



Original Research Paper

Enhancing Post-harvest Soil Fertility and Nutrient Sustainability through Nano-DAP Integrated Fertilization in African Marigold (*Tagetes erecta* L.)

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Abstract. Sustainable nutrient management in ornamental crops requires practices that improve productivity while maintaining residual soil fertility. The present study evaluated the post-harvest soil fertility status of African marigold (*Tagetes erecta* L.) under integrated Nano-DAP fertilization during 2022–23 and 2023–24 at the Experimental Farm, Assam Agricultural University, Jorhat. The experiment was conducted in factorial randomized block design with three planting dates and nine fertilizer treatments comprising conventional NPK and different combinations of reduced phosphorus with Nano-DAP root dip and foliar spray. Post-harvest soil samples (0–15 cm) were analysed for soil pH, organic carbon and available N, P₂O₅ and K₂O. The results showed increases in soil organic carbon (6.45%) and available N, P₂O₅ and K₂O (4.71, 5.59 and 5.46%, respectively) over the initial soil status. Among the treatments, F₉ (NPK 9:4.5:12 g m⁻² + Nano-DAP root dip 5 mL L⁻¹ + foliar spray 10 mL L⁻¹) recorded the highest post-harvest soil pH (5.18), organic carbon (0.68%), available N (289.17 kg ha⁻¹), P₂O₅ (30.23 kg ha⁻¹) and K₂O (154.39 kg ha⁻¹). The interaction D₁F₉ recorded the highest available N, P₂O₅ and K₂O of 290.50, 30.28 and 154.50 kg ha⁻¹, respectively. Correlation analysis showed positive relationships among major soil fertility parameters, while principal component analysis separated Nano-DAP integrated treatments from conventional fertilizer and control treatments. The study indicates that Nano-DAP integration can improve post-harvest nutrient availability and contribute to sustainable nutrient management in African marigold cultivation.

Keywords: Nano-DAP; African marigold; residual soil fertility; nutrient sustainability; organic carbon; nutrient-use efficiency

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1. Introduction

Sustainable production of ornamental crops requires not only achieving higher yield and quality but also maintaining soil fertility for continuous cultivation. Intensive fertilizer use and repeated cropping may alter soil nutrient balance, increase nutrient losses and reduce soil quality over time. Therefore, evaluation of post-harvest soil fertility status provides important information regarding the residual effect of nutrient management practices and their role in sustaining soil productivity.

African marigold (*Tagetes erecta* L.) is an important commercial flower crop cultivated widely for loose flower production, landscaping and value-added products. The productivity and quality of marigold depend greatly on balanced nutrient availability throughout crop growth. Nitrogen, phosphorus and potassium play essential roles in vegetative growth, flowering, nutrient metabolism and overall crop performance. However, conventional fertilizer application may result in nutrient losses through leaching, fixation and volatilization, reducing fertilizer-use efficiency.

Nano-fertilizers have emerged as a promising approach for improving nutrient-use efficiency by providing controlled nutrient release and better nutrient availability to plants. Nano-diammonium phosphate (Nano-DAP) contains nitrogen and phosphorus in nanoscale form, which may improve nutrient delivery and reduce losses compared with conventional phosphorus fertilizers. The combination of reduced soil-applied phosphorus with Nano-DAP application may provide a balanced nutrient supply while improving residual soil nutrient status [7,8]. This concept is supported by broader work on nano-fertilizers and

controlled nutrient delivery [7,8,11,12].

The influence of fertilizer management on post-harvest soil fertility is an important component of sustainable crop production. Changes in soil pH, organic carbon and available nutrient pools after harvest indicate the ability of a nutrient management strategy to maintain soil nutrient reserves. Previous studies have reported improved nutrient availability and nutrient-use efficiency under nano-fertilizer application; however, information regarding the residual soil effects of Nano-DAP integrated fertilization in African marigold remains limited. Previous studies in pigeonpea and rice have similarly reported improved residual nutrient availability and soil health under Nano-DAP-based nutrient management [2,3].

Planting time can also influence nutrient dynamics by affecting crop growth duration, nutrient uptake pattern and biomass accumulation.

However, the relative contribution of planting date and fertilizer management towards residual soil fertility requires further investigation.

The present investigation was undertaken to evaluate the effect of integrated Nano-DAP fertilization on post-harvest soil fertility status in African marigold. The specific objectives were:

1. To assess the effect of Nano-DAP integrated fertilization on post-harvest soil pH, organic carbon and available N, P₂O₅ and K₂O.
2. To compare residual nutrient availability among different fertilizer treatments.
3. To evaluate the interaction effect of planting date and fertilizer treatment on post-harvest soil fertility.
4. To understand nutrient relationships through multivariate analytical approaches including

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correlation analysis and principal component analysis.

Despite the growing literature on Nano-DAP, comparatively little information is available on its residual effect on soil fertility in African marigold, particularly where reduced soil-applied phosphorus is combined with both root dip and foliar Nano-DAP under different planting dates. The present study addresses this gap by evaluating post-harvest pH, organic carbon and available N, P_2O_5 and K_2O , together with correlation, principal component and cluster analyses of the fertility response.

For marigold specifically, integrated nutrient management has long been associated with improvements in vegetative growth and nutrient use. Gotmare *et al.* [14] documented positive responses of African marigold to integrated nutrient management, and Ghosh and Pal [15] reported favourable responses of cv. Siracole to combined organic and inorganic nitrogen sources. These studies support the principle that balanced and integrated nutrient supply is more important than dependence on a single nutrient source.

Broader crop evidence further supports a cautious integrated-use approach. Attri [19] reported that partial substitution of conventional urea and DAP with nano-formulations in fine rice improved crop performance and nutrient uptake without an adverse soil-health response. Choudhary [20] found that reduced phosphorus combined with Nano-DAP or phosphate-solubilizing bacteria in fodder oat could maintain productivity while improving phosphorus acquisition efficiency and soil biological activity. A review by Tatarko *et al.* [21] similarly emphasized that nanoparticle-based plant nutrition is highly dependent on particle properties, concentration and delivery method. Experimental work with cryo-milled nano-DAP also demonstrated that reduced phosphorus doses could improve plant growth and phosphorus uptake in wheat and tomato under controlled conditions [22].

Residual soil fertility is also influenced by

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organic matter dynamics and nutrient cycling. Brady and Weil [4] emphasized that soil pH, organic carbon and available nutrient pools are central indicators of fertility, while Lal [5] described the importance of soil organic carbon in sustaining soil function. Fertilizer-induced changes in microbial activity and nutrient cycling may further influence the persistence and availability of nitrogen, phosphorus and potassium after harvest [6].

The possible advantage of nano-formulated nutrients is consistent with the broader controlled-release and targeted-delivery concept. Gao *et al.* [11] reported that controlled-release fertilizers can improve nutrient-use efficiency by synchronizing nutrient supply with crop demand. DeRosa *et al.* [12] similarly highlighted nanotechnology as a pathway for more precise fertilizer delivery. However, the response cannot be generalized across crops and environments, and conventional balanced fertilization remains the agronomic baseline against which nano-fertilizer strategies should be assessed [4,13].

Nano-DAP response is strongly affected by the method of delivery. Root-zone exposure can support early nutrient acquisition, whereas foliar application can provide rapid supplementation during active growth. In cabbage, Chamuah *et al.* [10] found that seedling root-dip and foliar Nano-DAP treatments, used with reduced phosphorus and conventional N and K, improved nutrient uptake and maintained crop performance. Similar observations in okra showed that seed treatment plus foliar Nano-DAP improved growth and yield over less integrated nutrient regimes [9].

Evidence from other crops also indicates that Nano-DAP can influence residual nutrient availability. Girigoud *et al.* [2] observed improved post-harvest macro- and micronutrient status in pigeonpea under Nano-DAP application, while Sahoo *et al.* [3] reported that strategic nano-fertilizer management in rice could sustain yield and soil health under reduced conventional nutrient inputs. Comparable improvement in nutrient-use efficiency has also been reported in rainfed pigeonpea when Nano-DAP was combined with phosphate-solubilizing bacteria and partial phosphorus fertilization [16].

In African marigold, Sahithi *et al.* [1] reported that

- **D₁:** Mid-February planting
- **D₂:** Mid-April planting
- **D₃:** Mid-June planting

The fertilizer treatments consisted of conventional fertilizer application and Nano-DAP integrated nutrient management practices:

F₁: Control (no fertilizer)

F₂: NPK @ 9:0:12 g m⁻² (100% RDNK)

F₃: NPK @ 9:9:12 g m⁻² (100% RDF NPK)

F₄: NPK @ 9:0:12 g m⁻² + Nano-DAP root dip @ 5 mL L⁻¹

F₅: NPK @ 9:0:12 g m⁻² + Nano-DAP foliar spray @ 10 mL L⁻¹

F₆: NPK @ 9:0:12 g m⁻² + Nano-DAP root dip @ 5 mL L⁻¹ + foliar spray @ 10 mL L⁻¹

F₇: NPK @ 9:4.5:12 g m⁻² + Nano-DAP root dip @ 5 mL L⁻¹

F₈: NPK @ 9:4.5:12 g m⁻² + Nano-DAP foliar spray @ 10 mL L⁻¹

F₉: NPK @ 9:4.5:12 g m⁻² + Nano-DAP root dip @ 5 mL L⁻¹ + foliar spray @ 10 mL L⁻¹

The treatment combinations were maintained throughout the crop period and observations were recorded following standard procedures.

3.3 Soil sampling and chemical analysis

Soil samples were collected before planting and after harvest from the 0–15 cm soil depth. The collected samples were processed, air-dried, sieved and analysed for soil chemical properties.

The following parameters were estimated:

combinations of nano-urea and Nano-DAP with reduced conventional nitrogen and phosphorus improved growth, flowering and yield-related traits. The work is particularly relevant to the present study because it demonstrates a crop-specific response of *Tagetes erecta* to integrated nano-fertilizer nutrition and supports evaluation of residual soil effects in addition to crop performance.

Nano-fertilizers have been developed to improve nutrient delivery by increasing effective surface area, enhancing contact with plant tissues and potentially permitting lower application rates than conventional fertilizers. Their agronomic value depends on formulation, dose, crop, soil and application method, and they should therefore be considered as supplements to, rather than automatic substitutes for, balanced fertilization [7,8,12].

2. Literature Review and Research Gap

3. Materials and Methods

3.1 Experimental site

The experiment was conducted during the rabi season of 2022–23 and 2023–24 at the Experimental Farm, Department of Horticulture, Assam Agricultural University, Jorhat, Assam, India. The experimental site is located at 26°45' N latitude, 94°12' E longitude with an altitude of approximately 87 m above mean sea level. The region experiences a humid subtropical climate with high annual rainfall and distinct seasonal variation.

The soil of the experimental field was acidic in reaction and represented the typical soil condition of the region. Before initiation of the experiment, initial soil samples were collected from 0–15 cm depth and analysed for important soil chemical properties. The initial soil status recorded pH 5.06, organic carbon 0.62%, available nitrogen 266.00 kg ha⁻¹, available P₂O₅ 27.20 kg ha⁻¹ and available K₂O 141.50 kg ha⁻¹.

3.2 Experimental design and treatments

The experiment was laid out in a factorial randomized block design (FRBD) consisting of

- Soil pH
- Organic carbon content
- Available nitrogen
- Available phosphorus (P₂O₅)
- Available potassium (K₂O)

Standard analytical procedures were followed for estimation of soil fertility parameters.

The residual effect of fertilizer treatments was assessed by comparing post-harvest soil nutrient values with initial soil status.

Percentage change over initial soil status was calculated as:

$$\text{Percentage change} = \frac{\text{Post-harvest value} - \text{Initial value}}{\text{Initial value}} \times 100$$

3.4 Statistical analysis

The experimental data were analysed using analysis of variance (ANOVA) appropriate for factorial randomized block design. The significance of planting dates, fertilizer treatments and their interaction effects were tested.

Treatment means were compared using the critical difference (CD) at 5% level of significance. Pooled data over two years were used for interpretation.

To provide additional understanding of nutrient relationships, supplementary multivariate analyses were performed:

Pearson correlation analysis

Correlation coefficients were calculated among soil fertility parameters including:

- Soil pH
- Organic carbon
- Available nitrogen
- Available P₂O₅
- Available K₂O

The analysis was used to identify associations

Principal component analysis (PCA)

PCA was performed using standardized soil fertility variables to visualize treatment grouping and identify major factors contributing to variation among fertilizer treatments.

The PCA analysis was interpreted as an exploratory multivariate approach to understand overall soil fertility patterns rather than as a replacement for the experimental ANOVA.

3.5 Additional multivariate and sustainability analyses

To obtain deeper insight into treatment-related variation in post-harvest soil fertility, additional statistical analyses were performed using pooled treatment mean values.

Pearson correlation analysis was conducted to determine the relationships among soil fertility parameters including soil pH, organic carbon, available nitrogen, phosphorus (P₂O₅) and potassium (K₂O).

Principal component analysis (PCA) was performed using standardized soil fertility variables to visualize treatment distribution and identify the major variables contributing to variation among fertilizer treatments.

Hierarchical cluster analysis (HCA) using Euclidean distance and Ward's linkage method was carried out to classify fertilizer treatments according to similarity in post-harvest soil fertility characteristics.

A Relative Soil Fertility Improvement Index (RSFI) was calculated to integrate the improvement of major soil fertility parameters over initial soil status. The index was based on normalized improvement values of organic carbon, available nitrogen, phosphorus and potassium.

$$RSFI = (OC_i + N_i + P_i + K_i) / 4$$

where:

OC_i, N_i, P_i and K_i represent normalized improvement values of individual soil fertility parameters.

4. Results and Discussion

4.1 Effect of Nano-DAP integrated fertilization on post-harvest soil fertility

Post-harvest soil analysis revealed considerable variation among fertilizer treatments with respect to soil pH, organic carbon, available nitrogen, phosphorus and potassium. Overall, integrated Nano-DAP treatments maintained higher residual nutrient availability compared with conventional fertilizer treatments and control.

The improvement in soil fertility after harvest indicates better nutrient retention and reduced nutrient depletion under Nano-DAP-based nutrient management. The use of Nano-DAP along with reduced phosphorus application enhanced nutrient availability while maintaining soil nutrient balance.

The initial soil fertility status of the experimental field was:

Soil parameter	Initial value
Soil pH	5.06
Organic carbon (%)	0.62
Available N (kg ha ⁻¹)	266.00
Available P ₂ O ₅ (kg ha ⁻¹)	27.20
Available K ₂ O (kg ha ⁻¹)	141.50

After harvest, the pooled mean soil fertility values increased to:

Soil parameter	Post-harvest value	Change (%)
Soil pH	5.11	+0.99
Organic carbon (%)	0.66	+6.45
Available N (kg ha ⁻¹)	278.52	+4.71
Available P ₂ O ₅ (kg ha ⁻¹)	28.72	+5.59
Available K ₂ O (kg ha ⁻¹)	149.23	+5.46

The increase in organic carbon after harvest may be associated with improved crop growth, greater root biomass production and increased organic residue

The increase in available nitrogen, phosphorus and potassium indicates improved nutrient conservation under integrated nutrient management. Nano-DAP may improve nutrient-use efficiency through controlled nutrient release and improved nutrient availability near the root zone [2,3]. Similar residual nutrient responses under Nano-DAP application have been documented in pigeonpea and rice [2,3], while controlled-release fertilizer studies attribute improved efficiency partly to closer synchronization between nutrient supply and crop demand [11].

4.2 Effect of fertilizer treatments on soil chemical properties

Fertilizer treatments significantly influenced soil pH, organic carbon and available N, P₂O₅ and K₂O.

The control treatment (F₁) recorded the lowest values of soil fertility parameters, indicating depletion of available nutrients due to crop uptake without external nutrient addition.

In contrast, Nano-DAP integrated treatments showed progressive improvement in soil fertility.

Among all fertilizer treatments, F₉ recorded the highest post-harvest soil fertility status:

Treatment	pH	OC (%)	Available N (kg ha ⁻¹)	P ₂ O ₅ (kg ha ⁻¹)	K ₂ O (kg ha ⁻¹)
F ₉	5.18	0.68	289.17	30.23	154.39

The superior performance of F₉ may be attributed to the combined effect of reduced soil-applied phosphorus with Nano-DAP root treatment and foliar application. The dual application strategy may have improved nutrient synchronization with plant demand and reduced nutrient

losses [1-3,7]. The advantage of combining root-zone and foliar delivery is consistent with findings in cabbage and okra, where integrated Nano-DAP application improved nutrient uptake and crop response compared with less integrated schedules [9,10].

Nano-DAP integrated treatments (F₆-F₉) consistently maintained higher residual nutrient values than conventional fertilizer treatments. These results suggest that Nano-DAP supplementation may improve nutrient retention and maintain a favourable soil nutrient balance after crop harvest. These findings also agree with reports from pigeonpea, rice and other crops showing that Nano-DAP can support nutrient-use efficiency and residual fertility when integrated with conventional fertilizers rather than used in isolation [2,3,16,17].

This response is consistent with earlier reports in which nano-DAP application improved residual nutrient availability and soil fertility in pigeonpea and rice systems, while nano-DAP-based nutrition in African marigold also enhanced nutrient assimilation and crop performance [1-3].

4.3 Effect of planting dates on post-harvest soil fertility

Planting dates alone showed limited influence on post-harvest soil fertility parameters.

The pooled effect of planting dates showed only numerical variation:

Planting date	pH	OC (%)	N (kg ha ⁻¹)	P ₂ O ₅ (kg ha ⁻¹)	K ₂ O (kg ha ⁻¹)
D ₁	5.09	0.65	278.13	28.37	148.54
D ₂	5.12	0.64	276.22	28.25	148.04
D ₃	5.11	0.65	274.09	28.06	146.94

Most nutrient parameters remained statistically non-significant among planting dates. This indicates that fertilizer management played a greater role than planting date in determining residual soil fertility.

Although early planting showed slightly higher nutrient values numerically, the differences were not sufficient to influence post-harvest soil nutrient status significantly.

4.4 Interaction effect of planting date × fertilizer treatment

The interaction between planting date and fertilizer treatment significantly influenced post-harvest soil fertility.

The highest values were recorded under D₁F₉:

Parameter	D ₁ F ₉ value
Soil pH	5.17
Organic carbon (%)	0.68
Available N (kg ha ⁻¹)	290.50
Available P ₂ O ₅ (kg ha ⁻¹)	30.28
Available K ₂ O (kg ha ⁻¹)	154.50

The improved residual fertility under D₁F₉ may be due to favourable crop growth conditions during early planting combined with efficient nutrient management through Nano-DAP integration [2,3].

The treatment maintained higher nutrient availability compared with unfertilized and conventional fertilizer treatments, demonstrating the importance of combining appropriate planting time with efficient nutrient management.

4.5 Correlation analysis among soil fertility parameters

Pearson correlation analysis showed positive relationships among soil fertility indicators.

Available nitrogen showed strong association with available phosphorus and potassium, indicating that improvement in one nutrient component was accompanied by improvement in other fertility parameters.

The relationship pattern suggests that Nano-DAP integration influenced soil fertility as a combined system rather than affecting individual nutrients independently.

Figure 1: Nutrient Response Trend (F₁–F₉)

Shows residual available N, P₂O₅ and K₂O improvement across fertilizer treatments.

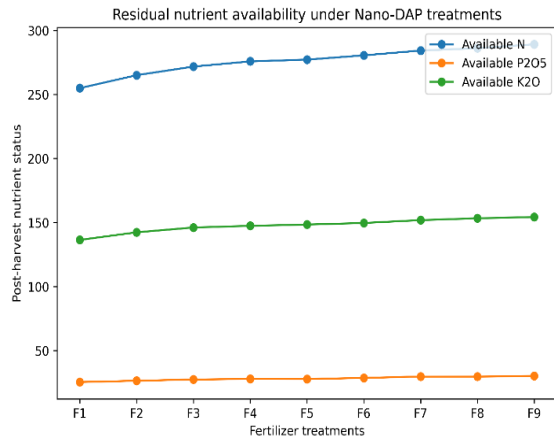
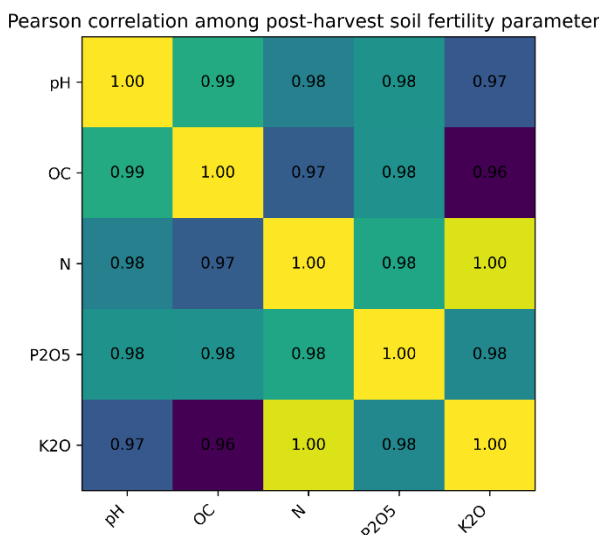


Figure 2: Pearson Correlation Heatmap

Shows relationships among soil pH, organic carbon, available N, P₂O₅ and K₂O.



4.6 Principal Component Analysis (PCA)

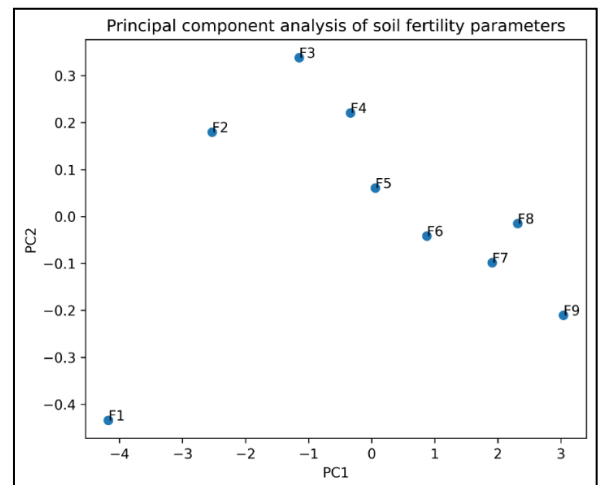
Principal component analysis was performed to visualize overall treatment variation based on soil fertility parameters.

The PCA showed separation between control, conventional fertilizer and Nano-DAP integrated treatments.

Control treatment (F₁) showed association with

The first principal component represented the major variation associated with nutrient availability, including available nitrogen, phosphorus and potassium.

Figure 3. Principal component analysis (PCA) biplot showing treatment distribution based on post-harvest soil fertility parameters under Nano-DAP integrated fertilization in African marigold.



The PCA confirms that Nano-DAP integrated treatments produced a distinct soil fertility profile compared with non-Nano treatments.

4.7 Hierarchical clustering of fertilizer treatments based on soil fertility characteristics

Hierarchical cluster analysis classified the fertilizer treatments into distinct groups based on their post-harvest soil fertility characteristics (Figure 4).

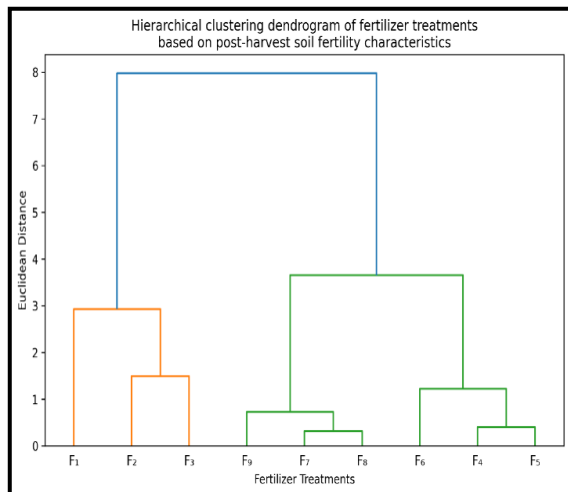
The clustering pattern clearly separated the unfertilized and conventional fertilizer treatments from Nano-DAP integrated treatments. The control treatment (F₁) showed the greatest distance from Nano-DAP treatments due to lower residual nutrient availability.

The Nano-DAP integrated treatments, particularly F₇, F₈ and F₉, formed a separate high fertility cluster characterized by higher available nitrogen, phosphorus and potassium status along with improved organic carbon

content.

The grouping pattern indicates that Nano-DAP integration produced a distinct soil fertility response compared with conventional fertilizer practices.

Figure 4. Hierarchical clustering dendrogram showing grouping of fertilizer treatments based on post-harvest soil fertility characteristics.



4.8 Overall discussion and scientific interpretation

The present study demonstrates that integrated Nano-DAP fertilization influenced post-harvest soil fertility status in African marigold by improving residual nutrient availability after crop harvest. Maintenance of soil fertility after harvest is an important indicator of sustainable nutrient management because it reflects the balance between nutrient addition, crop uptake and nutrient retention in the soil system. This interpretation is consistent with the wider nano-fertilizer literature, which emphasizes improved nutrient delivery and use efficiency while also recognizing strong dependence on crop, dose and application strategy [7,8,11]. Findings from rice, oat and controlled nano-DAP studies provide additional support for integrating nano-formulations with reduced conventional nutrient inputs rather than treating them as stand-alone replacements [19,20,22].

The improvement in soil organic carbon under

Nano-DAP treatments may be associated with enhanced crop biomass production, greater root growth and increased organic matter return to the soil. Improved root activity can stimulate microbial processes and contribute to better nutrient cycling [4-6]. Such changes are agronomically important because soil organic carbon contributes to aggregation, nutrient retention and biological activity [5], while fertilizer-mediated microbial processes influence nutrient cycling [6].

The increase in available nitrogen under Nano-DAP treatments indicates improved nitrogen retention and availability. Nano-sized nutrient formulations may provide gradual nutrient release and reduce losses compared with conventional fertilizer sources. The improved phosphorus availability observed in Nano-DAP treatments suggests better phosphorus management, particularly under reduced soil-applied phosphorus conditions combined with Nano-DAP supplementation [2,3,7]. Pigeonpea and rice studies have reported comparable increases or maintenance of residual N and P under Nano-DAP-based schedules [2,3].

The higher potassium availability under Nano-DAP integrated treatments indicates improved nutrient balance in the soil. Potassium plays an important role in plant water regulation, enzyme activation and stress tolerance, and maintaining adequate potassium reserves after harvest contributes to soil fertility sustainability.

The superior performance of F₉ may be explained by the combined application of Nano-DAP through root dip and foliar spray along with reduced phosphorus fertilizer application. This treatment provided both soil nutrient supply and foliar nutrient supplementation, potentially improving nutrient-use efficiency [1-3,7]. Similar benefits from combining soil or root-zone nutrition with foliar Nano-DAP have been reported in cabbage [10], okra [9] and rainfed pigeonpea [16].

However, the present study evaluates post-harvest soil fertility status after one crop cycle. Therefore, the findings demonstrate improved residual nutrient availability but should not be interpreted as proof of permanent long-term soil improvement. Long-term field

studies would be required to confirm changes in soil health over multiple seasons.

4.9 Relative Soil Fertility Improvement Index under Nano-DAP fertilization

To summarize the overall improvement in post-harvest soil fertility, a Relative Soil Fertility Improvement Index (RSFI) was developed using improvement in organic carbon and available N, P_2O_5 and K_2O compared with initial soil status.

Nano-DAP integrated treatments showed higher RSFI values compared with control and conventional fertilizer treatments.

The increasing trend from F_1 to F_9 indicates progressive improvement in residual soil nutrient status with increasing integration of Nano-DAP.

Treatment F_9 recorded the highest overall fertility improvement due to its combined application of reduced phosphorus fertilizer with Nano-DAP root dip and foliar supplementation.

Table 5. Relative Soil Fertility Improvement Index (RSFI) based on post-harvest soil fertility improvement under different fertilizer treatments

Treat ment	OC improvemen t (%)	Availa ble N improvemen t (%)	Availa ble P_2O_5 improvemen t (%)	Availabl e K_2O improvemen t (%)	RSFI
F_1	-1.61	-4.14	-6.25	-3.53	0.00
F_2	0.00	-0.34	-2.35	0.66	0.18
F_3	1.61	2.19	1.21	3.30	0.58
F_4	3.23	3.72	2.90	4.59	0.73
F_5	4.84	4.21	2.43	5.29	0.76
F_6	6.45	5.49	5.81	6.18	0.95
F_7	8.06	6.88	9.49	7.39	1.29
F_8	8.06	7.58	9.59	8.42	1.34
F_9	9.68	8.71	11.14	9.14	1.46

4.10 Phosphorus efficiency under Nano-DAP integrated fertilization

Phosphorus management is an important component of sustainable fertilizer use because excessive application of conventional phosphorus fertilizers may increase fixation losses in acidic soils [4,7].

The present study showed that Nano-DAP integration maintained higher post-harvest available phosphorus despite reduced soil-applied phosphorus in F_7 – F_9 treatments [2,3].

Treatment F_9 recorded available P_2O_5 of 30.23 kg ha^{-1} , which was higher than the conventional recommended fertilizer treatment F_3 (27.53 kg ha^{-1}).

This indicates that Nano-DAP supplementation improved phosphorus availability and may enhance phosphorus-use efficiency. Similar phosphorus-efficiency responses have been reported in fodder oat, rice and controlled nano-DAP experiments [19,20,22].

Table 6. Effect of reduced phosphorus application combined with Nano-DAP on post-harvest available phosphorus

Treatment	Fertilizer phosphorus strategy	Post-harvest available P_2O_5 (kg ha^{-1})	Improvement over F_3 (%)
F_3	100% recommended phosphorus	27.53	0.00
F_7	Reduced soil phosphorus + Nano-DAP root dip	29.78	8.17
F_8	Reduced soil phosphorus + Nano-DAP foliar spray	29.81	8.28
F_9	Reduced soil phosphorus + Nano-DAP root dip + foliar spray	30.23	9.80

The phosphorus response pattern indicated that Nano-DAP integration maintained higher post-harvest available phosphorus even under reduced conventional phosphorus application. Treatment F_9 recorded 30.23 kg ha^{-1} available P_2O_5 compared with 27.53 kg ha^{-1} under full conventional phosphorus application (F_3). This suggests

Parameter	pH	OC	Available N	Available P ₂ O ₅	Available K ₂ O
pH	1.00	0.98	0.97	0.96	0.97
OC	0.98	1.00	0.99	0.96	0.98
Available N	0.97	0.99	1.00	0.98	0.99
Available P ₂ O ₅	0.96	0.96	0.98	1.00	0.98
Available K ₂ O	0.97	0.98	0.99	0.98	1.00

Supplementary Table S2. PCA loading values

Soil fertility parameter	PC1 loading	PC2 loading
Soil pH	0.44	-0.31
Organic carbon	0.45	-0.19
Available N	0.46	0.08
Available P ₂ O ₅	0.45	0.47
Available K ₂ O	0.46	0.36

5. Conclusion

The present investigation revealed that integrated Nano-DAP fertilization improved post-harvest soil fertility status in African marigold (*Tagetes erecta* L.).

Nano-DAP treatments maintained higher residual availability of soil nutrients compared with control and conventional fertilizer treatments. Among fertilizer treatments, F₉ (NPK 9:4.5:12 g m⁻² + Nano-DAP root dip 5 mL L⁻¹ + foliar spray 10 mL L⁻¹) recorded superior post-harvest soil fertility characteristics, including higher soil organic carbon and available N, P₂O₅ and K₂O.

The interaction treatment D₁F₉ showed the highest residual nutrient availability, indicating that suitable planting time combined with efficient nutrient management can improve soil fertility outcomes.

Correlation analysis demonstrated positive associations among major soil fertility parameters, while PCA analysis separated Nano-DAP integrated treatments from

improved phosphorus availability through Nano-DAP supplementation; however, direct phosphorus recovery efficiency requires nutrient input data and should be interpreted as an indication of improved residual phosphorus status rather than complete fertilizer recovery.

4.11 Integrated interpretation of Nano-DAP effects on soil fertility sustainability

The combined statistical analyses demonstrate that Nano-DAP integration influenced soil fertility as a coordinated system rather than through individual nutrient improvement alone.

Correlation analysis showed positive relationships among soil fertility parameters, indicating that improvements in nitrogen, phosphorus, potassium and organic carbon occurred together.

PCA and cluster analysis further confirmed that Nano-DAP treatments formed a distinct fertility group compared with control and conventional fertilizer treatments.

These findings indicate that Nano-DAP-based nutrient management has potential for improving residual nutrient availability after harvest, although long-term experiments across multiple cropping cycles are required to confirm sustained soil health benefits [8].

Taken together with previous work in marigold, cabbage, okra, pigeonpea and rice, the present results support an integrated-use interpretation: Nano-DAP appears most useful when it complements a balanced nutrient program and is applied through a delivery strategy matched to crop demand [1–3,9,10,16,17]. This is consistent with the broader principle that improved fertilizer efficiency should reduce nutrient losses without compromising nutrient supply to the crop or residual soil fertility [11–13].

conventional fertilizer and control treatments, highlighting their distinct soil nutrient profile.

The study suggests that Nano-DAP integration can be an effective nutrient management approach for improving residual soil fertility in African marigold cultivation. Further long-term studies involving repeated cropping cycles are required to evaluate sustained effects on soil health.

Author Contributions (CRediT)

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2. Dr. Preeti Hatibarua: Conceptualization, Data curation, Supervision, Validation, Writing – review and editing, Methodology, Investigation, Funding acquisition.
3. Dr. Sailen Gogoi: Conceptualization, Data curation, Formal analysis, Validation, Supervision, Software.
4. Dr. Tanmoy Das: Writing – review and editing, Proofreading.
5. Mr. Paul Huda Baruah: Software, Validation, Visualization.
6. Dr. Samiron Dutta: Conceptualization, Data curation, Formal analysis.
7. Dr. Sangita Das: Resources, Investigation.
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Conflict of Interest Statement

The authors declare that there is no conflict of

Data Availability Statement

The datasets generated and analysed during the present study are available from the corresponding author upon reasonable request.

Ethics Statement

This study involved field experimentation on plants and soil only. No human or animal subjects were involved.

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