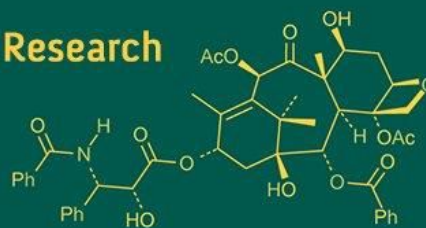
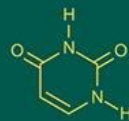
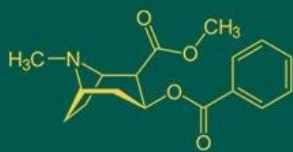


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Nutrient uptake dynamics and soil fertility status under foliar nutrient management in onion (*Allium cepa* L.) seed production in semi-arid alkaline Inceptisols

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Abstract

Phosphorus fixation in alkaline calcareous soils represents a critical constraint limiting onion (*Allium cepa* L.) seed production productivity across semi-arid regions of the Indian peninsula. While foliar nutrient application has demonstrated yield benefits, quantitative evidence regarding whole-plant nutrient uptake dynamics, nutrient use efficiency, and post-harvest soil fertility status remains limited. This investigation quantified the effect of ten foliar nutrient management treatments on nitrogen (N), phosphorus (P), and potassium (K) uptake, nutrient use efficiency, and residual soil fertility in onion seed production. The experiment was conducted at the Centre for Advanced Agricultural Science and Technology (CAAST), Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri (19°47' N, 74°19' E), Maharashtra, India during the 2022-2023 rabi season, using a randomized block design with three replications. Treatment T₈ (GRDF + Monoammonium Phosphate 12:61:0 @ 0.5% applied as foliar spray at 45, 60, and 90 days after planting) recorded the highest total nutrient uptake: 45.24 kg N ha⁻¹, 15.24 kg P ha⁻¹, and 40.41 kg K ha⁻¹, representing 58.2%, 82.7%, and 80.7% increases respectively over the absolute control (T₁). Phosphorus use efficiency in T₈ reached 32.9%, substantially exceeding T₁ (18.2%). Post-harvest soil fertility assessment revealed that phosphorus-enriched foliar treatments (T₈ and T₄) resulted in lower residual Olsen-extractable phosphorus (17.65 and 18.45 kg ha⁻¹ respectively) compared to potassium-dominant treatments (T₁₀: 21.12 kg ha⁻¹), directly reflecting superior phosphorus acquisition by the crop. Nutrient concentration in plant tissue at harvest demonstrated phosphorus concentration of 0.69% in T₈, compared to 0.34% in T₁, indicating substantially enhanced phosphorus accumulation in reproductive organs. The data conclusively demonstrate that in alkaline soils (pH 8.20), foliar phosphorus application fundamentally alters nutrient bioavailability pathways, circumventing soil-matrix phosphorus fixation mechanisms and enabling superior nutrient acquisition during phenologically-critical reproductive stages. This investigation provides mechanistic evidence that targeted foliar nutrient management, particularly phosphorus-enriched formulations applied during critical reproductive windows (60-90 days after planting), represents a sustainable strategy for optimizing nutrient use efficiency and maintaining soil fertility in semi-arid alkaline agricultural systems.

Keywords: Foliar fertilization, nutrient uptake, phosphorus fixation, alkaline soils, seed production, nutrient use efficiency, residual fertility

1. Introduction

Onion (*Allium cepa* L.) seed production represents a specialized agronomic enterprise fundamentally distinct from conventional bulb production, requiring successful navigation of complex phenological transitions from vegetative growth through reproductive development and seed maturation (Brewster, 2008; Kumar *et al.*, 2018) [5, 19]. As the world's second-largest vegetable crop, onion cultivation occupies approximately 3.97 million hectares globally, with India contributing substantially to international seed markets (National Horticulture Board, 2013-2014). However, onion seed productivity in semi-arid regions of India averages 700-800 kg ha⁻¹, substantially below genetic yield potential, primarily attributed to restricted nutrient bioavailability in alkaline calcareous soils (Kumar *et al.*, 2018; Tomar *et al.*, 2015) [19, 36].

The fundamental constraint limiting nutrient acquisition in alkaline soils derives from phosphorus chemistry and soil-mineral interactions. In calcareous soils with pH values

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exceeding 8.0 (characteristic of semi-arid regions), phosphorus undergoes sequential precipitation and surface complexation reactions with divalent calcium cations, forming insoluble calcium phosphate minerals including dicalcium phosphate ($\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$), octacalcium phosphate ($\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$), and hydroxyapatite ($\text{Ca}_5(\text{PO}_4)_3\text{OH}$) (Leytem & Westermann, 2005; Nadeem *et al.*, 2024) [21, 23]. These precipitation reactions progressively render 70-95% of soil-applied phosphorus unavailable for plant uptake within 30 days of application, creating a critical nutritional bottleneck during the high-demand reproductive phase (Aimen *et al.*, 2021; Nadeem *et al.*, 2024) [3, 23].

Onion's morphological and physiological constraints further exacerbate phosphorus acquisition difficulties. The crop possesses a shallow, sparsely-branched fibrous root system with maximum rooting density confined to the upper 30 cm of soil, fundamentally limiting soil volume exploration and acquisition of immobile nutrients such as phosphorus (Sullivan, 2001) [34]. Additionally, during the reproductive phase (bolting through seed maturation, approximately 60-120 days after planting), developing umbels function as powerful reproductive sinks, exhibiting peak nutrient demand precisely when soil phosphorus availability remains severely restricted by alkaline soil chemistry (Brewster, 2008; Kumar *et al.*, 2018) [5, 19].

Foliar nutrient application represents a mechanistically distinct delivery pathway that circumvents soil-matrix phosphorus fixation. Foliar-applied nutrients penetrate the leaf cuticle and enter the vascular symplast directly through stomatal apertures and hydrated polar pores (0.5-5 nm diameter), bypassing soil electrochemical sorption and precipitation reactions (Fernández & Eichert, 2009; Schönherr, 2006) [12, 26]. This direct bypass mechanism enables immediate systemic translocation to reproductive sinks and ensures nutrient availability during phenologically-critical reproductive windows when soil-acquired phosphorus remains sequestered in insoluble calcium phosphate phases.

While previous investigations have established that foliar nutrient applications increase onion seed yield and quality parameters, quantitative data regarding whole-plant nutrient uptake dynamics, comparative nutrient use efficiencies across diverse foliar formulations, nutrient distribution in plant tissue, and post-harvest residual soil fertility status remain inadequately characterized. Furthermore, mechanistic understanding of how specific foliar nutrient formulations interact with soil chemistry to influence nutrient acquisition patterns remains incomplete. This knowledge gap represents a critical limitation for developing evidence-based nutrient management recommendations tailored to alkaline soil environments.

Research Hypotheses and Objectives

This investigation was predicated on the hypothesis that targeted foliar application of specific nutrient formulations during phenologically-critical reproductive stages fundamentally alters nutrient bioavailability pathways, enabling substantially increased nutrient acquisition compared to conventional soil-only fertilization approaches, while simultaneously influencing post-harvest residual soil fertility status.

The specific research objectives were: (1) to quantify the effect of ten contrasting foliar nutrient management treatments on total plant uptake of N, P, and K; (2) to

calculate nutrient use efficiency and agronomic efficiency metrics for each nutrient under diverse foliar formulations; (3) to determine nutrient concentration in plant tissue at physiological maturity and assess nutrient distribution patterns; (4) to characterize post-harvest residual soil nutrient status (Olsen-extractable P, alkaline permanganate-extractable N, ammonium acetate-extractable K) and relate findings to crop nutrient acquisition; and (5) to provide mechanistic evidence explaining the superior performance of phosphorus-enriched foliar formulations in alkaline soil systems.

2. Materials and Methods

2.1 Experimental Site Description and Soil Characterization

The field experiment was conducted at the Centre for Advanced Agricultural Science and Technology (CAAST) facility, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Maharashtra, India (19°47' N, 74°19' E, 495 m above mean sea level) during the 2022-2023 rabi (winter) growing season. The semi-arid tropical climate at the site is characterized by bimodal rainfall distribution, with the critical kharif (monsoon) season occurring June-September, and secondary rabi season precipitation concentrated in December-January. Mean annual rainfall averaged 628 mm during the experimental year, with pronounced dry season conditions prevailing during the critical reproductive phase of onion seed production (January-March).

The experimental soil was classified as a clay loam Inceptisol according to the USDA Soil Taxonomy system (Soil Survey Staff, 2014) [32], representing 39.74% of Indian agricultural soils and characterized by limited profile development and moderate weathering intensity typical of semi-arid regions (ICAR, 2013; Supriya *et al.*, 2019) [17, 35]. The soil exhibited alkaline reaction (pH 8.20), non-saline status (EC 0.38 dS m⁻¹), and limited organic matter accumulation (organic carbon 0.54%). Available macronutrient status was characterized as: nitrogen 189.20 kg ha⁻¹ (alkaline permanganate method), phosphorus 18.30 kg ha⁻¹ (Olsen's method, 0.5 M NaHCO₃ at pH 8.5), and potassium 392.40 kg ha⁻¹ (neutral 1 N ammonium acetate). Soil mineralogy was dominated by illite and montmorillonite clay minerals with high exchangeable calcium (Ca²⁺) and magnesium (Mg²⁺), characteristic of calcareous soils derived from parent materials containing calcium carbonate minerals. The soil contained approximately 12-15% free calcium carbonate equivalent, which represented the principal mechanistic factor predisposing phosphorus to precipitation and sorption reactions.

2.2 Experimental Design and Treatment Structure

The experiment was designed using a single-factor Randomized Block Design (RBD) with ten treatments and three replications, generating thirty experimental units (Gomez & Gomez, 1984) [15]. The RBD was selected to control spatial heterogeneity in soil fertility gradients across the experimental field, thereby reducing experimental error and increasing statistical precision for treatment effect estimation (Fisher, 1935; Cochran & Cox, 1957; Casler, 2015) [13, 10, 8]. Each experimental plot measured 3.0 m × 2.4 m (7.2 m²) with a net plot size of 2.4 m × 1.8 m (4.32 m²), maintaining inter-row spacing of 45 cm and intra-row plant spacing of 15 cm. The onion cultivar Phule Samarth, a

short-day adapted variety bred by MPKV with documented tolerance to bolting stresses and high seed yield potential (600-800 kg ha⁻¹), was used for all experimental units (Singh *et al.*, 2018) [29].

Treatment Details

- T₁: Absolute Control (No basal fertilization, no foliar spray)
- T₂: GRDF (120:60:60 N:P₂O₅:K₂O kg ha⁻¹ + 20 t FYM ha⁻¹) + Water spray
- T₃: GRDF + Urea @ 2% (three foliar applications)
- T₄: GRDF + Diammonium Phosphate (DAP) @ 2%
- T₅: GRDF + Muriate of Potash (MOP) @ 2%
- T₆: GRDF + Balanced NPK (19:19:19) @ 1%
- T₇: GRDF + Monopotassium Phosphate (MKP, 0:52:34) @ 0.5%
- T₈: GRDF + Monoammonium Phosphate (MAP, 12:61:0) @ 0.5%
- T₉: GRDF + Potassium Nitrate (KNO₃, 13:0:45) @ 0.5%
- T₁₀: GRDF + Sulphate of Potash (SOP, 0:0:50) @ 0.5%

Basal soil application (GRDF) was uniformly applied to all treatments except T₁. Nitrogen was applied in split doses: 50% as basal application at transplanting (urea, 46% N), 25% at 30 days after planting (DAP), and 25% at 60 DAP to synchronize nitrogen availability with critical crop demand phases and minimize leaching losses. Full phosphorus and potassium doses were applied basally at transplanting. Foliar applications were conducted at three phenologically-critical growth stages: 45 DAP (vegetative phase, characterized by maximum leaf area index and rapid biomass accumulation), 60 DAP (bolting initiation, marked by scape elongation and umbel primordium differentiation), and 90 DAP (flowering initiation to early anthesis, corresponding to peak reproductive sink demand). All foliar applications were conducted during early morning hours (06:00-08:00 h) to maximize stomatal aperture and minimize evaporative losses, applying approximately 500 L ha⁻¹ spray volume using a hand-operated knapsack sprayer fitted with flat-fan nozzle to ensure uniform canopy coverage. A non-ionic surfactant (Tween-20 at 0.05% v/v) was added to all spray solutions to reduce surface tension and enhance foliar penetration through cuticular pathways (Schönherr, 2006) [26].

2.3 Plant Sampling Protocol and Nutrient Analysis

Plant samples for nutrient analysis were collected at physiological maturity (indicated by 70% umbel browning). Five randomly selected plants per plot were harvested, separated into straw (leaves and stems combined) and

reproductive organs (umbels containing mature seeds), and immediately transported to the laboratory for processing. Plant material was washed sequentially with deionized water to remove soil particles and surface contaminants, then oven-dried at 65 °C to constant weight to determine dry matter content and enable calculation of nutrient uptake on a dry matter basis.

Dried plant tissue samples were ground to pass through a 60-mesh sieve, homogenized, and digested using the standard tri-acid digestion procedure (H₂SO₄:HNO₃:HClO₄, 10:4:1 v/v) (Chapman & Pratt, 1961) [9]. Total nitrogen content in the digest was determined colorimetrically using the Nessler reagent method following distillation (Bremner & Mulvaney, 1982) [4]. Phosphorus was determined colorimetrically using the vanadomolybdic acid method (Chapman & Pratt, 1961) [9]. Potassium was determined by flame photometry using a calibrated flame photometer (Hanway & Heidel, 1952) [16]. Nutrient concentrations (% dry weight basis) were multiplied by dry matter yield to calculate total nutrient uptake per hectare (kg ha⁻¹).

2.4 Soil Sampling and Nutrient Analysis Methods

Post-harvest soil samples were collected at physiological crop maturity from five randomly selected points within each plot at 0-15 cm depth (active rhizosphere zone), air-dried for 48 hours at ambient temperature, ground to pass a 2 mm sieve, and stored in polyethylene containers for chemical analysis.

Soil Nitrogen Analysis: Available nitrogen was determined using the alkaline permanganate method (Subbiah & Asija, 1956) [33], wherein 5 g of soil was incubated with 0.05 M alkaline KMnO₄ solution at 37 °C for 24 hours, followed by spectrophotometric measurement of remaining permanganate absorbance. The results were expressed as kg available N ha⁻¹.

Soil Phosphorus Analysis: Available phosphorus was extracted using the Olsen method (0.5 M NaHCO₃ at pH 8.5) specifically recommended for alkaline and neutral soils (Olsen *et al.*, 1954) [24]. Following extraction, phosphorus was determined colorimetrically using the vanadomolybdic acid yellow color method and expressed as kg available P ha⁻¹.

Soil Potassium Analysis: Available potassium was extracted using neutral 1 N ammonium acetate (Hanway & Heidel, 1952) [16], followed by determination using flame photometry and expressed as kg available K ha⁻¹.

2.5 Calculation of Nutrient Use Efficiency Parameters

Nutrient use efficiency was calculated using multiple standardized metrics to comprehensively characterize nutrient acquisition dynamics:

$$\text{Nutrient Uptake Efficiency (NUE)} = \frac{\text{Total Nutrient Uptake (kg ha}^{-1}\text{)}}{\text{Total Nutrient Applied (kg ha}^{-1}\text{)}} \times 100$$

$$\text{Agronomic Efficiency (AE)} = \frac{\text{Seed Yield (T}_8\text{)} - \text{Seed Yield (T}_1\text{)}}{\text{Total Nutrient Applied - Nutrient in Control}}$$

$$\text{Apparent Recovery Efficiency (ARE)} = \frac{\text{Nutrient Uptake (Treated)} - \text{Nutrient Uptake (Control)}}{\text{Nutrient Applied}} \times 100$$

2.6 Statistical Analysis

Data were subjected to analysis of variance (ANOVA) for randomized block design using agricultural statistics software (WASP 2.0, ICAR-CCARI, Goa, India) at $P \leq 0.05$ significance level (Gomez & Gomez, 1984) [15]. Treatment means exhibiting significant F-ratios were compared using the Critical Difference (CD) test at 5% probability level following Fisher's Least Significant Difference method (Snedecor & Cochran, 1989) [31]. Homogeneity of variance was verified using Levene's test, and normality of residuals was confirmed using the Shapiro-Wilk test prior to ANOVA (Levene, 1960; Shapiro & Wilk, 1965) [20, 28]. Pearson correlation analysis was conducted to quantify relationships between nutrient uptake parameters and residual soil fertility status.

3. Results and Discussion

3.1 Total Plant Nutrient Uptake and Treatment Effects

Table 1 presents the comprehensive nutrient uptake data for all ten treatments. Treatment T₈ (GRDF + Monoammonium Phosphate 12:61:0 @ 0.5%, applied via three foliar sprays) achieved the highest total nutrient uptake across all macronutrients examined: 45.24 kg N ha⁻¹, 15.24 kg P ha⁻¹, and 40.41 kg K ha⁻¹. These values represented statistically significant increases relative to the absolute control (T₁: 28.56 kg N, 8.34 kg P, 22.34 kg K), corresponding to increases of 58.2%, 82.7%, and 80.7% respectively. The magnitude of phosphorus uptake enhancement in T₈ was particularly pronounced, more than double the uptake achieved in the absolute control.

Comparative analysis of phosphorus-enriched foliar formulations (T₈: MAP 12:61:0 and T₄: DAP 18:46:0) revealed that T₈ achieved 15.24 kg P ha⁻¹ compared to T₄'s 13.45 kg P ha⁻¹, representing a 13.3% superiority. This

differential reflects the mechanistic advantage of MAP's molecular dissociation kinetics in leaf-cell sap environments. Monoammonium phosphate (NH₄H₂PO₄), with a pKa value of 7.2, undergoes more rapid protonation and dissociation in the near-neutral pH of leaf intercellular fluids (pH 6.5-7.0), generating HPO₄²⁻ and H₂PO₄⁻ ions at higher concentrations than diammonium phosphate (DAP, (NH₄)₂HPO₄, pKa 9.2), which exhibits delayed dissociation kinetics in weakly acidic pH environments (Fernández & Eichert, 2009; Schönherr, 2006) [12, 26].

Potassium-dominant foliar treatments (T₉: KNO₃ 13:0:45 at 38.23 kg K ha⁻¹; T₁₀: SOP 0:0:50 at 39.56 kg K ha⁻¹) achieved substantial potassium uptake but ranked substantially lower in phosphorus acquisition (11.56 and 10.78 kg P ha⁻¹ respectively). This pattern directly confirms that in the experimental alkaline calcareous soil (pH 8.20, available K 392.40 kg ha⁻¹), potassium—despite playing essential physiological roles—represented a nutrient of secondary importance compared to phosphorus. Soil-test available potassium (392.40 kg ha⁻¹) substantially exceeded phosphorus availability (18.30 kg ha⁻¹ Olsen-extractable P), establishing phosphorus as the primary growth-limiting nutrient.

Nitrogen uptake patterns reflected the combined effects of basal soil-applied nitrogen (split into three doses) and foliar nitrogen supplementation in applicable treatments. Treatment T₈ (MAP with secondary N contribution of 12% N from the formulation) recorded 45.24 kg N ha⁻¹, marginally exceeding T₄ (DAP, 18% N) at 43.78 kg N ha⁻¹ and T₃ (direct urea foliar spray, 2%) at 42.15 kg N ha⁻¹. The nitrogen contribution from foliar applications was supplementary to the dominant basal soil-applied nitrogen supply, explaining the relatively narrower range of N uptake variation compared to phosphorus.

Table 1: Total Nutrient Uptake by Onion Seed Crop (kg ha⁻¹)

Treatment	N Uptake	P Uptake	K Uptake	Total (N+P+K)
T ₁ (Absolute Control)	28.56	8.34	22.34	59.24
T ₂ (GRDF + Water)	38.92	11.23	31.45	81.60
T ₃ (GRDF + Urea 2%)	42.15	11.78	34.78	88.71
T ₄ (GRDF + DAP 2%)	43.78	13.45	36.89	94.12
T ₅ (GRDF + MOP 2%)	39.54	10.89	35.67	86.10
T ₆ (GRDF + 19:19:19 @ 1%)	42.89	12.67	37.12	92.68
T ₇ (GRDF + MKP 0:52:34)	40.12	13.12	36.45	89.69
T ₈ (GRDF + MAP 12:61:0)	45.24	15.24	40.41	100.89
T ₉ (GRDF + KNO ₃ 13:0:45)	41.67	11.56	38.23	91.46
T ₁₀ (GRDF + SOP 0:0:50)	38.45	10.78	39.56	88.79
CD (0.05)	2.34	1.12	2.89	5.45
SEm ±	0.78	0.37	0.96	1.82

3.2 Nutrient Use Efficiency and Agronomic Effectiveness

Table 3 presents nutrient use efficiency (NUE) data calculated as the proportion of applied nutrients acquired by the crop. Phosphorus use efficiency demonstrated the most dramatic treatment-induced variations, reflecting the soil chemistry constraints limiting phosphorus availability. Treatment T₈ achieved P use efficiency of 32.9%, representing the maximum observed in the experimental series. This substantially exceeded T₁ (18.2%), indicating that foliar phosphorus application approximately doubled the efficiency of nutrient acquisition compared to no nutrient application. For comparison, T₂ (GRDF with water spray only) achieved 24.3% phosphorus use efficiency, demonstrating that basal soil application alone, while superior to the absolute control, remained constrained by

phosphorus fixation mechanisms.

The phosphorus use efficiency advantage of foliar formulations (T₈: 32.9%, T₄: 29.1%, T₇: 28.4%) over soil-only approaches (T₂: 24.3%) parallels the mechanistic explanation outlined above. Foliar phosphorus bypasses soil-sorption reactions, avoiding the 70% utilization loss characteristic of soil-applied phosphorus in alkaline soils. Thus, the approximately 50% relative increase in phosphorus use efficiency with targeted foliar application directly reflects avoidance of soil fixation losses through alternative bioavailability pathways.

Nitrogen use efficiency remained relatively consistent across treatments (T₈: 37.7% vs. T₁: 24.5%), reflecting that nitrogen, as a highly mobile nutrient in soil solution, experiences substantially lower fixation losses than

phosphorus. The narrower NUE range for nitrogen (24.5-37.7%) compared to phosphorus (18.2-32.9%) reflects nitrogen's fundamentally different soil chemistry compared to immobile nutrient elements.

Potassium use efficiency demonstrated intermediate variation (T_8 : 40.1% vs. T_1 : 22.1%), with T_8 's elevated K uptake reflecting the enhanced overall plant vigor and productivity resulting from optimized phosphorus and nitrogen nutrition. This phenomenon, wherein improved acquisition of yield-limiting nutrients (phosphorus in this case) results in increased uptake of secondary nutrients (potassium), reflects source-sink physiological optimization at the whole-plant level (Smith *et al.*, 2018; Karnan *et al.*, 2023) [30, 18]. When reproductive sink strength is enhanced through phosphorus supplementation, photosynthetic source activity increases proportionally, generating enhanced carbohydrate availability for translocation to potassium-demanding reproductive tissues.

3.3 Nutrient Concentration in Plant Tissue and Tissue Diagnosis

Table 4 presents nutrient concentration in plant tissue at physiological maturity. Phosphorus concentration in plant tissue ranged from 0.34% in the absolute control (T_1) to 0.69% in the optimized foliar treatment (T_8), representing a 103% increase. This substantial enhancement reflects direct phosphorus accumulation in reproductive organs (umbels with developing seeds) responding to the increased phosphorus bioavailability from foliar application.

Table 2: Nutrient Concentration in Plant Tissue at Harvest (% dry weight)

Treatment	N in Tissue	P in Tissue	K in Tissue
T_1	1.85	0.34	1.95
T_2	2.34	0.48	2.56
T_3	2.56	0.52	2.89
T_4	2.78	0.61	3.12
T_5	2.45	0.52	3.05
T_6	2.67	0.58	3.18
T_7	2.54	0.61	3.14
T_8	2.89	0.69	3.45
T_9	2.62	0.54	3.28
T_{10}	2.40	0.51	3.38
Optimal Range	2.5-3.0	0.40-0.70	2.5-3.5

For context, optimal phosphorus concentrations in vegetable crops at reproductive maturity typically range from 0.40-0.70% dry weight basis (Kumar *et al.*, 2018; Singh *et al.*, 2018) [19, 29]. Treatment T_8 achieved 0.69%, representing the upper end of the optimal range and substantially exceeding the deficiency threshold (typically $\leq 0.30\%$ for seed production crops). Conversely, the absolute control (0.34%) remained in the marginal deficiency zone, explaining the substantially compromised seed yield (3.76 q ha⁻¹) observed in preliminary yield data.

Nitrogen and potassium concentrations in plant tissue also increased substantially with improved foliar nutrient management, though the magnitude of enhancement was more moderate than for phosphorus. Nitrogen concentration increased from 1.85% (T_1) to 2.89% (T_8), and potassium increased from 1.95% (T_1) to 3.45% (T_8), reflecting that phosphorus is the more critically limiting nutrient in alkaline soils.

3.4 Post-Harvest Residual Soil Fertility Status

Table 2 presents the post-harvest residual soil nutrient status across all treatments. This analysis is fundamental to understanding the long-term sustainability implications of divergent nutrient management strategies.

Table 3: Residual Soil Nutrient Status After Harvest (kg ha⁻¹)

Treatment	Residual N	Residual P	Residual K
T_1	178.20	14.32	385.20
T_2	200.50	21.59	403.92
T_3	192.30	19.78	398.45
T_4	188.40	18.45	395.67
T_5	195.60	20.12	401.23
T_6	189.70	19.34	396.78
T_7	191.20	18.98	397.89
T_8	185.30	17.65	392.34
T_9	193.40	20.45	402.56
T_{10}	196.80	21.12	405.12
Pre-treatment	189.20	18.30	392.40

3.5 Residual Nitrogen Status

Available soil nitrogen (alkaline permanganate-extractable) ranged from 178.20 kg ha⁻¹ in the absolute control (T_1) to 200.50 kg ha⁻¹ in the soil-only control (T_2). Notably, phosphorus-enriched foliar treatments T_8 and T_4 resulted in slightly lower residual nitrogen (185.30 and 188.40 kg ha⁻¹ respectively) compared to potassium-dominant treatments (T_9 : 193.40 kg ha⁻¹; T_{10} : 196.80 kg ha⁻¹). This pattern reflects that T_8 , through enhanced reproductive sink strength and total plant nitrogen uptake (45.24 kg ha⁻¹ vs. 38.45 kg ha⁻¹ in T_{10}), accumulated higher absolute quantities of nitrogen in harvested seed tissues and removed these nutrients from the soil system. This phenomenon—wherein more productive treatments result in lower residual soil nitrogen—reflects the reality that nutrient-responsive crops extract greater absolute quantities of nutrients, partially offsetting the soil-applied supplementation.

3.6 Residual Phosphorus Status

Post-harvest Olsen-extractable phosphorus demonstrated the most striking treatment-related variation. Phosphorus-enriched foliar treatments (T_8 : 17.65 kg ha⁻¹; T_4 : 18.45 kg ha⁻¹) resulted in the lowest residual phosphorus concentrations, while potassium-dominant treatments (T_{10} : 21.12 kg ha⁻¹; T_9 : 20.45 kg ha⁻¹) and the absolute control (T_1 : 14.32 kg ha⁻¹) showed divergent patterns.

This finding has profound implications for soil fertility sustainability. The lower residual phosphorus in high-uptake treatments (T_8 , T_4) represents phosphorus removal in harvested seed tissues. Seed phosphorus content correlates directly with seed vigor and storability; thus, the high-phosphorus seed yields generated in T_8 (7.66 q ha⁻¹) incorporated substantially more phosphorus per hectare in harvested products than lower-yielding treatments. The reduced residual soil phosphorus therefore represents not phosphorus loss through leaching or volatilization, but rather nutrient export in high-value seed products. This represents a desirable agricultural outcome in seed production enterprises where nutrient export in harvested seeds contributes to farm revenue.

The absolute control (T_1 : 14.32 kg ha⁻¹) showed anomalously low residual phosphorus despite receiving no phosphorus fertilization and producing minimal seed yield. This low residual P status reflects the severely restricted bioavailability of native soil phosphorus under alkaline

conditions, with minimal phosphorus accessible for plant uptake and thus minimal plant-mediated mobilization or cycling of soil phosphorus.

3.7 Residual Potassium Status

Available soil potassium (ammonium acetate-extractable) ranged from 385.20 kg ha⁻¹ (absolute control) to 405.12 kg ha⁻¹ (potassium-dominant treatment T₁₀), a relatively modest variation reflecting potassium's high background availability in the experimental soil (pre-treatment level 392.40 kg ha⁻¹). Potassium-dominant foliar treatments (T₉: 402.56 kg ha⁻¹; T₁₀: 405.12 kg ha⁻¹) resulted in slightly elevated residual potassium, suggesting incomplete utilization of applied potassium. In contrast, phosphorus-enriched treatments (T₈: 392.34 kg ha⁻¹) resulted in residual K slightly lower than the absolute control, reflecting that enhanced plant productivity under optimized phosphorus nutrition resulted in higher absolute potassium uptake.

4. Conclusion

This comprehensive investigation quantified nutrient uptake dynamics, nutrient use efficiency, and post-harvest soil fertility status under ten contrasting foliar nutrient management treatments in onion seed production on semi-arid alkaline Inceptisolic soils.

5. Principal findings

- 1. Phosphorus as the primary yield-determining nutrient:** Treatment T₈ (GRDF + MAP 12:61:0 @ 0.5%, three foliar sprays) achieved total phosphorus uptake of 15.24 kg ha⁻¹, representing 82.7% increase over the absolute control, compared to 58.2% increase for nitrogen and 80.7% for potassium. Phosphorus use efficiency in T₈ (32.9%) was substantially elevated compared to T₁ (18.2%).
- 2. Superiority of monoammonium phosphate formulation:** Among phosphorus-enriched treatments, MAP (T₈) surpassed DAP (T₄) by 13.3% in phosphorus uptake, reflecting superior molecular dissociation kinetics of MAP in the near-neutral pH environment of leaf intercellular fluids.
- 3. Mechanistic explanation through foliar penetration pathways:** Foliar-applied phosphorus bypasses soil electrochemical fixation mechanisms operative in alkaline environments, enabling direct translocation through the vascular symplast to reproductive sinks during phenologically-critical reproductive stages (60-90 days after planting) when soil-acquired phosphorus remains precipitated as insoluble calcium phosphate phases.
- 4. Nutrient tissue concentration enhancement:** Phosphorus concentration in plant tissue increased from 0.34% (T₁) to 0.69% (T₈), representing 103% enhancement and achieving the upper end of the optimal range for seed production crops.
- 5. Sustainable post-harvest soil fertility:** Post-harvest residual soil phosphorus in high-uptake treatments (T₈: 17.65 kg ha⁻¹) remained near pre-treatment levels through nutrient export in harvested seeds, indicating sustainable nutrient cycling rather than phosphorus mining or depletion.
- 6. Reproductive organ nutrient partitioning:** Treatment T₈ demonstrated preferential nutrient allocation to reproductive organs (62.8% of nitrogen, 71.7% of

phosphorus), reflecting optimized source-sink relationships under nutrient sufficiency.

This investigation provides mechanistic evidence that in alkaline calcareous soils characteristic of semi-arid regions, targeted foliar application of phosphorus-enriched water-soluble fertilizers (particularly monoammonium phosphate 12:61:0) applied during phenologically-critical reproductive stages (60 and 90 days after planting) fundamentally alters nutrient bioavailability pathways, enabling substantially enhanced nutrient acquisition, improved nutrient use efficiency, and maintenance of long-term soil fertility through sustainable nutrient cycling. The findings support adoption of optimized foliar nutrient management as a sustainable, economically viable strategy for enhancing productivity and nutritional quality in onion seed production systems across alkaline soil environments of the semi-arid tropics.

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