimized fertigation treatments, indicating improved metabolic activity and nutrient assimilation (Abid et al., 2020). The increased nitrate reductase activity reflects enhanced nitrogen assimilation, as this enzyme catalyzes the reduction of nitrate to nitrite, a key step in nitrogen metabolism. Improved nitrogen assimilation supports amino acid and protein synthesis, thereby promoting cell division, growth, and reproductive development. This improvement in nitrogen metabolism was accompanied by higher numerical chlorophyll content and greater leaf area, supporting enhanced photosynthetic capacity. The coordination between carbon assimilation and nitrogen metabolism ensures a balanced supply of assimilates required for biomass accumulation and flower production (Fahad et al., 2023).

Higher phenol content under optimized treatments indicates activation of secondary metabolic pathways, particularly the phenylpropanoid pathway, which contributes to structural integrity and stress tolerance (Ninkuu *et al*., 2025). Similarly, increased IAA oxidase activity suggests regulated auxin turnover and improved hormonal balance, which may have contributed to enhanced branching and growth (Figueiredo and Strader, 2022).

The increase in specific leaf weight and dry matter production further confirms improved carbon assimilation and biomass accumulation. These parameters reflect enhanced photosynthetic efficiency and assimilate partitioning under optimal nutrient supply (Kuai et al., 2022). The comparatively better performance of iron over zinc suggests a more prominent role of iron in photosynthetic electron transport and metabolic efficiency, although zinc also contributes through its involvement in enzyme activation (Abbasi-Karvaneh et al., 2024).

4.3 Reproductive Efficiency and Yield Formation

Flowering and yield were strongly influenced by fertigation and micronutrient application, with optimized treatments showing superior reproductive performance. This improvement can be attributed to enhanced source-sink relationships driven by increased physiological efficiency. Higher leaf area, nitrate reductase activity, protein content, and dry matter production collectively contribute to greater assimilate generation, which is subsequently translocated to developing floral structures. The strong association between yield and parameters such as dry matter production, specific leaf weight, and number of cymes per plant indicates that yield is primarily governed by assimilate production capacity and sink strength. Specific leaf weight reflects photosynthetic efficiency, while dry matter production represents overall biomass accumulation, and cyme number determines sink demand. The superiority of iron-treated plants highlights its critical role in reproductive metabolism. Iron is a key component of cytochromes and Fe–S proteins involved in mitochondrial electron transport and ATP synthesis, which are essential for energy-intensive processes such as floral initiation and development (Read et al., 2021). Additionally, iron enhances chloroplast function, thereby increasing carbohydrate availability for reproductive growth. The generally higher numerical values of several flower quality traits under optimized treatments may reflect enhanced nutrient availability and metabolic activity, although only bud diameter differed significantly among treatments. Specific leaf weight also contributed significantly, indicating that photosynthetic efficiency plays a crucial role in supporting assimilate supply. Nitrate reductase activity further influenced yield, reflecting the importance of nitrogen assimilation in enhancing metabolic efficiency and reproductive development. These results provide strong evidence that yield improvement under fertigation is driven by integrated physiological processes rather than isolated growth traits.

Nitrogen supports protein synthesis and meristematic activity, potassium regulates osmotic balance and cell expansion, and phosphorus facilitates energy transfer through ATP synthesis, all of which are essential for floral development (Shah *et al*., 2024; Khan *et al*., 2023). Nitrate reductase activity ($r = 0.88$) and protein content ($r = 0.86$) also showed significant positive relationships with yield, highlighting the importance of nitrogen metabolism in supporting growth and flowering. These findings indicate that yield formation in *J. multiflorum* is governed by coordinated interactions between carbon assimilation and nitrogen metabolism rather than individual traits alone. The decline in yield and flowering parameters under treatments with greater reliance on straight fertilizers highlights the importance of nutrient solubility and availability. Reduced nutrient uptake likely limits photosynthetic efficiency and assimilate supply, thereby affecting reproductive development (Qin *et al*., 2023). This clearly demonstrates that nutrient use efficiency, rather than nutrient quantity alone, governs crop performance. Fertigation enhances nutrient use efficiency (NUE) by ensuring precise and timely nutrient delivery, minimizing losses, and maximizing uptake efficiency. The poor performance of conventional fertilizer application further confirms its limitations in meeting crop nutrient demand during critical growth stages.

5 Conclusions

The present study demonstrated that integrated nutrient management through fertigation combined with foliar micronutrient application improved growth, physiological and biochemical performance, and flower yield of *Jasminum multiflorum* 'Pink Kakada'. Among the treatments, 100% of the recommended fertilizer dose supplied as water-soluble fertilizers together with a 0.25% foliar iron spray produced the most favorable overall response. Correlation and principal component analyses showed that flower yield was closely associated with dry matter production, the number of cymes per plant, specific leaf weight, nitrate reductase activity, and protein content. These relationships emphasize the combined importance of biomass accumulation, sink development, and nitrogen metabolism in supporting reproductive performance. The integrated fertigation–foliar iron treatment therefore represents a practical nutrient-management option for improving winter flower production of 'Pink Kakada' under conditions comparable to those of the present study.

Authors' Contributions

Conceptualization: M.K., D.B.A. and S.S.; Data curation: A.N., M.S. and M.G.G.; Formal analysis: A.N., M.S. and M.G.G.; Investigation: A.N., M.S. and M.G.G.; Methodology: M.K., D.B.A. and S.S.; Supervision: M.K. and S.S.; Validation: V.A.A., S.S. and M.S.; Visualization: A.N. and M.S.; Writing—original draft: M.K. and A.N.; Writing—review and editing: M.K., D.B.A., S.S., A.N., V.A.A., M.G.G. and M.S.

All authors read and approved the final manuscript.

Ethical Approval

This study did not involve human participants or animals, and therefore ethical approval was not required.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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