



RESEARCH ARTICLE

Micronutrient dynamics and morphological performance of African marigold (*Tagetes erecta* L.) under North Bihar agroclimatic conditions

Roshni Agnihotri¹, Santosh Kumar Singh² & Hemlata Singh^{3*}

¹Department of Horticulture, Post Graduate College of Agriculture, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur 848 125, Bihar, India

²Department of Soil Science, Pandit Deen Dayal Upadhyay College of Horticulture and Forestry, Dr Rajendra Prasad Central Agricultural University, Piprakothi, Pusa, Samastipur 848 125, Bihar, India

³Department of Botany, Plant Physiology and Biochemistry, College of Basic Sciences and Humanities, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur 848 125, Bihar, India

*Correspondence email - hemlata.singh9243@gmail.com

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Abstract

African marigold (*Tagetes erecta* L.) is an economically important ornamental crop in North Bihar, India. There are fertiliser recommendations for commercial cultivation of marigolds, but systematic information on leaf micronutrient composition and its relationship with floral performance remains limited. A three-year (2021–2024) randomised block design (RBD) field trial was conducted with nine micronutrient treatment combinations involving soil and foliar applications of Zn, Mn, Fe and B, with leaf micronutrient profiling in African marigold (*Tagetes erecta* L. cv. Arka Abhi) under the humid subtropical conditions of North Bihar, India. Results of the analysed data showed significant phenotypic variation in micronutrient levels of the following from lower to upper range, i.e., Fe (555–847 ppm), Mn (61–130 ppm), Zn (14.7–44.4 ppm), Cu (10.6–26.5 ppm) and B (29–67 ppm). Strong positive correlations were observed between Fe-Mn content and flower yield ($r = 0.70$) and flowering duration ($r = 0.74$). Zinc showed a positive association with plant height ($r = 0.61$), while boron correlated with the shelf life of the flower ($r = 0.59$). Among the treatments, the combined application of micronutrients including soil application of Zn (2.5 kg/ha) + Mn (2.5 kg/ha) + B (1 kg/ha) + Fe (1.25 kg/ha) at planting and Zn-ethylenediaminetetraacetic acid (EDTA) + Mn-EDTA + B + Fe-EDTA (0.2 % each) foliar application, exhibited optimal micronutrient balance with highest yield (762.55 g/plant), tallest plants (126.2 cm), longest flowering (81.66 days) and best shelf life (5.88 days), representing 78.9 % yield advantage over the check. The findings suggest that maintaining Fe (600–700 ppm), Mn (90–110 ppm), Zn (25–30 ppm) and B (45–60 ppm) in leaf tissue is crucial for superior floral performance under North Bihar's humid subtropical conditions. Maintaining optimal leaf levels of Fe (600–700 ppm), Mn (90–110 ppm), Zn (25–30 ppm) and B (45–60 ppm) is crucial for superior floral performance. Balanced micronutrient ratios rather than high individual levels drive crop performance and support effective, site-specific nutrient management in alkaline alluvial soils.

Keywords: micronutrient interaction; morphological traits; North Bihar; *Tagetes erecta*; yield

Introduction

African marigold (*Tagetes erecta* L.) is one of the most commercially significant locally consumed flower crops, which is prized for its vivid blooms in religious and social ceremonies. The marigold is also being utilised as a natural source of lutein and zeaxanthin carotenoids for the poultry and nutraceutical industries (1). It is called as a versatile crop, well suited for year-round production in the Indo-Gangetic plains due to its exceptional flexibility across a variety of agroclimatic zones (2). The micronutrients serve as components of chlorophyll, co-factors for enzymes and regulators of photosynthetic efficiency and are essential to plant metabolism (3). Balanced micronutrition has a direct impact on flower size, colour intensity, vase life and overall quality in ornamental crops (4). Iron and manganese are essential for oxidative metabolism and

photosynthetic electron transport chains (5), whereas zinc controls auxin biosynthesis and meristematic activity (6). Copper is involved in the production of lignin and the regulation of oxidative stress (7), while boron preserves cell wall integrity and the development of reproductive tissue (8). Although the rich alluvial soil of Bihar has sufficient total stocks, they show cryptic micronutrient deficits due to its moderate organic matter (0.4–0.6 %), slightly alkaline pH (7.2–7.6) and monsoon-mediated leaching (9). In flower crops like marigolds, the micro-nutrient deficit is expressed as decreased vegetative vigour, delayed flowering and poor bloom quality (10). Although earlier research has shown that marigolds respond favourably to specific micronutrient administrations (11–13), a thorough understanding of leaf micronutrient profiles and their connections to morphological performance of commercial cultivar “Arka Abhi” in

North Bihar environments is still lacking.

Fertilisation must depend on an understanding of genotype-specific micronutrient requirements and how they relate to yield characteristics. Thus, the purpose of this study was to measure the concentrations of micronutrients in leaves along with their yield and quality performance and eventually to determine statistical correlations between nutritional status and phenotypic expression for commercial production.

Materials and Methods

Experimental site and climatic conditions

The field experiment was conducted during three consecutive growing seasons (2021–2022, 2022–2023 and 2023–2024) at the Horticulture Research Farm, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India (25°59'N latitude, 85°40' E longitude, 52 m above mean sea level (MSL)). The experimental site has a humid subtropical climate with distinct seasonal variations. Mean annual rainfall averages 1150 mm, concentrated between June and September. Temperatures ranged during the period of experimentation was 15 °C–25 °C (October–February). The soil was sandy loam (sand: 58 %, silt: 26 %, clay: 16 %) with slightly alkaline reaction (pH 7.4), low organic carbon (0.48 %) and medium fertility status (available N: 245 kg/ha, P₂O₅: 18.5 kg/ha, K₂O: 195 kg/ha).

Plant materials and experimental design

The experiment was laid out in a randomised block design (RBD) with three replications with 24 plants per plot (3.0 m × 2.4 m). Thirty-day old seedlings of *Tagetes erecta* cv “Arka Abhi” were transplanted during the second week of October in all three years. Uniform cultural practices were followed across all treatments. Farmyard manure (FYM) at 25 t/ha was incorporated two weeks before transplanting. Recommended dose of nitrogen, phosphorus and potassium (NPK) (150:100:75 kg/ha) was applied. Full phosphorus and potassium with half nitrogen were given as basal, while the remaining nitrogen was top-dressed at 30 and 60 days after transplanting (DAT). Irrigation was provided through a drip system at 3–4 days of interval. The initial micronutrient status of the soil was recorded for clarity (Supplementary Table 1).

Treatment details

The treatments were designed to evaluate the effects of key micronutrients (Zn, Fe, Mn and B) under varying doses, application methods (soil vs foliar) and their integrated use, in order to understand nutrient interactions and optimise micronutrient balance for improved growth, yield and floral quality in African marigold under North Bihar conditions.

T1: Zn (5 kg/ha) + Mn (5 kg/ha) + B (2 kg/ha) + Fe (2.5 kg/ha) soil application at planting

T2: Zn (2.5 kg/ha) + Mn (2.5 kg/ha) + B (1 kg/ha) + Fe (1.25 kg/ha) soil application at planting

T3: Zn-EDTA + Mn-EDTA + B + Fe-EDTA (0.2 % each) foliar application

T4: Zn-EDTA + Mn-EDTA + B + Fe-EDTA (0.1 % each) foliar application

T5: T1 soil + T3 foliar application

T6: T1 soil + T4 foliar application

T7: T2 soil + T3 foliar application

T8: T2 soil + T4 foliar application

T9: recommended dose fertiliser (RDF); control

For soil application, zinc sulphate, ferrous sulphate, manganese sulphate, and borax were used. The quantities were calculated based on nutrient content. For foliar application, boron was supplied as disodium octaborate tetrahydrate. The foliar sprays were applied 3 times at 30, 45, 60 days after transplanting (DAT). In order to take morphological observations viz., plant height (cm), days to flower initiation, flowering duration (days), flower diameter (cm), yield/plant (g), flower weight (g), shelf life (days), 10 plants per plot were tagged and data was recorded according to standard procedure. Shelf life was assessed by keeping harvested flowers at ambient conditions (25 ± 2 °C, 60 ± 5 % relative humidity (RH) and recording was made in days until 50 % flowers showed visible deterioration.

Leaf sampling and micronutrient analysis were carried out from fully expanded mature leaves (4th–6th from apex) collected at peak flowering (75–80 DAT), washed, dried and ground. Then Fe, Mn, Zn, Cu were analysed by atomic absorption spectrophotometer (Varian AA240FS).

Leaf sampling and micronutrient analysis

Fully expanded mature leaves were collected from five randomly selected plants per plot at the peak flowering stage (75–80 DAT). After removing surface impurities with tap water, 0.1 N hydrochloric acid (HCl) and distilled water, samples were oven-dried at 65 ± 2 °C until their weight remained constant. Samples of dried leaves were placed in airtight polythene bags after being pulverised to fit through a 0.5 mm sieve. A microwave digestion device (Milestone ETHOS Easy) was used to digest 0.5 g of powdered leaf material in a di-acid combination (HNO₃:HClO₄, 3:1 v/v) for micronutrient analysis. The solution was filtered using Whatman No. 42 filter paper after full digestion and double-distilled water was added to get the volume up to 50 mL. The concentrations of iron, manganese, zinc and copper were measured using an atomic absorption spectrophotometer (Varian AA240FS) equipped with the proper hollow cathode lamps. Boron was estimated calorimetrically at 420 nm wavelength using the azomethine-H method (14). All biochemical analyses were performed in duplicate and values expressed on a dry weight basis as parts per million (ppm).

Statistical analysis

Data collected over the duration of three years were pooled after testing for homogeneity of error variance using Bartlett's test. Analysis of variance (ANOVA) was performed using WASP 2.0 (Web Agri Stat Package) following a randomised block design. Duncan's multiple range test (DMRT) was used to compare means at 5 % level of significance (15). Pearson's correlation coefficients were computed between micronutrient concentrations and morphological parameters. All data are presented as mean ± standard error. Figures were prepared using Python programming language with matplotlib and seaborn visualisation libraries.

Results

Variability in leaf micronutrient concentrations

The nine treatments showed significant differences ($p < 0.01$) in leaf micronutrient concentration (Table 1). The iron concentration in the leaf showed variation from 555 ppm (T8) to 847 ppm (T9). Manganese ranged from 61 ppm (T4) to 130 ppm (T3). The zinc

content was highest in T3 (44.4 ppm) and lowest in T5 (14.7 ppm). The copper content in leaf ranged from 10.6 ppm (T5) to 26.5 ppm (T2). The average boron ranged from 29 ppm (T3) to 67 ppm (T1). Treatment 7 maintained a balanced micronutrient profile with Fe (629 ppm), Mn (102 ppm), Zn (22.1 ppm), Cu (14.2 ppm) and B (41 ppm), while T3 showed a contrasting pattern with the highest Zn (44.4 ppm) and Mn (130 ppm) but lowest B (29 ppm). Treatment T9, used as a check, had the highest Fe (847 ppm) but lowest Zn (18.0 ppm), correlating with its inferior morphological performance.

Morphological and floral performance traits

Pooled analysis over three years revealed highly significant ($p < 0.01$) treatment effects for all morphological parameters except days to flower initiation (Table 2). Plant height ranged from 81.2 cm (T9) to 126.2 cm (T7), representing 55.4 % superiority of best treatment over check. Days to flower initiation ranged from 50.9 days (T1) to 55.7 days (T4), with non-significant variation ($p > 0.05$), demonstrating similar phenological response across treatments under the given environment. The duration of flowering, however, varied significantly between 59.4 days (T2) and 81.7 days (T7), with T7 exhibiting a 20.4 % greater flowering period than the check (67.8 days).

Flower diameter varied from 6.88 cm (T9) to 8.28 cm (T7), with T7, T4 and T3 forming a statistically homogeneous group superior to the remaining treatment. Flower yield per plant, the most economically important trait, ranged from 426.2 g (T9) to 762.6 g (T7), representing 78.9 % yield advantage. Treatment T4 (673.6 g) and T5 (651.5 g) also demonstrated significantly higher yield than

check, forming an intermediate group.

The weight of individual flowers ranged from 8.42 g in T1 to 9.93 g in T4, whereas the shelf life ranged from 3.33 days in T9 to 5.92 days in T4. The second-highest shelf life (5.88 days) was recorded in T7, which was significantly higher than the control.

Analysis of variance

Pooled ANOVA data represented in Table 3 showed that treatments had a highly significant effect ($p < 0.01$) on plant height ($F = 7.12$), flowering time ($F = 31.86$), floral diameter ($F = 3.98$), yield per plant ($F = 12.45$), individual flower weight ($F = 4.51$) and shelf life ($F = 3.40$). Substantial seasonal influence on trait expression was indicated by a highly significant year (block) effect. This validates the use of pooled, multi-year data for analysis.

Correlation between micronutrients and morphological traits

Pearson's correlation analysis highlighted distinct patterns of association between leaf micronutrient status and observed phenotypic traits (Table 4, Fig. 1). Manganese showed a positive correlation with flower duration ($r = 0.71, p < 0.01$) and yield ($r = 0.68, p < 0.01$). Similarly, iron also showed a positive correlation with flower duration ($r = 0.74, p < 0.01$) and flower yield ($r = 0.70, p < 0.01$). Zinc concentration was positively linked to floral diameter ($r = 0.47, p < 0.05$) and plant height ($r = 0.61, p < 0.05$), suggesting its role in flower size and plant growth. However, zinc showed a negative correlation with shelf life ($r = -0.38, p > 0.05$). Boron, known for its role in preserving membrane integrity and delaying senescence, showed a positive correlation with shelf life ($r = 0.59, p < 0.05$). Copper and flower diameter had a weak negative connection ($r = -0.45, p < 0.05$), which may indicate antagonistic interactions at higher concentrations. Both Fe and Mn showed a significant positive connection ($r = 0.76, p < 0.01$), suggesting that they work together in photosynthetic metabolism.

Discussion

Genotypic variation in micronutrient accumulation

Differential genetic control of absorption, transport and accumulation mechanisms was observed in the significant diversity in leaf micronutrient concentrations among African marigold treatments. Iron content varied from 555 ppm to 847 ppm, indicating genotypic variations in the plant's iron acquisition capacity, which may be mediated by different ferric reductase activity and phytosiderophore secretion efficiency at the root-soil interface (16). Slightly alkaline soil conditions (pH 7.4) of the

Table 1. Leaf micronutrient concentrations (ppm, dry weight basis) in different micronutrient treatments

Treatments	Fe	Mn	Zn	Cu	B
T1	803 ^a	94 ^{bcd}	30.8 ^{bc}	13.9 ^{cd}	67 ^a
T2	578 ^d	79 ^{cde}	28.2 ^{bcd}	26.5 ^a	49 ^{bc}
T3	754 ^{ab}	130 ^a	44.4 ^a	17.9 ^{bc}	29 ^e
T4	641 ^{cd}	61 ^e	18.5 ^{de}	13.8 ^{cd}	33 ^{de}
T5	702 ^{bc}	78 ^{cde}	14.7 ^e	10.6 ^d	43 ^{cd}
T6	656 ^{cd}	116 ^{ab}	28.4 ^{bcd}	15.5 ^{cd}	50 ^{bc}
T7	629 ^{cd}	102 ^{abc}	22.1 ^{cde}	14.2 ^{cd}	41 ^{cde}
T8	555 ^d	80 ^{cde}	26.1 ^{bcd}	17.4 ^{bc}	34 ^{de}
T9 (Check)	847 ^a	106 ^{abc}	18.0 ^{de}	12.6 ^{cd}	62 ^{ab}
Mean	685.1	93.9	25.5	15.8	45.3
SE(m) $\pm$	29.8	7.2	2.8	1.5	3.5
CD ($p = 0.05$)	87.4	21.1	8.2	4.4	10.3
CV (%)	14.3	25.2	37.4	18.9	25.6

Values with same superscript letters within a column are not significantly different according to Duncan's multiple range test at $p = 0.05$; SE(m): standard error of mean; CD: critical difference; CV (%): coefficient of variation.

Table 2. Morphological and floral performance traits of African marigold treatments (pooled over 2021–22, 2022–23, 2023–24)

Treatments	Plant height (cm)	Days to flower initiation	Flowering duration (days)	Flower diameter (cm)	Yield/plant (g)	Flower weight (g)	Shelf life (days)
T1	84.2 ^d	50.9 ^{bc}	60.5 ^d	7.33 ^{bc}	519.2 ^{cd}	8.42 ^d	3.97 ^{bc}
T2	84.5 ^d	53.3 ^{abc}	59.4 ^d	7.17 ^c	493.4 ^{cd}	8.46 ^d	4.16 ^{abc}
T3	93.4 ^{cd}	54.1 ^{abc}	62.8 ^{cd}	7.76 ^{ab}	523.3 ^{bcd}	9.00 ^{bcd}	4.41 ^{abc}
T4	100.9 ^{bc}	55.7 ^a	80.3 ^a	7.96 ^{ab}	673.6 ^{ab}	9.93 ^a	5.92 ^a
T5	101.6 ^{bc}	51.7 ^c	78.9 ^{ab}	7.76 ^{ab}	651.5 ^{ab}	9.55 ^{ab}	4.78 ^{abc}
T6	95.1 ^{cd}	53.1 ^{abc}	74.7 ^b	7.64 ^{abc}	620.9 ^{abc}	8.62 ^{cd}	4.73 ^{abc}
T7	126.2 ^a	54.0 ^{abc}	81.7 ^a	8.28 ^a	762.6 ^a	9.82 ^a	5.88 ^a
T8	87.1 ^d	51.9 ^{bc}	61.8 ^{cd}	7.74 ^{ab}	528.1 ^{bcd}	9.14 ^{abc}	4.28 ^{abc}
T9 (Check)	81.2 ^d	53.5 ^{abc}	67.8 ^c	6.88 ^c	426.2 ^d	8.63 ^{cd}	3.33 ^c
SE(m) $\pm$	4.98	1.22	1.48	0.20	27.91	0.20	0.44
CD ($p = 0.05$)	18.29	(NS)	5.42	0.74	102.41	0.73	1.60
CV (%)	9.18	4.01	3.62	4.53	8.56	3.71	16.54

Values with same superscript letters within a column are not significantly different according to Duncan's multiple range test at $p = 0.05$; SE (m): standard error of mean; CD: critical difference; CV (%): coefficient of variation; NS: non-significant.

Table 3. Pooled analysis of variance for morphological and floral traits

Character	Source	df	Sum of squares	Mean square	F-value	Significance
Plant height (cm)	Treatments	8	4247.01	530.88	7.12	**
	Blocks (Years)	2	1756.94	878.47	11.78	**
	Error	16	1193.22	74.58	-	-
	CD (0.05)			18.291	CV% = 9.18	
Flowering duration (days)	Treatments	8	1663.38	207.92	31.86	**
	Blocks (Years)	2	55.19	27.60	4.23	**
	Error	16	104.44	6.53	-	-
	CD (0.05)			5.416	CV% = 3.62	
Yield/plant (g)	Treatments	8	232758.42	29094.80	12.45	**
	Blocks (Years)	2	229537.53	114768.77	49.12	**
	Error	16	37386.12	2336.63	-	-
	CD (0.05)			102.412	CV% = 8.56	

** Significant at $p < 0.01$; df: degrees of freedom; CD: critical difference; CV (%): coefficient of variation; F: F-statistic.

Table 4. Pearson's correlation coefficients between leaf micronutrients and morphological traits

Parameter	Fe	Mn	Zn	Cu	B	Height	Duration	Diameter	Yield	Shelf life
Fe	1.00									
Mn	0.76**	1.00								
Zn	-0.52*	-0.34	1.00							
Cu	0.18	0.05	-0.14	1.00						
B	0.45*	0.51*	-0.63**	0.22	1.00					
Plant height	0.28	0.33	0.61*	-0.15	-0.22	1.00				
Flowering duration	0.74**	0.71**	-0.29	-0.21	0.48*	0.42	1.00			
Flower diameter	0.38	0.44*	0.47*	-0.45*	0.18	0.53*	0.55*	1.00		
Yield/plant	0.70**	0.68**	-0.18	-0.28	0.52*	0.65**	0.85**	0.72**	1.00	
Shelf life	0.41	0.47*	-0.38	-0.31	0.59*	0.28	0.62**	0.44*	0.58*	1.00

* Significant at $p < 0.05$; ** Significant at $p < 0.01$.

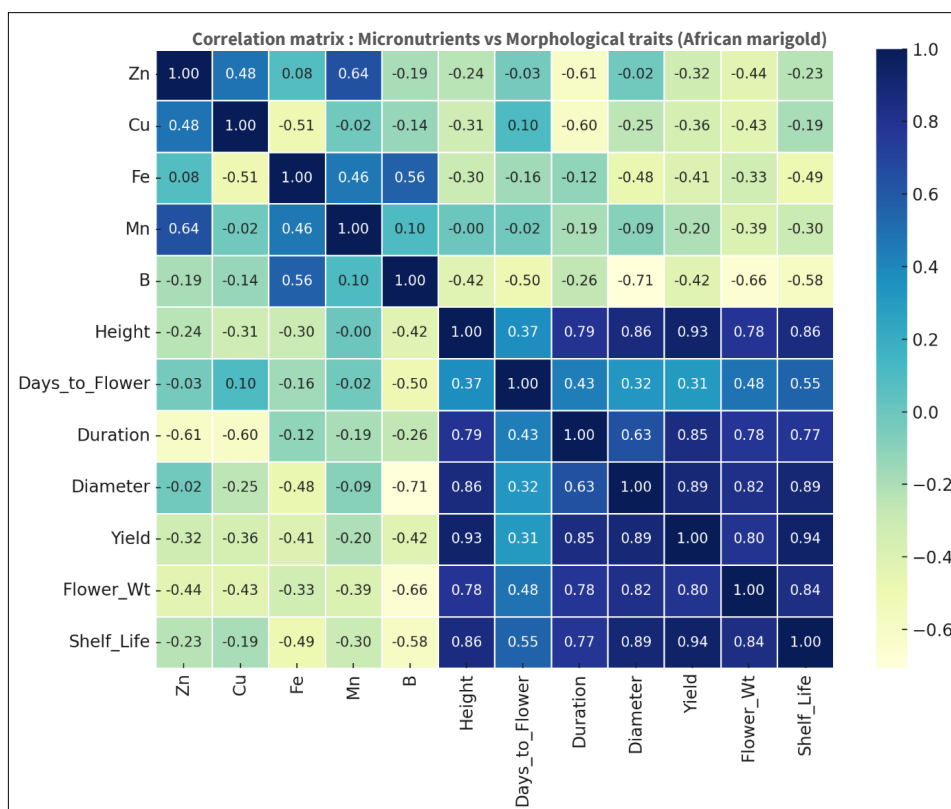


Fig. 1. Correlation heatmap showing relationships between leaf micronutrient concentrations (Fe, Mn, Zn, Cu, B) and morphological traits (plant height, flowering duration, flower diameter, yield per plant, shelf life) in African marigold treatments. Colour intensity indicates strength of correlation: red (positive), blue (negative). * $p < 0.05$; ** $p < 0.01$.

experimental site limit iron availability due to the formation of insoluble ferric hydroxides, requiring improved plant-mediated mobilisation mechanisms (17). The concentration of manganese varied significantly more (coefficient of variation (CV) = 25.2 %), from 61 ppm in T4 to 130 ppm in T3. Given that Mn is a cofactor for the enzymes superoxide dismutase and catalase, which are involved in the scavenging of reactive oxygen species (ROS), this significant

variability suggests genotype-specific changes in tolerance to oxidative stress (18). Interestingly, the comparison between the less yielding check (T9) with Mn levels of 106 ppm and the high-yielding treatments (T7: 102 ppm, T4: 61 ppm) suggests that a higher Mn level does not necessarily result in better yield.

With a three-fold difference between T5 (14.7 ppm) and T3

(44.4 ppm), zinc displayed the highest variability (CV = 37.4 %). Differential expression of ZIP (zinc-regulated transporter, iron-regulated transporter-like protein) family transporters that mediate Zn absorption and root-to-shoot translocation is probably the cause of this large discrepancy (19). The Treatment T3, had the highest Zn concentration (44.4 ppm), but it did not show proportionate superiority in yield attributes. This might be due to Fe deficiency caused by Zn through competitive inhibition of iron transporters. Such antagonistic interaction between Zn and Fe is extensively studied in dicotyledonous species (20). Boron concentration ranged from 29 ppm (T3) to 67 ppm (T1), with mean of 45.3 ppm. Since boron is primarily transported through xylem via transpiration stream and its phloem mobility is limited in many species (21), the observed variation may partly reflect differences in transpiration rates and water use efficiency among treatments.

Morphological performance and yield components

Among all the treatments, T7 performed better than all the treatments across multiple traits, yielding 78.9 % more than check (T9). This superior performance appears to be a consequence of a balanced micronutrient profile rather than higher levels of individual elements. Longer flowering duration for T7 (81.7 days) could be possible by balanced micronutrient Fe:Mn:Zn:B (629:102:22.1:41), as reported by previous works, where they reported that continuous flower production depends on sustained nutrient availability (22). Similarly, up to 70 % yield improvement in marigolds was reported through balanced nutrient supply by previous researchers (23).

Furthermore, flowering duration showed a positive correlation with yield ($r = 0.85$, $p < 0.01$) suggested that the treatments having longer period of flower duration utilise resources for more flower production and compensate for occasional flower drop during stress, resulting in higher yield. Our results corroborate earlier findings in *Tagetes patula* L. where prolonged flowering was associated with sustained cytokinin biosynthesis and delayed senescence signalling (24).

The data on plant height showed a significant positive association with yield ($r = 0.65$). Plants in treatment T7 reached up to 126.2 cm and developed extensive branches that provided more space for flower bud formation. This observation is consistent with established source-sink relationship theory, which states that increased vegetative biomass serves as a reserve of carbohydrates to support reproductive growth (25). Flower diameter, which is not directly related to yield but is an important parameter for the market value of the flower, a positive correlation was observed between diameter and yield ($r = 0.72$), suggesting that factors influencing cell expansion in floral tissues also enhance overall productivity. Plants in treatment T7 had the largest flower (8.28 cm diameter), possibly because of sufficient Zn availability for auxin production (26).

Micronutrient interactions and physiological implications

Both Fe and Mn showed a strong positive correlation with yield ($r = 0.70$ and $r = 0.68$ respectively), suggesting a synergistic effect. This was expected, as both nutrients perform complementary roles in the photosynthetic machinery: Mn, a component of photosystem II (PS II), catalyses water oxidation, whereas Fe is essential for proteins associated with photosystem I (PS I) (27). Together they enhanced photosynthetic efficiency and carbon fixation, resulting in more yield. Previous work on *Chrysanthemum morifolium* (Ramat.) Hemsl. demonstrated a 34 % increase in net photosynthetic rate when Fe

and Mn were applied together rather than separately (28). However, Zn and iron showed a negative correlation ($r = -0.52$). This could be due to competitive antagonism at absorption or translocation sites, as similar transport proteins belonging to ZIP and natural resistance-associated macrophage protein (NRAMP) families are involved in the transport of Zn^{2+} and Fe^{2+} cations (29). The excess Zn concentration in T3 (44.4 ppm) limited Fe^{2+} cation uptake in plants, despite its sufficient concentration in soil. This competitive interaction becomes pronounced in alkaline soil like the present experimental site soil, where metal-chelate complexes favour Zn over Fe with root exudates (30).

Boron plays an important role in maintaining cell wall integrity by preserving pectin cross-linking (31), which may explain the positive correlation observed between boron and shelf life ($r = 0.59$, $p < 0.05$). Previous studies (32) reported that boron application in roses improved vase life by 40 % through enhanced aquaporin expression and water uptake capacity. Treatment T4 and T7 had moderate levels of B 33 and 41 ppm respectively, showing the highest shelf life in T4 (5.92 days) and T7 (5.88 days), supports the principle that optimum level of boron is beneficial.

Copper showed a weak negative correlation ($r = -0.45$) with flower diameter, suggesting phytotoxic effects at higher concentrations. As a redox-active metal, copper can generate reactive oxygen species through fenton-like reactions, leading to oxidative stress in plants (33). Treatment T2 with the highest Cu concentration (26.5 ppm) had comparatively smaller flower diameter (7.17 cm), which could be due to oxidative stress in the plant during petal growth. Previous studies (7) reported that excess of Cu concentration in plant disturbs cellular redox haemostasis and disrupts the normal cell expansion process. Furthermore, excess Cu interferes with Fe metabolism by competing for ferritin binding sites, aggravating the symptoms of Fe deficiency even when sufficient Fe is present in the soil (34).

Optimal micronutrient ranges for superior performance

The ideal leaf micronutrient ranges for optimising African marigold output in North Bihar conditions, according to the current trials, are Fe (600–700 ppm), Mn (90–110 ppm), Zn (20–30 ppm), Cu (12–16 ppm) and B (40–50 ppm). The micro-nutrient range excludes antagonistic interactions and gives optimal performance. Although some treatments had desirable amounts of nutrients, T3 produced only 523.3 g/plant due to the lowest B (29 ppm), resulting in reproductive problems, although having adequate Fe (754 ppm), very high Mn (130 ppm) and Zn (44.4 ppm). Similarly, T9 (check) had the lowest Zn (18.0 ppm) and the highest Fe (847 ppm), which led to poor vegetative growth and the lowest yield (426.2 g/plant). These findings support Liebig's law of minimum and Steenbjerg's theory of optimal nutrition, which holds that the most deficient nutrient limits crop performance and that production is determined by optimal rather than maximum concentrations of all nutrients combined (35). Maintaining balanced nutrition becomes much more crucial in ornamental crops, where aesthetic quality of ornamentals is as vital as yield.

Implications for nutrient management in North Bihar

The findings will be helpful for developing site-specific nutrient management strategies for African marigold cultivation in North Bihar. The alluvial soils of Indo-Gangetic plain are generally considered rich in total micronutrients, but there is low availability

due to alkaline pH, high calcium carbonate content and periodic waterlogging during monsoon (36). Conventional soil applications of micronutrients fail to rectify deficiencies due to rapid fixation and conversion into unavailable forms. Foliar application of micronutrient cocktails in optimal ratios at critical stages proves to be a more effective approach. Application of Fe-EDTA (0.5 %), MnSO₄ (0.3 %), ZnSO₄ (0.2 %) and borax (0.1 %) at vegetative and bud initiation stages may help achieve target leaf concentrations. Chelated forms are preferable for Fe and Zn to prevent precipitation under alkaline foliar surface pH (37).

Alternatively, development and deployment of nutrient-efficient cultivars through conventional breeding or biotechnological interventions offers long-term sustainable solution. Treatments like T7, T4 and T5 identified in this study possess an inherent capacity to maintain optimal nutrient balance under given soil conditions and can serve as donor parents for introgressing nutrient efficiency traits into high-yielding commercial cultivars.

Conclusion

This three-year field study showed that maintaining a balanced supply of micronutrients Fe, Zn, Mn and B improved morphological and floral performance. Both Fe and Mn were found to be the most significant factors influencing flowering duration and yield. Zinc improved plant height and flower size when present within a 20–30 ppm range, while boron at 40–50 ppm improved postharvest shelf life. Among the treatments, treatment T7 outperformed all the treatments. The T7 consisted of a combined approach, where micronutrients were applied both through soil and foliar application. This balanced nutrient management in this treatment resulted in the highest yield with a yield of 762.6 g/plant, a flowering period of 81.7 days and a shelf life of 5.88 days. The study highlights that crop performance is determined by balanced micronutrient ratios rather than high individual concentrations. Excessive amounts can reduce crop performance due to negative interactions, especially between zinc and iron. Maintaining an ideal micronutrient profile by combined applications of nutrients is an effective strategy to improve marigold yield and flower quality under the humid subtropical conditions and alkaline alluvial soils of North Bihar. Future research should validate the optimal micronutrient ranges identified here across diverse marigold cultivars and agroclimatic zones. Mechanistic studies using enzyme assays and transporter gene expression analyses would elucidate the observed Fe-Mn synergism and Zn-Fe antagonism at the molecular level.

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Authors' contributions

RA contributed to conceptualisation, project administration, and writing of the original draft. SKS performed validation and laboratory analysis. HS contributed to investigation, formal analysis, writing, and review. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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