

NANO-DAP-MEDIATED NITROGEN AND PHOSPHORUS USE EFFICIENCY, NUTRIENT UPTAKE, GROWTH AND FLOWER PRODUCTION OF AFRICAN MARIGOLD (*TAGETES ERECTA* L.) CV. SERACOLE

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ABSTRACT

A two-year field experiment (2022 and 2023) was conducted at Assam Agricultural University, Jorhat, to determine whether Nano-DAP integrated with reduced conventional phosphorus could improve nutrient acquisition, nutrient-use efficiency, growth and flower production of African marigold cv. Seracole across three planting dates (15 February, 15 April and 15 June). Nine fertilizer treatments were evaluated in a factorial randomized block design with three replications. The integrated treatment F₉ [NPK 9:4.5:12 g m⁻² + Nano-DAP root dip (5 mL L⁻¹) + foliar spray (10 mL L⁻¹)] produced the highest pooled flower yield (259.72 q ha⁻¹), N uptake (78.82 kg ha⁻¹), P uptake (14.22 kg ha⁻¹) and K uptake (70.55 kg ha⁻¹) at 90 DAT. Relative to full recommended NPK (F₃), F₉ increased pooled flower yield by 9.6% while using approximately half the conventional soil-applied P₂O₅. Using the Nano-DAP nutrient composition specified for the notified IFFCO liquid formulation (8% N and 16% P₂O₅, w/v) for derived calculations, F₉ achieved a P partial factor productivity of 573.9 kg flowers kg⁻¹ P₂O₅ compared with 263.2 under F₃, and an apparent P recovery efficiency of 38.8% compared with 4.8% under F₃. Across planting dates, D₁F₉, D₂F₉ and D₃F₉ exceeded the corresponding full-RDF treatment F₃ by 7.0, 6.6 and 15.9%, respectively, for flower yield. Nutrient uptake at 90 DAT was positively associated with flower yield across the 27 pooled treatment means ($r=0.63$ for N, 0.65 for P and 0.66 for K). The results demonstrate that Nano-DAP can support high flower production with reduced conventional phosphorus input, although derived nutrient-use-efficiency indices should be interpreted as treatment-mean estimates and confirmed using replicate-level efficiency calculations and the exact nutrient analysis of the Nano-DAP formulation used in the experiment.

KEYWORDS: African marigold; Nano-DAP; nitrogen use efficiency; phosphorus use efficiency; nutrient uptake; flower yield; planting date

INTRODUCTION

African marigold (*Tagetes erecta* L.) is an important loose-flower crop in eastern and north-eastern India. Productivity is strongly affected by planting season and nutrient management because canopy development, dry-matter accumulation, flowering and nutrient acquisition are sensitive to temperature, rainfall, humidity and nutrient availability [1–4]. Nitrogen supports vegetative growth and photosynthetic capacity, whereas phosphorus is central to root development, energy transfer and reproductive growth [5–7]. In acidic soils, however, a substantial fraction of conventionally applied phosphorus can become less available to plants, increasing the importance of strategies that improve phosphorus acquisition and use.

Nano-fertilizers have been proposed as a means of improving nutrient delivery through high surface area, targeted uptake and root or foliar entry pathways [8–12]. Nano-DAP has shown positive responses in marigold, cabbage, tomato, rice and other crops when integrated with reduced or recommended fertilizer doses [13–18]. In African marigold cv. Super Ball, reduced conventional N and P combined with nano-fertilizer application improved growth and yield components [13], while root-dip and foliar Nano-DAP have also been associated with improved nutrient uptake and crop performance in other species [14–18].

The present experiment was originally designed to evaluate Nano-DAP under contrasting planting dates, and the thesis dataset contains repeated plant N, P and K uptake measurements at 30, 60 and 90 DAT, growth and biomass data, flower yield, post-harvest soil fertility and economics. The present paper re-analyses these data around a nutrient-use-efficiency framework. Particular emphasis is placed on the comparison between full recommended

NPK (F₃) and treatments receiving 50% of conventional phosphorus together with Nano-DAP (F₇–F₉), while retaining all nine fertilizer treatments and all 27 planting-date × fertilizer combinations.

The objectives were to: (i) quantify temporal N, P and K uptake under Nano-DAP-based nutrient management; (ii) estimate nitrogen and phosphorus productivity/use-efficiency indices from fertilizer input, nutrient uptake and flower yield; (iii) evaluate the interaction of planting date and fertilizer treatment for nutrient uptake and flower yield; and (iv) relate nutrient acquisition to biomass and flower production.

2. MATERIALS AND METHODS

2.1 Experimental site and weather

The experiment was conducted during 2022 and 2023 at the Experimental Farm, Department of Horticulture, Assam Agricultural University, Jorhat (26°45' N, 94°12' E; 86.6 m above mean sea level). The soil was sandy loam and acidic (initial pH 5.06), with 0.62% organic carbon and available N, P₂O₅ and K₂O of 266, 27.20 and 141.50 kg ha⁻¹, respectively. Meteorological observations were obtained from the Agrometeorological Observatory, Assam Agricultural University, Jorhat. The experimental period covered a transition from relatively cool and dry February conditions to the warm, humid monsoon period; monthly rainfall peaked during June in both years.

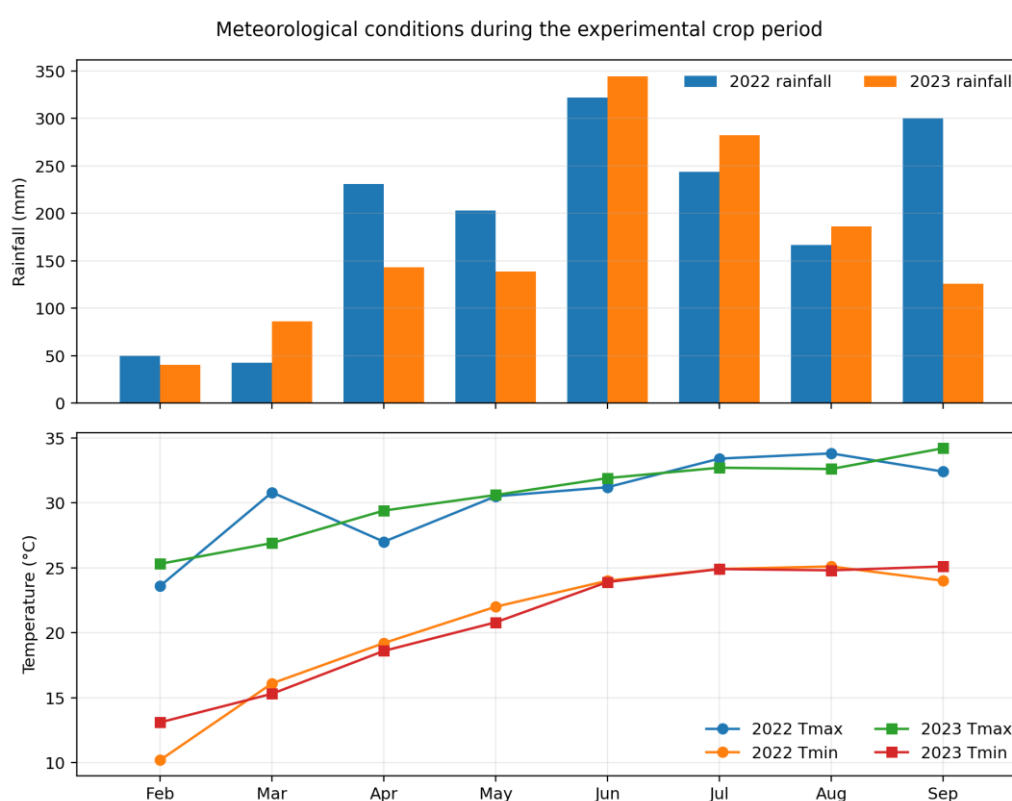


Fig. 1. Monthly rainfall and maximum/minimum temperature during the experimental crop period in 2022 and 2023.

2.2 Experimental design and nutrient treatments

The experiment was laid out in a factorial randomized block design with three planting dates—D₁: 15 February, D₂: 15 April and D₃: 15 June—and nine fertilizer treatments, each replicated three times in each year. Plants were spaced at 45 × 45 cm. Urea, single superphosphate (SSP) and muriate of potash (MOP) were used as the conventional N, P and K sources. Urea was split between transplanting and 30 DAT. Nano-DAP treatments received a root dip at 5 mL L⁻¹ and/or a foliar spray at 10 mL L⁻¹ at 45 DAT.

Table 1. Nutrient-management treatments and fertilizer input rates used in the two-year African marigold experiment.

Treatment	Conventional nutrient schedule (g m ⁻²)	Nano-DAP	Conventional N (kg ha ⁻¹)	Conventional P ₂ O ₅ (kg ha ⁻¹)	Nano-DAP requirement
F ₁	Control	None	0	0	—
F ₂	NPK 9:0:12	None	90	0	—
F ₃	NPK 9:9:12 (100% RDF)	None	90	90	—

F ₄	NPK 9:0:12	Root dip	90	0	100 mL product ha ⁻¹
F ₅	NPK 9:0:12	Foliar spray	90	0	1.50 L product ha ⁻¹
F ₆	NPK 9:0:12	Root dip + foliar	90	0	1.60 L product ha ⁻¹
F ₇	NPK 9:4.5:12	Root dip	90	45	100 mL product ha ⁻¹
F ₈	NPK 9:4.5:12	Foliar spray	90	45	1.50 L product ha ⁻¹
F ₉	NPK 9:4.5:12	Root dip + foliar	90	45	1.60 L product ha ⁻¹

2.3 Growth, biomass, flower yield and nutrient uptake

Growth observations were recorded at 30, 60 and 90 DAT as applicable. At 90 DAT, shoot and root fresh weights were recorded and plant material was oven-dried at 65 °C to constant weight. Flower yield was recorded per plant, per square metre and per hectare. For plant nutrient analysis, samples were collected at 30, 60 and 90 DAT, washed, oven-dried, powdered and analysed for N, P and K; uptake was calculated from dry matter and nutrient concentration using the procedures described in the thesis [19,20].

2.4 Derived nutrient-use-efficiency indices

The primary efficiency calculations used pooled treatment means. Nano-DAP quantities recorded in the thesis were converted to nutrient inputs using the product composition adopted for the present calculations. Measured flower yield and plant N, P and K uptake are also presented directly so that the treatment responses can be interpreted independently of the derived efficiency indices.

Nutrient-use index	Formula	Reference treatment
Nitrogen partial factor productivity (PFP-N)	$PFP-N = \text{Flower yield (kg ha}^{-1}) / \text{Applied N (kg ha}^{-1})$	Indicates flower yield produced per unit of applied nitrogen.
Phosphorus partial factor productivity (PFP-P)	$PFP-P = \text{Flower yield (kg ha}^{-1}) / \text{Applied P}_2\text{O}_5 \text{ (kg ha}^{-1})$	Indicates flower yield produced per unit of applied phosphorus fertilizer.
Agronomic efficiency of phosphorus (AE-P)	$AE-P = [\text{Yield of P-containing treatment} - \text{Yield of corresponding P-omission treatment}] / \text{Applied P}_2\text{O}_5 \text{ (kg ha}^{-1})$	F ₂ was used as the P-omission reference because it received the same conventional N and K schedule but no conventional P.
Apparent phosphorus recovery efficiency (ARE-P)	$ARE-P (\%) = [(P \text{ uptake of P-containing treatment} - P \text{ uptake of corresponding P-omission treatment}) / \text{Elemental P applied}] \times 100$	F ₂ was used as the P-omission reference. Applied P ₂ O ₅ should be converted to elemental P before calculation.

2.5 Statistical analysis

The original experiment was analysed by analysis of variance for a factorial randomized block design, with treatment means compared using the critical difference (CD) at P=0.05. The present paper retains the original pooled means, SED and CD values for measured traits. Pearson correlations among pooled 27-combination treatment means were calculated only as descriptive associations and are not presented as independent-replicate inference.

3. RESULTS

3.1 Growth and biomass response

Fertilizer management strongly affected vegetative growth and biomass. F₉ produced the tallest plants at 90 DAT (73.94 cm), the greatest shoot fresh and dry biomass (73.61 and 31.97 g plant⁻¹) and the greatest root dry biomass (20.18 g plant⁻¹). Relative to F₃, F₉ increased shoot fresh and dry biomass by 21.6 and 21.9%, respectively, while root dry biomass increased by 80.7%. These responses indicate that the integrated root-dip + foliar Nano-DAP treatment altered dry-matter accumulation more strongly than a simple increase in plant height.

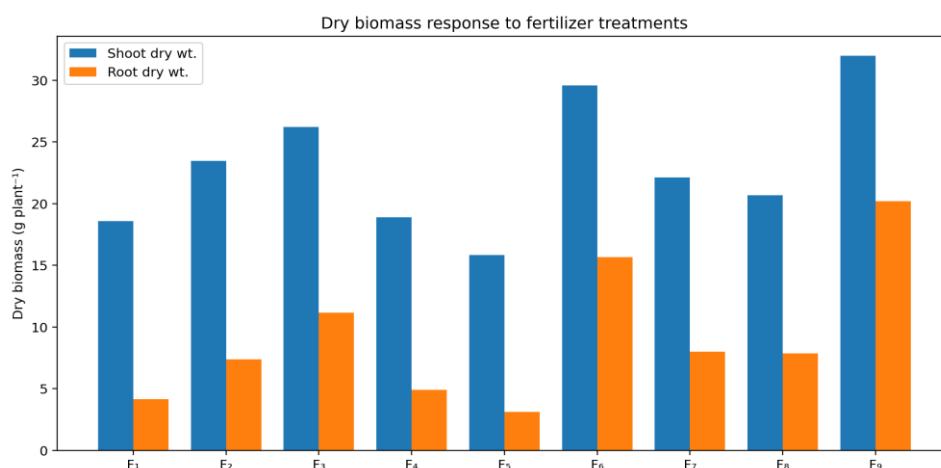


Fig. 2. Pooled shoot and root dry weight of African marigold under the nine fertilizer treatments.

3.2 Temporal N, P and K uptake

Nutrient uptake increased progressively from 30 to 90 DAT in all treatments. F₉ consistently recorded the highest pooled N uptake (38.32, 70.38 and 78.82 kg ha⁻¹ at 30, 60 and 90 DAT), P uptake (6.65, 11.38 and 14.22 kg ha⁻¹) and K uptake (35.18, 61.00 and 70.55 kg ha⁻¹). At 90 DAT, F₉ increased N, P and K uptake by 93.7, 141.4 and 93.3%, respectively, relative to the unfertilized control. F₇ also produced high N and P uptake, while F₈ maintained high flower yield despite lower N uptake than F₇, suggesting that nutrient acquisition and conversion to harvestable flower biomass did not respond identically among Nano-DAP delivery strategies.

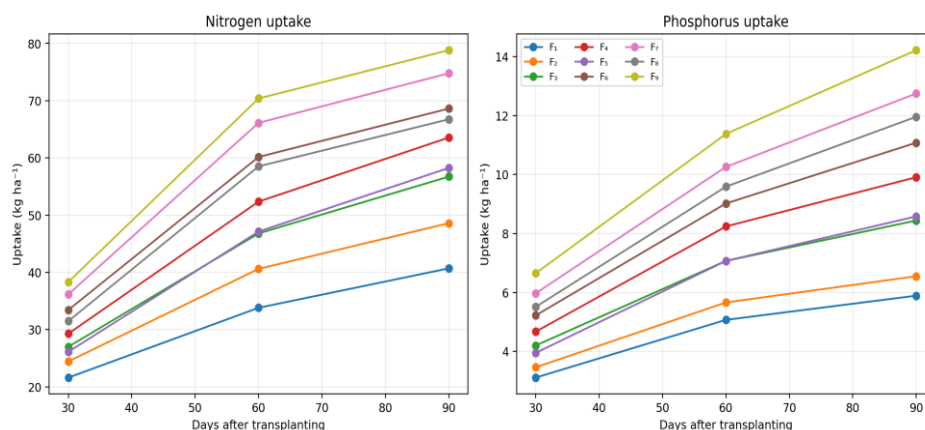


Fig. 3. Pooled plant nitrogen and phosphorus uptake at 30, 60 and 90 DAT under the nine fertilizer treatments.

Table 2. Pooled flower yield, plant N, P and K uptake at 90 DAT, and derived nutrient-productivity indices for fertilizer treatments. Yield change is expressed relative to the untreated control (F₁).

Trt.	Yield (q ha ⁻¹)	N uptake 90 DAT	P uptake 90 DAT	K uptake 90 DAT	PFP-N	PFP-P ₂ O ₅	AE-P ₂ O ₅ vs F ₂	ARE-P vs F ₂ (%)	Yield gain vs F ₁ (%)	P input (kg P ₂ O ₅ ha ⁻¹)
F ₁	169.46	40.70	5.89	36.49	—	—	—	—	0.0	0.000
F ₂	195.77	48.59	6.55	43.72	217.5	—	—	—	15.5	0.000
F ₃	236.92	56.73	8.44	49.44	263.2	263.2	45.7	4.8	39.8	90.000
F ₄	191.45	63.56	9.91	55.21	212.7	—	—	—	13.0	0.016
F ₅	182.76	58.25	8.58	48.24	202.8	—	—	—	7.8	0.240
F ₆	209.56	68.62	11.08	60.44	232.5	—	—	—	23.7	0.256
F ₇	204.55	74.79	12.75	66.09	227.3	454.4	19.5	31.6	20.7	45.016
F ₈	246.72	66.75	11.96	59.15	273.8	545.4	112.6	27.4	45.6	45.240
F ₉	259.72	78.82	14.22	70.55	288.2	573.9	141.3	38.8	53.3	45.256

3.3 Planting date × fertilizer interaction for nutrient uptake

Interaction effects were pronounced. At 90 DAT, pooled N uptake ranged from 37.60 kg ha⁻¹ in D₃F₁ to 82.00 kg ha⁻¹ in D₁F₉. P uptake ranged from 5.38 kg ha⁻¹ in D₃F₁ to 14.67 kg ha⁻¹ in D₁F₉. K uptake similarly peaked at

73.10 kg ha⁻¹ in D₁F₉. Thus, the early planting window strengthened the nutrient-acquisition response of F₉, although F₉ remained among the strongest treatments in all three planting windows.

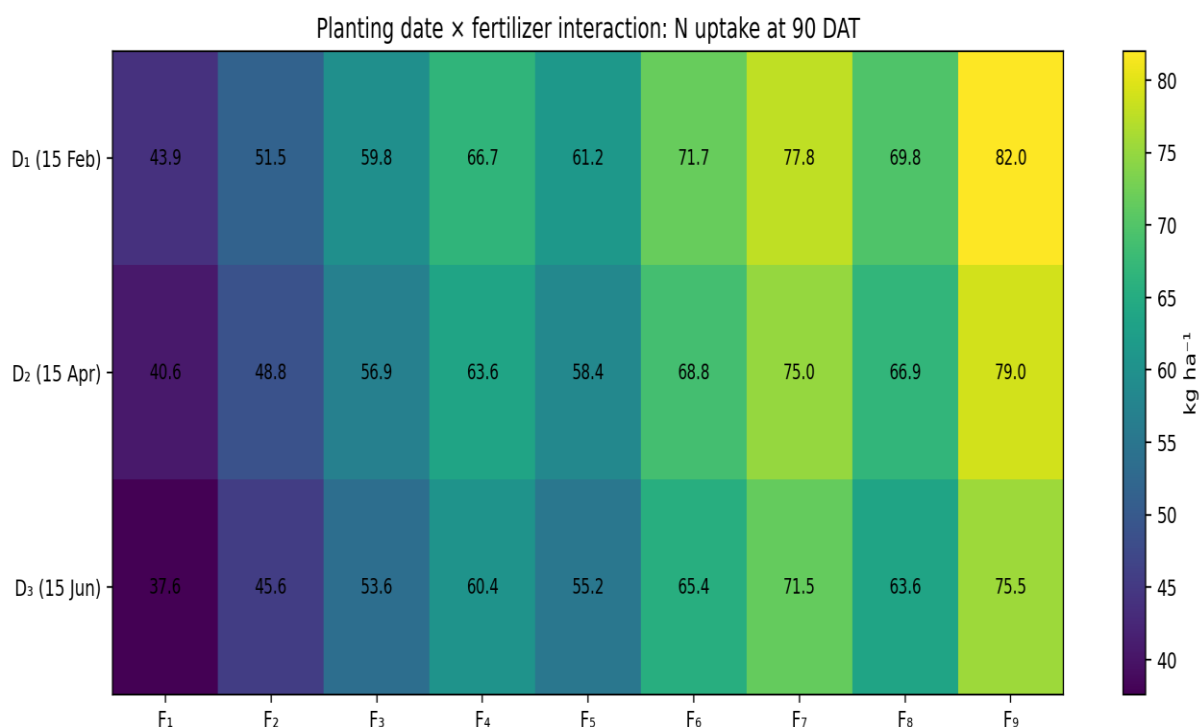


Fig. 4. Pooled plant N uptake at 90 DAT for the 27 planting date × fertilizer treatment combinations.

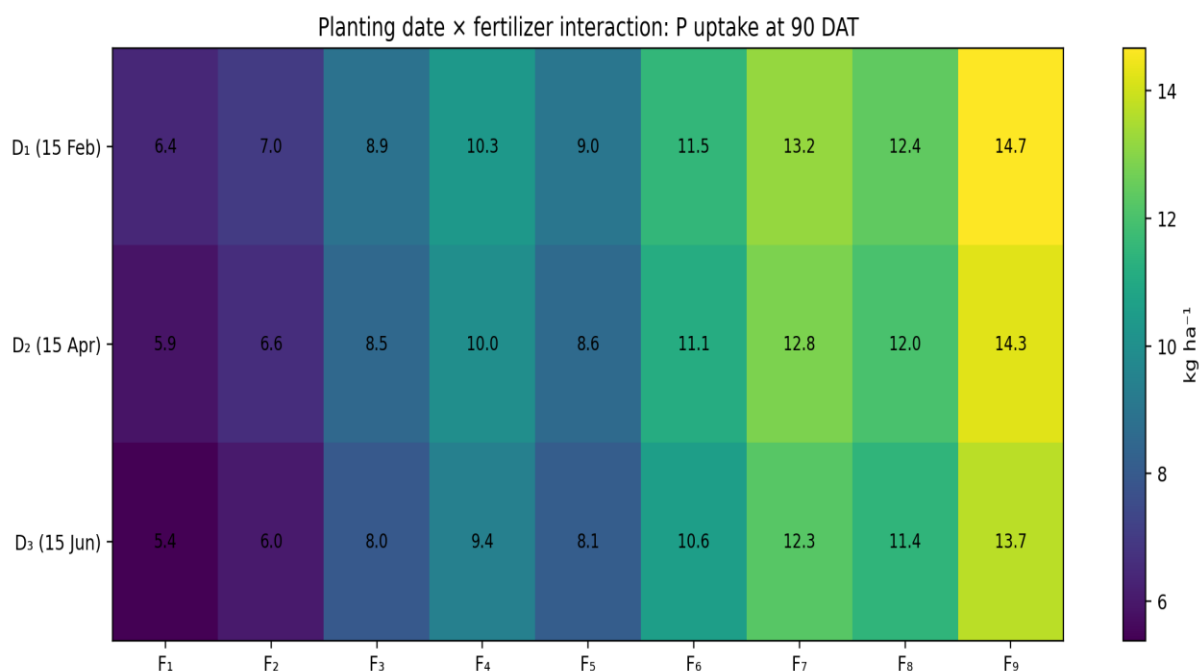


Fig. 5. Pooled plant P uptake at 90 DAT for the 27 planting date × fertilizer treatment combinations.

3.4 Flower yield and reduced-phosphorus performance

Flower yield showed a clear interaction between nutrient treatment and planting date. D₁F₉ produced the highest pooled yield (264.76 q ha⁻¹), followed closely by D₃F₉ (257.39 q ha⁻¹) and D₂F₉ (257.02 q ha⁻¹). The full-RDF treatment F₃ produced 247.54, 241.15 and 222.06 q ha⁻¹ under D₁, D₂ and D₃, respectively. Consequently, F₉ exceeded F₃ by 7.0% under D₁, 6.6% under D₂ and 15.9% under D₃. This indicates that combined root and foliar Nano-DAP did not merely compensate for the 50% reduction in conventional P; it maintained or increased yield under each planting window.

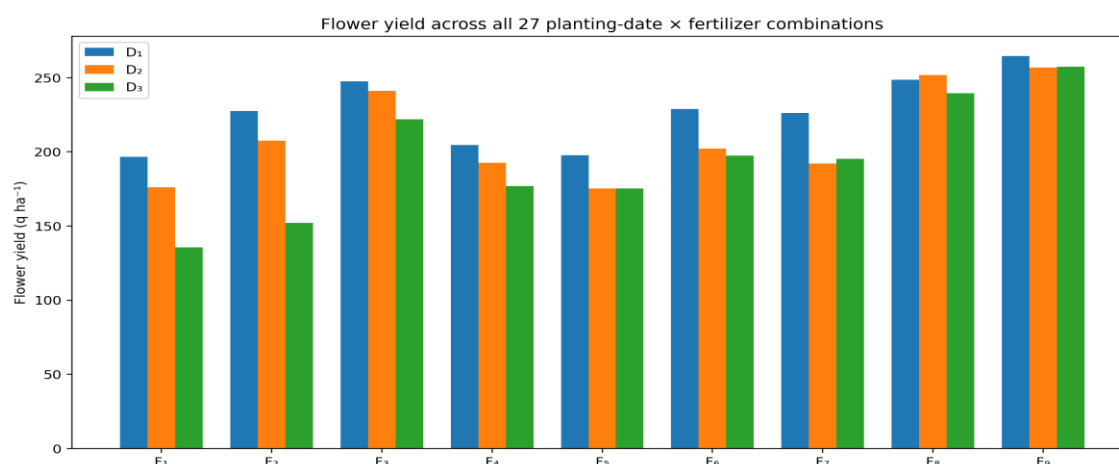


Fig. 6. Pooled flower yield of African marigold for all 27 planting date × fertilizer treatment combinations.

Table 3. Pooled flower yield, phosphorus input and P uptake for the full recommended fertilizer treatment (F₃) and the reduced-conventional-phosphorus + Nano-DAP treatments (F₇–F₉) under each planting date.

Planting	Treatment	P ₂ O ₅ input (kg ha ⁻¹)	Yield (q ha ⁻¹)	Yield vs F ₃ (%)	P uptake (kg ha ⁻¹)	ARE-P (%)
D ₁	F ₃	90.000	247.54	+0.0	8.87	4.8
D ₁	F ₇	45.016	226.15	-8.6	13.19	31.6
D ₁	F ₈	45.240	248.59	+0.4	12.42	27.5
D ₁	F ₉	45.256	264.76	+7.0	14.67	38.9
D ₂	F ₃	90.000	241.15	+0.0	8.51	4.9
D ₂	F ₇	45.016	192.10	-20.3	12.82	31.7
D ₂	F ₈	45.240	251.98	+4.5	12.02	27.5
D ₂	F ₉	45.256	257.02	+6.6	14.27	38.8
D ₃	F ₃	90.000	222.06	+0.0	7.96	4.9
D ₃	F ₇	45.016	195.39	-12.0	12.26	31.6
D ₃	F ₈	45.240	239.60	+7.9	11.45	27.4
D ₃	F ₉	45.256	257.39	+15.9	13.72	38.8

3.5 Nutrient-use-efficiency indices

For the treatment main effects, F₉ achieved a PFP-N of approximately 288 kg flowers kg⁻¹ N compared with 263 kg kg⁻¹ under F₃. The contrast was much larger for P: PFP-P₂O₅ increased from 263 kg flowers kg⁻¹ P₂O₅ under F₃ to 574 kg kg⁻¹ under F₉. Apparent P recovery, calculated relative to F₂, increased from 4.8% under F₃ to 38.8% under F₉. F₈ also combined high yield with high P productivity, whereas F₇ produced high nutrient uptake but lower yield, demonstrating that greater nutrient acquisition does not necessarily translate proportionally into flower production.

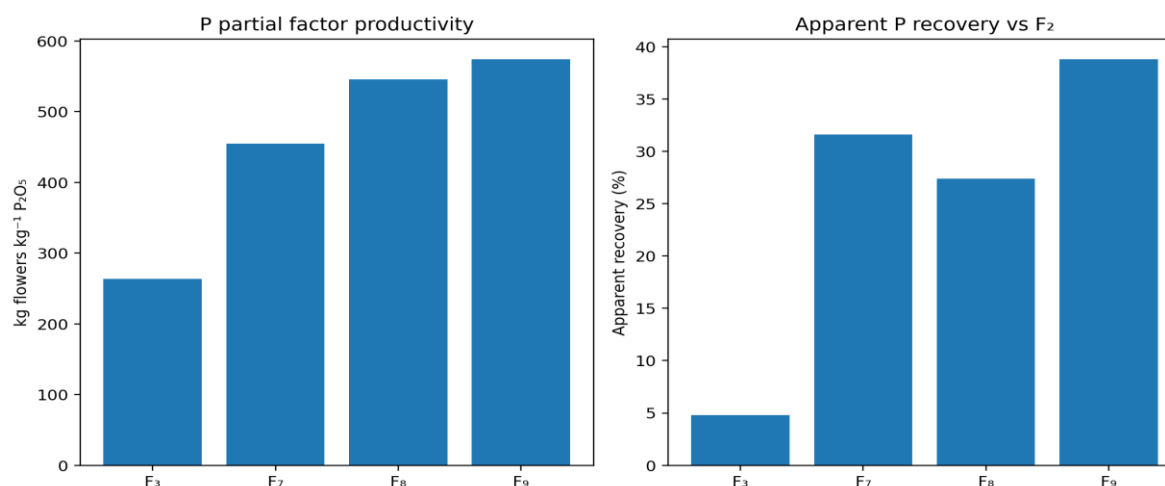


Fig. 7. Phosphorus partial factor productivity and apparent P recovery for full RDF (F₃) and reduced-conventional-P + Nano-DAP treatments (F₇–F₉).

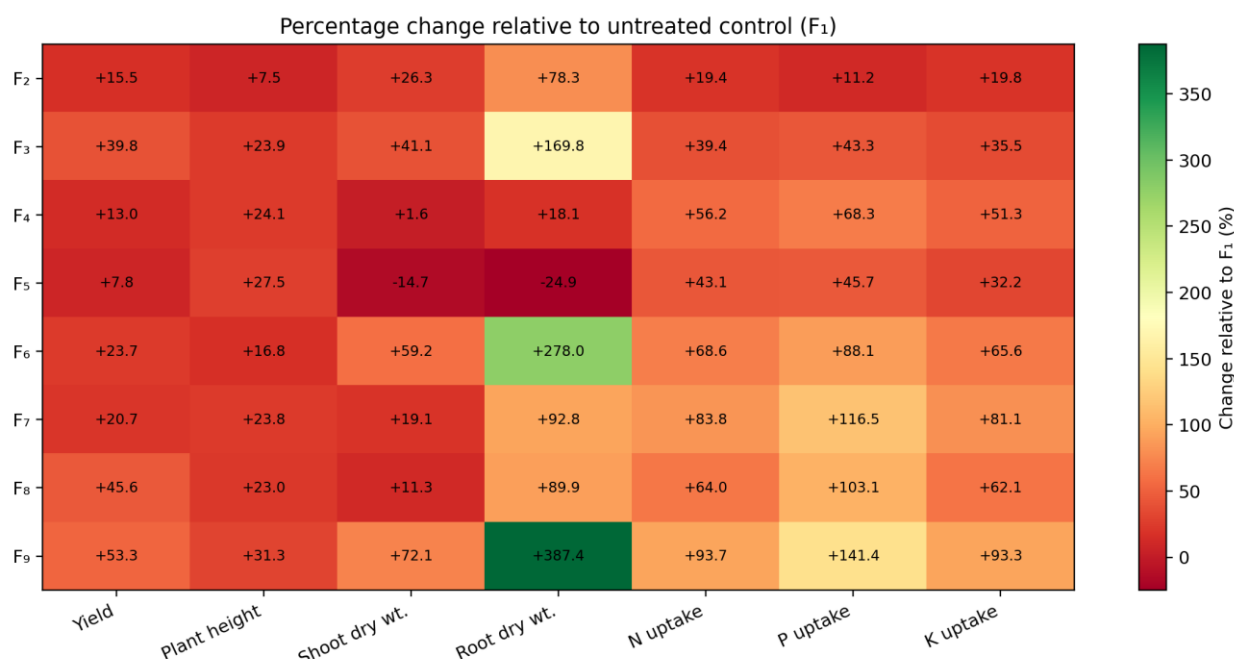


Fig. 8. Percentage change in pooled flower yield, plant height, shoot and root dry weight, and 90-DAT N, P and K uptake under F₂–F₉ relative to the untreated control F₁.

Relative to the untreated control (F₁), F₉ increased pooled flower yield by 53.3%, plant height by 31.3%, shoot dry weight by 72.1%, root dry weight by 387.4%, N uptake by 93.7%, P uptake by 141.4% and K uptake by 93.3%. Because F₁ received no fertilizer, PFP values are not defined for the control; compared with full RDF (F₃), F₉ increased PFP-N by 9.5% and PFP-P₂O₅ by approximately 118.0%, while apparent P recovery increased from 4.8% to 38.8%.

3.6 Relationship between nutrient acquisition and flower production

Across the 27 pooled planting-date × fertilizer means, flower yield was positively associated with N uptake ($r=0.63$), P uptake ($r=0.65$) and K uptake ($r=0.66$) at 90 DAT. The nutrient uptake variables were themselves highly inter-correlated ($r=0.98$ – 0.99), reflecting the coordinated improvement in whole-plant nutrient acquisition under the stronger fertilizer regimes. Because these correlations use treatment means rather than independent replicate observations, they are interpreted as descriptive patterns rather than formal causal tests.

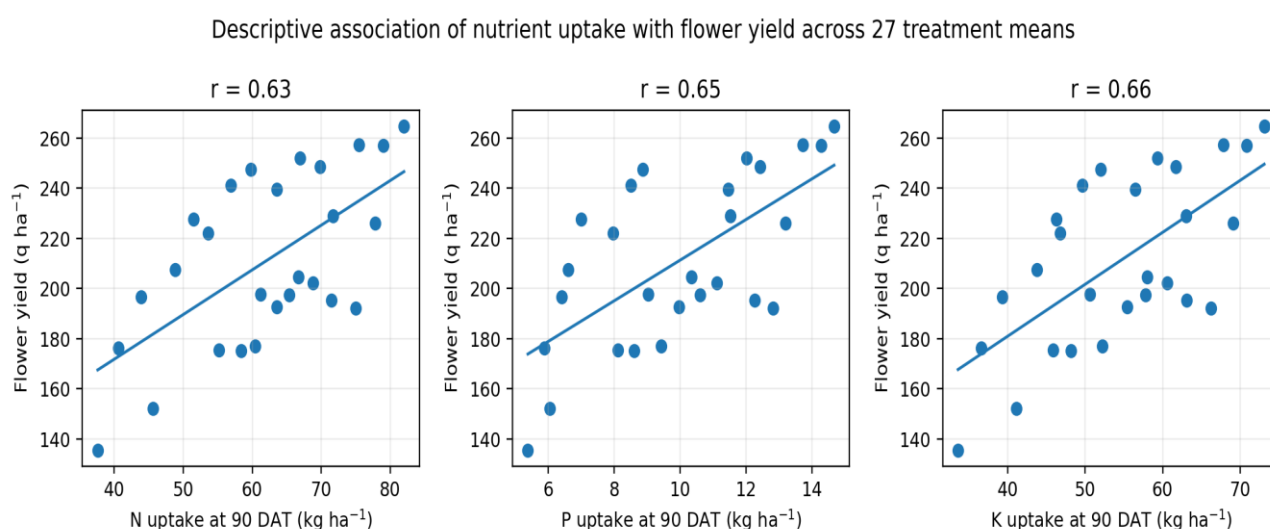


Fig. 9. Relationship between 90-DAT N, P and K uptake and pooled flower yield across the 27 treatment combinations.

4. DISCUSSION

The superiority of F₉ for N, P and K uptake is consistent with the concept that synchronized nutrient supply and multiple delivery pathways can increase nutrient interception and assimilation. Nano-fertilizers have been

proposed to improve nutrient delivery through high surface area and root/foliar entry mechanisms [8–12]. In the present dataset, F₉ combined an early root-dip exposure with a later foliar application and retained 50% of the conventional P dose. This configuration provided strong early-to-mid-season nutrient acquisition and maintained the highest uptake at 90 DAT. Comparable responses to Nano-DAP or nano-fertilizer integration have been reported in African marigold, cabbage, tomato, rice, pigeonpea and wheat [13–18,24].

The biomass response supports this interpretation. F₉ increased shoot dry biomass by 21.9% and root dry biomass by 80.7% relative to full RDF F₃. Phosphorus is central to ATP-linked energy transfer, root development and metabolic activity [5–7,25,26], while adequate N supports photosynthetic tissue and protein synthesis. Greater root dry matter may have further increased nutrient interception, producing a reinforcing relationship between root growth and nutrient uptake. The high K uptake observed under F₉, despite identical conventional K application across fertilized treatments, also suggests that improved overall plant growth enhanced K acquisition; K is required for osmotic regulation, enzyme activation and stress tolerance [27,28].

The strongest efficiency result is the comparison of F₃ with F₇–F₉. F₃ received the full conventional P₂O₅ rate, whereas F₇–F₉ received 50% conventional P plus Nano-DAP. F₉ simultaneously increased yield and P uptake while reducing the conventional P input. This is reflected in the more than twofold increase in P partial factor productivity and the markedly higher apparent P recovery relative to the P-omission treatment. Similar work has shown that reduced conventional P combined with Nano-DAP can maintain or improve crop productivity and P-use efficiency [13,16–18,24].

Phosphorus-efficiency comparisons in this paper focus on F₃ and F₇–F₉, because these treatments provide directly comparable conventional phosphorus rates (100% versus 50% of the recommended P₂O₅ dose) while differing in Nano-DAP application. F₄–F₆ are retained in the measured yield and nutrient-uptake tables, but P-efficiency indices are not used for treatment ranking.

Nitrogen partial factor productivity increased from 263.2 kg flowers kg⁻¹ N under full RDF (F₃) to 288.2 kg flowers kg⁻¹ N under F₉, representing a 9.5% improvement. This indicates greater flower production per unit of applied nitrogen under the combined root-dip + foliar Nano-DAP treatment. The higher N uptake recorded under F₉ further supports the improved nutrient-acquisition response [21–23].

Planting date modified the response of fertilizer treatments. D₁F₉ showed the highest N, P and K uptake and the highest pooled flower yield. Mid-February planting allowed establishment under cooler conditions before the heavy monsoon period, whereas D₂ and D₃ crops encountered progressively warmer and wetter conditions during early or mid-development. Previous work on marigold has similarly demonstrated strong planting-date effects on growth, biomass partitioning and flower productivity [1–4]. The present weather comparison should be interpreted descriptively; a formal meteorological correlation would require a larger number of independent temporal observations.

Notably, F₉ maintained a yield advantage over full RDF under all planting dates, and its relative advantage was greatest under D₃. This may indicate greater resilience of the combined Nano-DAP strategy when establishment occurs closer to the monsoon period. However, because nutrient treatment and crop microclimate were not independently manipulated, this interpretation should be verified in targeted experiments.

From a production perspective, F₉ is the most consistent treatment in the dataset: it combined the highest pooled flower yield, high dry biomass, the highest 90-DAT N/P/K uptake, strong P-use-efficiency indices and high performance across all three planting dates. F₈ also deserves attention because it produced high flower yield with somewhat lower nutrient uptake, implying efficient conversion of acquired nutrients into harvested flower biomass. F₇, in contrast, produced high N and P uptake but did not translate that uptake into equally high flower yield. These contrasts show the value of reporting both uptake and yield-based efficiency metrics rather than ranking treatments from nutrient uptake alone.

The post-harvest soil data in the thesis further show that F₉ maintained the highest pooled soil pH (5.18), organic carbon (0.68%) and available N, P and K (289.17, 30.23 and 154.39 kg ha⁻¹), indicating that increased crop uptake did not coincide with depletion of the measured post-harvest nutrient pools. Improved nutrient retention under balanced fertilization and nano-fertilizer integration has also been reported in other systems [16–18,29–31]. These soil results should nevertheless be interpreted as post-harvest status rather than a complete nutrient balance because fertilizer inputs, plant removal, leaching and other losses were not all quantified.

5. CONCLUSION

Nano-DAP integrated with reduced conventional phosphorus substantially improved nutrient acquisition and flower production of African marigold cv. Seracole. F₉—50% conventional P₂O₅ together with Nano-DAP root dip and foliar spray—produced the highest pooled flower yield (259.72 q ha⁻¹), N uptake (78.82 kg ha⁻¹), P uptake (14.22 kg ha⁻¹) and K uptake (70.55 kg ha⁻¹). Compared with full RDF F₃, F₉ increased pooled yield by 9.6% while approximately halving conventional P input. The treatment also showed markedly higher P partial factor productivity and apparent P recovery. The F₉ advantage was maintained under all three planting dates, with yield gains over F₃ of 7.0, 6.6 and 15.9% under D₁, D₂ and D₃, respectively.

The data therefore support the use of Nano-DAP as a component of phosphorus-saving nutrient management in African marigold. For publication, the exact nutrient composition of the Nano-DAP formulation used in the experiment should be confirmed, and replicate-level nutrient-use-efficiency indices should be calculated where raw replicate data are available so that standard errors and significance tests can be reported for NUE/PUE metrics.

Statements and declarations

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Competing interests: The authors declare that they have no conflict of interest.

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Supplementary Table S1. Pooled flower yield, 90-DAT N, P and K uptake, derived nutrient-productivity indices, and percentage changes relative to the corresponding untreated control for all 27 planting date × fertilizer combinations

Combo	Yield (q ha ⁻¹)	N90 (kg ha ⁻¹)	P90 (kg ha ⁻¹)	K90 (kg ha ⁻¹)	PFP-N	PFP-P ₂ O ₅	Yield change vs control (%)	N uptake change vs control (%)	P uptake change vs control (%)	K uptake change vs control (%)
D1F1	196.69	43.90	6.41	39.30	—	—	+0.0	+0.0	+0.0	+0.0
D1F2	227.63	51.50	6.99	46.30	252.9	—	+15.7	+17.3	+9.0	+17.8
D1F3	247.54	59.80	8.87	52.00	275.0	275.0	+25.9	+36.2	+38.4	+32.3
D1F4	204.57	66.70	10.35	58.00	227.3	—	+4.0	+51.9	+61.5	+47.6
D1F5	197.66	61.20	9.03	50.60	219.3	—	+0.5	+39.4	+40.9	+28.8
D1F6	228.97	71.70	11.52	63.00	254.0	—	+16.4	+63.3	+79.7	+60.3
D1F7	226.15	77.80	13.19	69.10	251.3	502.4	+15.0	+77.2	+105.8	+75.8
D1F8	248.59	69.80	12.42	61.70	275.8	549.5	+26.4	+59.0	+93.8	+57.0
D1F9	264.76	82.00	14.67	73.10	293.8	585.0	+34.6	+86.8	+128.9	+86.0
D2F1	176.16	40.60	5.88	36.60	—	—	+0.0	+0.0	+0.0	+0.0
D2F2	207.55	48.80	6.60	43.80	230.6	—	+17.8	+20.2	+12.2	+19.7
D2F3	241.15	56.90	8.51	49.60	267.9	267.9	+36.9	+40.1	+44.7	+35.5
D2F4	192.77	63.60	9.97	55.40	214.2	—	+9.4	+56.7	+69.6	+51.4
D2F5	175.21	58.40	8.60	48.20	194.4	—	-0.5	+43.8	+46.3	+31.7
D2F6	202.16	68.80	11.12	60.60	224.3	—	+14.8	+69.5	+89.1	+65.6
D2F7	192.10	75.00	12.82	66.20	213.4	426.7	+9.0	+84.7	+118.0	+80.9
D2F8	251.98	66.90	12.02	59.30	279.6	557.0	+43.0	+64.8	+104.4	+62.0
D2F9	257.02	79.00	14.27	70.80	285.2	567.9	+45.9	+94.6	+142.7	+93.4
D3F1	135.54	37.60	5.38	33.60	—	—	+0.0	+0.0	+0.0	+0.0
D3F2	152.15	45.60	6.05	41.10	169.1	—	+12.3	+21.3	+12.5	+22.3
D3F3	222.06	53.60	7.96	46.80	246.7	246.7	+63.8	+42.6	+48.0	+39.3
D3F4	177.01	60.40	9.42	52.20	196.7	—	+30.6	+60.6	+75.1	+55.4
D3F5	175.40	55.20	8.11	45.90	194.6	—	+29.4	+46.8	+50.7	+36.6
D3F6	197.55	65.40	10.60	57.80	219.2	—	+45.8	+73.9	+97.0	+72.0
D3F7	195.39	71.50	12.26	63.10	217.1	434.0	+44.2	+90.2	+127.9	+87.8
D3F8	239.60	63.60	11.45	56.50	265.9	529.6	+76.8	+69.1	+112.8	+68.2
D3F9	257.39	75.50	13.72	67.80	285.6	568.7	+89.9	+100.8	+155.0	+101.8

Percent changes are calculated relative to the corresponding untreated control within each planting date. An em dash indicates that an efficiency index is not applicable for that treatment.

Supplementary Table S2. Pooled plant N, P and K uptake at 30, 60 and 90 DAT under the nine fertilizer treatments.

Trt.	N30	N60	N90	P30	P60	P90	K30	K60	K90
F ₁	21.61	33.81	40.70	3.11	5.07	5.89	17.42	29.89	36.49
F ₂	24.43	40.61	48.59	3.46	5.66	6.55	21.45	36.73	43.72
F ₃	27.00	46.80	56.73	4.20	7.07	8.44	24.42	41.38	49.44

F ₄	29.29	52.36	63.56	4.67	8.24	9.91	26.71	45.83	55.21
F ₅	26.12	47.13	58.25	3.95	7.07	8.58	23.58	40.83	48.24
F ₆	33.43	60.16	68.62	5.22	9.02	11.08	29.94	51.78	60.44
F ₇	36.16	66.12	74.79	5.97	10.26	12.75	32.87	57.17	66.09
F ₈	31.48	58.52	66.75	5.51	9.59	11.96	28.51	50.92	59.15
F ₉	38.32	70.38	78.82	6.65	11.38	14.22	35.18	61.00	70.55