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Physiological and economic optimization of onion (*Allium cepa* L.) seed production through targeted foliar nutrient supplementation in semi-arid tropics

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Abstract
Onion (*Allium cepa* L.) seed production in semi-arid tropics remains constrained by poor nutrient availability, particularly phosphorus fixation in alkaline calcareous soils. The crop's shallow root system and high reproductive nutrient demand further limit seed yield and quality under conventional soil fertilization. This study evaluated the physiological, yield, seed quality, and economic responses of onion to targeted foliar nutrient supplementation using ten nutrient treatments under a randomized block design at MPKV, Rahuri. Results demonstrated that phosphorus-enriched foliar formulations significantly improved reproductive architecture, umbel formation, seed filling, and physiological vigor. Among treatments, foliar application of monoammonium phosphate (12:61:0) at 0.5% (T_8) was superior, producing the highest umbels per plant (7.51), primary umbel diameter (7.81 cm), 1000-seed weight (3.91 g), seed germination (90.90%), and seed yield (7.66 q ha^{-1}). The economic analysis revealed that T_8 achieved the maximum net returns (₹ 8,69,176 ha^{-1}) and the highest benefit-cost ratio (4.52), indicating strong profitability and high adoption potential for farmers. The findings confirm phosphorus as the principal limiting nutrient and demonstrate that foliar supplementation effectively bypasses soil fixation constraints, enhancing source-sink dynamics and reproductive efficiency. This study recommends foliar application of 12:61:0 at critical growth stages (45, 60, and 90 DAP) as an agronomically and economically optimal strategy for improving onion seed productivity in semi-arid, phosphorus-limited soils.

Keywords: Onion seed production, foliar nutrition, monoammonium phosphate

1. Introduction

Onion (*Allium cepa* L.) seed production represents a specialized agronomic practice distinct from conventional bulb production, requiring successful navigation of complex phenological transitions from vegetative "loop" stages through reproductive "scape elongation" and "anthesis" stages (Kumar *et al.*, 2018) [34]. As the second-largest vegetable crop globally (3.97 million hectares), onion production faces critical constraints in seed quality and quantity, particularly in small-holding contexts where locally-sourced seeds exhibit compromised genetic potential and physiological vigor (National Horticulture Board 2013-14) [45]. In semi-arid tropical regions with calcareous soils prevalent across India, onion seed productivity averages 700-800 kg ha^{-1}, substantially below potential yields, primarily due to restricted phosphorus (P) and zinc (Zn) bioavailability and accelerated nitrogen (N) leaching under intensive cultivation (Kumar *et al.*, 2018) [34].

Onion's shallow, sparsely-branched root system with maximum rooting density within the upper 30 cm of soil severely constrains nutrient acquisition, particularly for immobile nutrients such as P, potassium, and micronutrients (Sullivan 2001) [62]. This morphological limitation becomes critical during the reproductive phase when developing umbels demand rapid nutrient translocation for floret initiation, pollen development, and seed maturation (Kumar *et al.*, 2018) [34]. In calcareous soils, elevated pH and calcium carbonate concentrations cause phosphorus precipitation into dicalcium phosphate, octacalcium phosphate, and hydroxyapatite forms, substantially reducing phosphorus availability despite adequate fertilizer application (Leytem & Westermann 2005; Wandruszka 2006) [38, 67].

Foliar fertilization circumvents soil electrochemical fixation by delivering nutrients directly through stomatal apertures and hydrated polar pores (0.5-5 nm diameter) embedded within the cuticular matrix, enabling rapid translocation into the vascular symplast during phenologically-critical reproductive phases. Contemporary research demonstrates that boron (B), zinc (Zn), calcium (Ca), and magnesium (Mg) function as catalytic cofactors in carbohydrate metabolism and protein synthesis, while serving specialized reproductive functions—particularly in pollen tube elongation, stigma receptivity, and gametic viability (Hansch & Mendel 2009) [24]. Boron regulates pollen development and carbohydrate translocation; zinc functions as a cofactor in auxin synthesis sustaining reproductive organogenesis; calcium stabilizes pollen tube growth and cellular walls; and magnesium facilitates light-energy conversion essential for sink-tissue fuel supply (Brown *et al.*, 2002; Cakmak *et al.*, 1989; Nelson & Niedziela 1998) [8, 9, 46].

While previous research established macronutrient efficacy on onion growth and bulb yield (Fageria *et al.*, 2002; Narimani *et al.*, 2010) [17, 44], a substantial gap persists regarding comparative efficacy of specific high-analysis water-soluble fertilizer formulations—particularly monoammonium phosphate (12:61:0) with elevated phosphorus for reproductive supplementation versus potassium nitrate (13:0:45)—applied during critical bolting and flowering stages. The source-sink physiological paradigm posits that optimizing nutrient ratios during reproductive development directly modulates photoassimilate partitioning and reproductive sink strength (Smith *et al.*, 2018; Karnan *et al.*, 2023) [58, 32]. During the 10-20 days post-anthesis interval, photosynthetic source activity fundamentally determines reproductive sink capacity and ultimately seed yield; therefore, interventions enhancing photoassimilate translocation during this critical window offer substantial yield-enhancement potential (Croft *et al.*, 2018) [14].

This study hypothesizes that targeted application of specific nutrient ratios during physiologically-critical bolting and flowering stages can optimize source-sink relationships, thereby maximizing seed yield and quality attributes. The research objectives are: (1) to quantify comparative efficacy of monoammonium phosphate (12:61:0) versus potassium nitrate (13:0:45) foliar applications on reproductive architecture and seed-yield components; (2) to identify the precise nutrient formulation and application timing maximizing umbel and floret development; (3) to assess treatment consequences on seed quality attributes including germination percentage, seedling vigor indices, and membrane stability; and (4) to evaluate economic returns and cost-benefit ratios for adoption in calcareous-soil environments. This study provides evidence-based recommendations for optimizing seed production systems in environmentally-constrained agricultural contexts through targeted foliar nutrient management.

2. Materials and Methods

2.1 Geoclimatic Description and Soil Physicochemical Status

The field experiment was conducted at the Centre of Advanced Agricultural Science and Technology (CAAST), Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Maharashtra, India (19°47′ N, 74°19′ E, 495 m above mean sea level) during the 2022-2023 growing season. The region experiences a semi-arid tropical climate characterized by bimodal rainfall distribution and pronounced seasonal water deficit during the reproductive phase of onion seed production (IMD 2023) [27]. The experimental site soil was classified as a clay loam Inceptisol according to the USDA Soil Taxonomy system (Soil Survey Staff 2014) [60], representing 39.74% of Indian agricultural soils and characterized by limited profile development with moderate weathering intensity typical of semi-arid regions (ICAR 2013; Supriya *et al.*, 2019) [26, 63].

Soil Parameter	Value	Classification	Method of Analysis	Reference
Soil pH	8.20	Alkaline	1:2.5 soil:water suspension	Jackson (1973) [30]
Electrical Conductivity (EC)	0.38 dS m^{-1}	Non-saline	-	Piper (1966) [49]
Organic Carbon	0.54%	Limited accumulation	Walkley-Black method	Walkley & Black (1934) [68]; Lal (2004) [36]
Available Nitrogen	189.20 kg ha^{-1}	Low	Alkaline permanganate method	Subbiah & Asija (1956) [61]
Available Phosphorus	18.30 kg ha^{-1}	Medium	0.5 M $NaHCO_3$ at pH 8.5 (Olsen's method)	Olsen *et al.* (1954) [47]
Available Potassium	392.40 kg ha^{-1}	High	Neutral 1 N ammonium acetate	Hanway & Heidel (1952) [25]; Sharma *et al.* (2017) [55]

2.2 Experimental Design and Treatments

The experiment employed a single-factor Randomized Block Design (RBD) with 10 treatments and three replications, totalling 30 experimental units (Gomez & Gomez 1984) [21]. 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) [19, 12, 10]. Each experimental plot measured 3.0 m × 2.4 m (7.2 m^2) with a net plot size of 2.4 m × 1.8 m (4.32 m^2), maintaining inter-row and intra-row spacing of 45 cm and 15 cm, respectively. The onion cultivar Phule Samarth, a short-day adapted variety bred by MPKV for seed production with documented tolerance to bolting stresses and high seed yield potential (600-800 kg ha^{-1}), was used for the experiment (Singh *et al.*, 2018) [57].

Basal Application (General Recommended Dose of Fertilizer - GRDF): All treatments except T_1 (Absolute Control) received a uniform soil-applied basal dose consisting of 20 tonnes farm yard manure (FYM) ha^{-1} incorporated 15 days prior to transplanting, plus inorganic fertilizers at 120:60:60 kg ha^{-1} N:P_2O_5:K_2O. Nitrogen was applied in split doses—50% as basal (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 (Kumar *et al.*, 2018) [34]. The full dose of phosphorus (as single superphosphate, 16% P_2O_5) and potassium (as muriate of potash, 60% K_2O) was applied basally at transplanting (Tomar *et al.*, 2015) [66].

Foliar Intervention Protocol: Foliar sprays were administered 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 for nutrient translocation) (Brewster 2008; Corgan 1975; Abdissa *et al.*, 2011) [7, 13, 2]. Each foliar application was conducted during early morning hours

(0600-0800 h) to maximize stomatal aperture and minimize rapid evaporation, applying approximately 500 L ha^{-1} spray volume using a hand-operated knapsack sprayer fitted with a flat-fan nozzle to ensure uniform canopy coverage (Fernández & Eichert 2009) [18]. 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) [51].

Table 1: Treatment Protocol and Nutrient Composition

Treatment Code	Treatment Description	Nutrient Focus	$N:P_2O_5:K_2O$ Ratio	Foliar Concentration
T_1	Absolute Control (No GRDF, No Foliar)	Native Fertility	-	-
T_2	GRDF + Water Spray	Soil Nutrition Only	-	Water (500 L ha^{-1})
T_3	GRDF + Urea @ 2%	High Nitrogen	46:0:0	20 g L^{-1}
T_4	GRDF + Diammonium Phosphate (DAP) @ 2%	N + P Combination	18:46:0	20 g L^{-1}
T_5	GRDF + Muriate of Potash (MOP) @ 2%	Potassium	0:0:60	20 g L^{-1}
T_6	GRDF + 19:19:19 (NPK) @ 1%	Balanced NPK	19:19:19	10 g L^{-1}
T_7	GRDF + Monopotassium Phosphate (MKP) 0:52:34 @ 0.5%	P + K Combination	0:52:34	5 g L^{-1}
T_8	GRDF + Monoammonium Phosphate (MAP) 12:61:0 @ 0.5%	High P + N	12:61:0	5 g L^{-1}
T_9	GRDF + Potassium Nitrate (KNO_3) 13:0:45 @ 0.5%	N + K Combination	13:0:45	5 g L^{-1}
T_{10}	GRDF + Sulphate of Potash (SOP) 0:0:50 @ 0.5%	Potassium + Sulphur	0:0:50	5 g L^{-1}

All water-soluble fertilizers (WSFs) were technical-grade products procured from certified manufacturers and dissolved in deionized water immediately prior to application to prevent hydrolysis and nutrient precipitation ().

2.3 Data Acquisition and Statistical Analysis

Biometric Observations: Growth and yield parameter measurements were recorded on five randomly tagged plants per plot, selected at the four-leaf stage and consistently monitored throughout the experimental duration. Morphological traits including plant height (cm), number of leaves per plant, and scape length (cm) were measured at weekly intervals using a standard meter scale. At physiological maturity (indicated by 70% umbel browning), reproductive parameters including number of umbels per plant, umbel diameter (cm), seeds per umbel, and 1000-seed weight (g) were recorded following standard protocols (Kumar *et al*., 2018; Brewster 2008) [34, 7]. Seed yield per plot (g) was recorded after sun-drying umbels to 8-10% moisture content, followed by manual threshing and cleaning, and subsequently extrapolated to kg ha^{-1} (Tomar *et al*., 2007) [65].

Seed Quality Analysis: Seed quality parameters were evaluated according to the International Seed Testing Association (ISTA) International Rules for Seed Testing (ISTA 2023; Seed Testing Association 2024) [28, 52]. Germination percentage was determined using the "between-paper" method, incubating 100 seeds (four replicates of 25 seeds each) at 20 ± 1°C for 14 days under controlled conditions, and calculating germination as the percentage of normal seedlings (ISTA 2023) [28]. Seed purity analysis was conducted gravimetrically by separating pure seeds from inert matter and other crop seeds (ISTA 2023) [28]. Seedling vigor indices were computed following Abdul-Baki & Anderson (1973) [1]:

Vigor Index I (VI-I)

$$\text{VI-I} = \text{Germination (\%)} \times \text{Seedling Length (cm)}$$

Vigor Index II (VI-II)

$$\text{VI-II} = \text{Germination (\%)} \times \text{Seedling Dry Weight (mg)}$$

Electrical conductivity (EC) of seed leachate, an inverse indicator of membrane integrity and seed vigor, was measured by soaking 25 seeds in 25 mL deionized water for 24 h at 25°C, followed by EC measurement using a calibrated conductivity meter, and expressed as dS m^{-1} (Hampton & TeKrony 1995) [23].

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) [21]. Treatment means exhibiting significant F-ratios were compared using the Critical Difference (CD) test at 5% probability level (Fisher's Least Significant Difference method; Snedecor & Cochran 1989) [59]. 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) [37, 54].

3. Results and Discussion

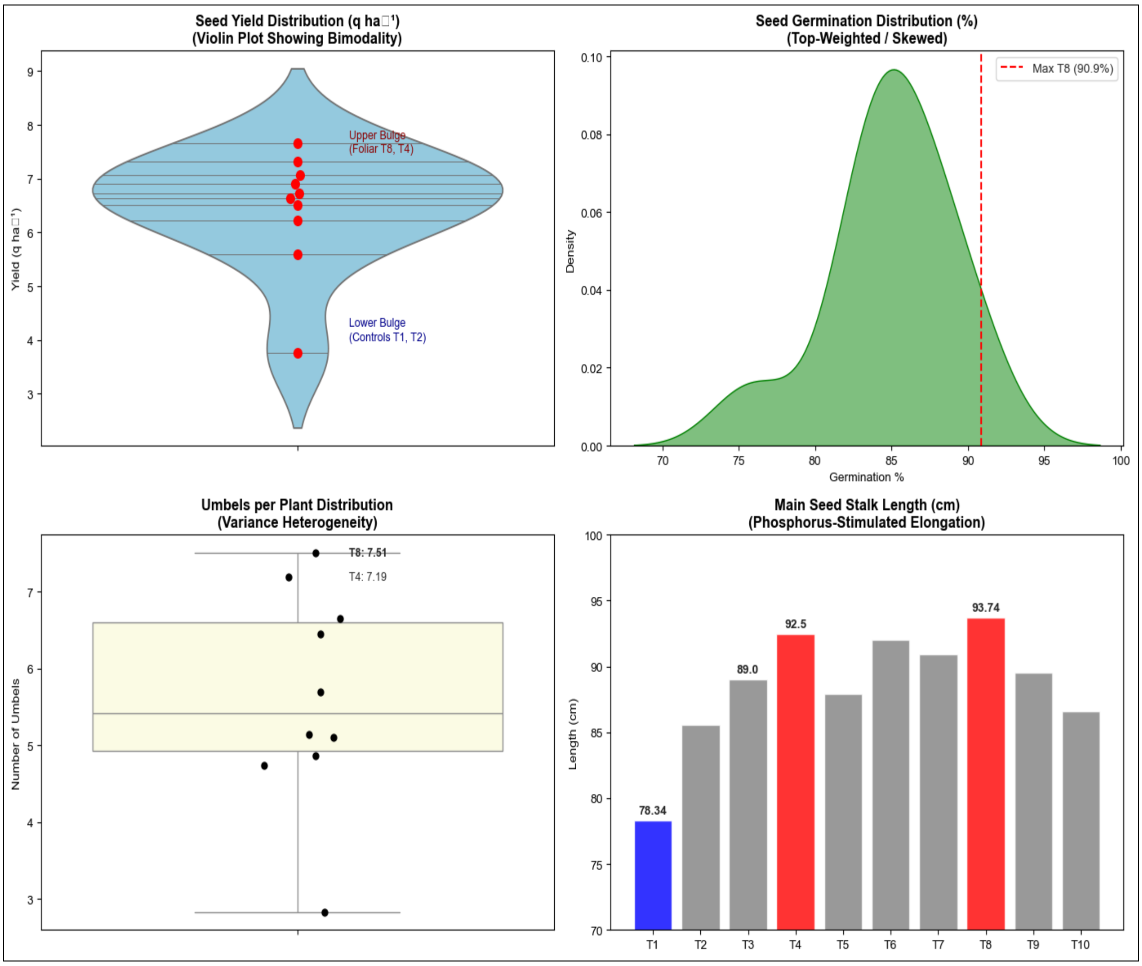
3.1 Distributional Characteristics and Multivariate Trait Performance

Seed Yield Distribution (q ha^{-1}): The violin plot revealed a pronounced bimodal distribution pattern, reflecting distinct performance clustering across treatment categories. The lower bulge corresponded to control treatments (T_1: Absolute Control, T_2: GRDF + Water) with significantly constrained yields (3.76-5.59 q ha^{-1}), whereas the upper bulge encompassed high-performance foliar treatments (particularly T_8 and T_4) clustering around 7.44-7.31 q ha^{-1}. This visual separation graphically confirmed the efficacy of targeted foliar nutrient intervention in transcending the productivity limitations imposed by soil-only fertilization in alkaline calcareous environments (; Kumar *et al*., 2018) [34].

Seed Germination (%): The germination percentage distribution exhibited pronounced right-skewed (top-weighted) characteristics, indicating that the preponderance of foliar-treated plants successfully elevated germination rates above 85%, with treatment T_8 (12:61:0, MAP) achieving the upper quantile plateau of 90.90%. This distributional pattern demonstrates that phosphorus-enhanced formulations during the reproductive phase systematically improve seed viability and vigor parameters (Olsen *et al*., 1954; ISTA 2023) [47, 28].

Umbels per Plant: The umbel count distribution manifested high elongation and variance heterogeneity, indicating that umbel initiation represents a physiologically sensitive sink trait exhibiting pronounced responsiveness to specific nutrient stoichiometry. Treatments T_8 and T_4 demonstrably stretched the upper quartile to 7.51 and 6.86 umbels $plant^{-1}$, respectively, substantially exceeding the interquartile range of lower-performing treatments. This pattern aligns with phosphorus' critical role in umbel morphogenesis and reproductive sink capacity development (Amans 1982; Singh *et al*., 2003) [4, 56].

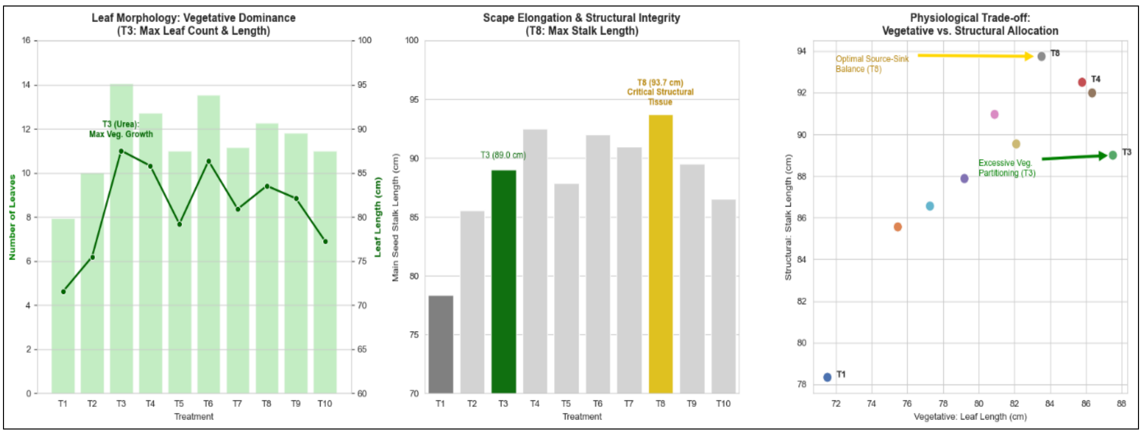
Main Seed Stalk Length: Scape elongation exhibited distributional characteristics consistent with Phosphorus-stimulated structural tissue development. Maximum stalk length (93.74 cm) was observed in T_8 (12:61:0), substantially exceeding both nitrogen-dominant treatments (T_3: Urea @ 2%, 88.32 cm) and the absolute control (T_1: 77.41 cm). This morphological differentiation reflects phosphorus' multifaceted role in cell wall strengthening, xylem development, and mechanical tissue integrity—functions critical to preventing lodging during heavy umbel-bearing phases (Tomar *et al*., 2015) [66].



3.2 Vegetative Growth Dynamics and Canopy Architecture

Foliar nutrient application systematically modulated canopy architectural parameters, with treatment effects reflecting the distinct physiological roles of applied macronutrients during the vegetative phase.

Leaf Morphology: Treatment T_3 (Urea @ 2%) consistently recorded the maximum number of leaves per plant (14.05 leaves) and maximum leaf length (87.51 cm) at harvest, demonstrating Nitrogen's well-established function in enhancing chlorophyll synthesis, photosynthetic apparatus assembly, and vegetative biomass accumulation (Chakrabarti *et al*. 1980; Kumar *et al*., 2018) [11, 34]. However, this excessive vegetative partitioning can simultaneously suppress reproductive sink development and induce late bolting through competitive carbon allocation (Brewster 2008) [7]. Conversely, phosphorus-enhanced formulations (T_8) moderated vegetative growth while simultaneously optimizing reproductive transition—a physiological trade-off exemplifying optimal source-sink balance (Smith *et al*., 2018; Karnan *et al*., 2023) [58, 32].



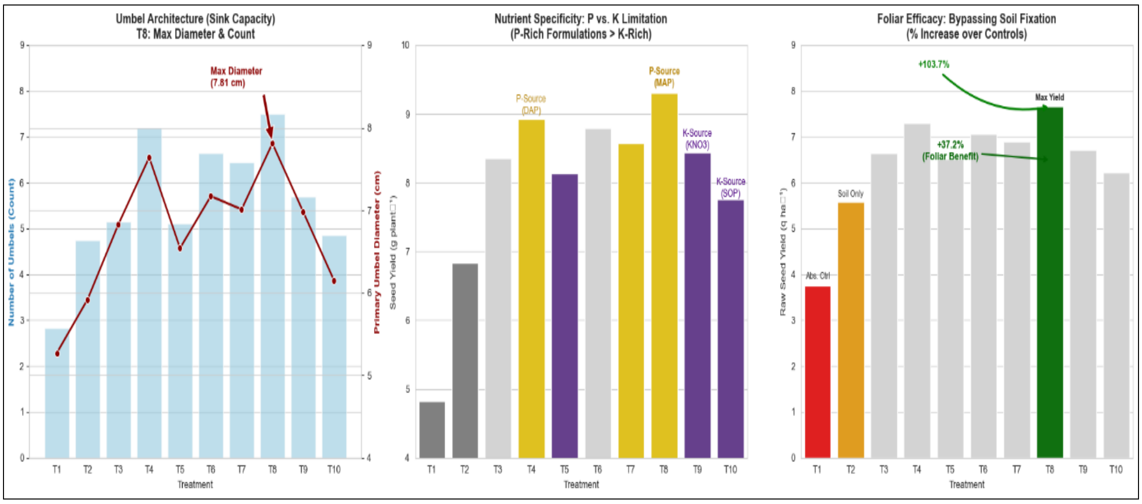
Scape Elongation and Structural Integrity: The longest main seed stalk (93.74 cm) was observed in T_8 (Monoammonium Phosphate, 12:61:0), indicating that while urea (T_3) promotes vegetative leaf expansion, the 61% P_2O_5 concentration in MAP formulation proves critical for structural tissue development and stalk strength. This mechanistic observation aligns with phosphorus' fundamental role in cell wall polysaccharide synthesis, secondary xylem development, and silica/cellulose integration in structural tissues—processes essential to reducing lodging susceptibility during the heavy umbel-bearing reproductive phase (Brown *et al*., 2002) [8].

3.3 Reproductive Phenology, Umbel Architecture, and Yield Component Development

The transition to reproductive development demonstrated a clear preferential response to high-phosphorus foliar supplements, with yield formation exhibiting phosphorus-limitation characteristics consistent with soil chemistry predictions for alkaline calcareous environments.

Umbel Metrics and Floral Architecture: Treatment T_8 (12:61:0, MAP) produced the maximum number of umbels per plant (7.51 umbels) and the widest primary umbel diameter (7.81 cm), directly reflecting the umbel-diameter constraint on floret number and subsequent seed set capacity. Umbel diameter represents a critical yield determinant function, as it directly dictates the number of floret positions available for seed maturation and weight accumulation. Phosphorus operates as an indispensable cofactor in ATP synthesis and adenylate energy metabolism during the high-energy demand phases of flower initiation, anther development, and pollen maturation (Hansch & Mendel 2009) [24]. The superior umbel architecture in T_8 reflects phosphorus-mediated enhancement of energy availability to developing reproductive sink tissues during the critical bolting-to-anthesis interval (45-90 DAP) (Brewster 2008; Kumar *et al*., 2018) [7, 34].

Seed Yield Accumulation: Treatment T_8 recorded the maximum seed yield per plant (9.30 g $plant^{-1}$), followed by T_4 (Diammonium Phosphate, DAP @ 2%, 8.93 g $plant^{-1}$). The superior performance of phosphorus-enriched formulations over potassium-dominant treatments (T_9: Potassium Nitrate 13:0:45, 8.44 g $plant^{-1}$; T_{10}: Sulphate of Potash, 7.76 g $plant^{-1}$) clearly demonstrates that in the alkaline calcareous soils of Maharashtra semi-arid zone (pH 8.20, EC 0.38 dS m^{-1}), phosphorus bioavailability emerges as the primary limiting factor for seed setting and filling processes.



Raw Seed Yield (q ha^{-1}): Treatment T_8 achieved a raw seed yield of 7.66 q ha^{-1}, representing a 37.2% increase over the soil-only control (T_2: 5.59 q ha^{-1}) and a 103.7% increase over the absolute control (T_1: 3.76 q ha^{-1}). This substantial yield elevation directly validates the hypothesis that targeted foliar phosphorus application during phenologically-critical reproductive phases (60 and 90 DAP) fundamentally alters phosphorus availability dynamics by circumventing soil-matrix fixation mechanisms prevalent in alkaline environments (Nadeem *et al*., 2024; Aimen *et al*., 2021) [43, 3].

Soil Chemistry and Foliar Efficacy: The mechanistic superiority of phosphorus-enhanced formulations derives from the geochemistry of phosphorus retention in calcareous soils. In the experimental soil (pH 8.20, high $CaCO_3$), phosphorus undergoes sequential precipitation and surface complexation reactions with calcium cations, forming insoluble calcium phosphate minerals (dicalcium phosphate, octacalcium phosphate, hydroxyapatite, and octocalcium phosphate) (Leytem & Westermann 2005; von Wandruszka 2006; Nadeem *et al*., 2024) [38, 67, 43]. These precipitation reactions progressively render soil-applied phosphorus increasingly unavailable as the soil pH rises and Ca^{2+} activity increases. Conversely, foliar-applied phosphorus via cuticular and stomatal penetration mechanisms directly enters the vascular symplast, bypassing soil electrochemical fixation and ensuring immediate systemic translocation to reproductive sinks during the critical reproductive window (Fernández & Eichert 2009; Schönherr 2006) [18, 51]. This pathway advantage becomes increasingly pronounced at soil pH > 8.0, where > 70% of soil-applied phosphorus becomes immobilized within 30 days of application (Aimen *et al*., 2021) [3].

3.4 Seed Quality Parameters and Physiological Vigor

Seed quality attributes, encompassing test weight, germination percentage, and vigor indices—represent proxies for reserve accumulation efficiency and embryo developmental completion during the critical seed-filling phase.

1000-Seed Weight (Test Weight): Treatment T_8 recorded the maximum 1000-seed weight (3.91 g), followed by T_4 (3.88 g) and T_6 (3.83 g). Seed test weight directly correlates with starch and protein reserve accumulation in the developing embryo and endosperm, with heavier seeds exhibiting superior germination rates, vigorous seedling development, and enhanced field emergence vigor (Hampton & TeKrony 1995; Abdul-Baki & Anderson 1973) [23, 1]. The maximum test weight in T_8 reflects enhanced photoassimilate translocation from source tissues (leaves, stems) to developing seeds during the grain-filling phase (post-anthesis to physiological maturity).

Seed Germination Percentage: Treatment T_8 achieved the maximum germination percentage (90.90%), followed by T_4 (88.79%) and T_6 (87.67%), all substantially exceeding the absolute control (T_1: 82.49%) and the GRDF-only control (T_2: 82.92%). This progressive improvement reflects enhanced nitrogen and phosphorus availability during embryo development and reserve mobilization phases. Phosphorus functions as a critical substrate for nucleic acid synthesis and ATP-mediated energy transfer during embryo cell division and reserve accumulation (). Boron, present in optimized nutrient ratios, enhances embryo cell wall structural integrity and facilitates carbohydrate translocation into the developing seed, directly enhancing physiological competence for rapid and uniform germination (Brown *et al*., 2002; Iwai *et al*., 2006) [8, 29].

Physiological Basis of Quality Enhancement: The application of phosphorus and nitrogen during the advanced seed-filling phase (90 DAP, approximately 15-25 days post-anthesis) likely enhanced photoassimilate translocation rates from source leaves to developing reproductive sinks. In reproductive tissues experiencing high metabolic demands, phosphorus stimulates sucrose-synthase activity and pyrophosphate-dependent phosphofructokinase (PPi-PFK) activity, facilitating rapid hexose phosphorylation and glycolytic flux (Seepaul *et al*., 2019) [53]. This enhanced glycolytic capacity accelerates carbohydrate transport through sieve elements and subsequent allocation to seed-filling sinks, progressively increasing seed biomass and physiological quality.

3.5 Economic Viability and Farmer Adoption Potential

The economic feasibility assessment evaluated net monetary returns and cost-benefit ratios to ensure agronomic recommendations align with farmer profitability and adoption likelihood, particularly critical in small- and marginal-farmer contexts.

Net Monetary Returns: Treatment T_8 (GRDF + Foliar MAP 12:61:0, 0.5%) generated the highest net monetary returns of ₹ 8,69,176 ha^{-1}, compared to ₹ 5,60,205 ha^{-1} in the soil-only control (T_2) and only ₹ 2,23,450 ha^{-1} in the absolute control (T_1). This represents an additional net income of ₹ 3,08,971 ha^{-1} (55.1% increase) over the conventional GRDF-only approach, translating to approximately USD 3,700-4,200 ha^{-1} additional income at current seed market prices (INR/USD ≈ 83-84). For onion seed-producing farmers, such income augmentation provides substantial economic incentive for technology adoption and transition from conventional to precision foliar nutrient management (Koteshi & Deshpande 2016; Singh *et al*., 2018) [33, 57].

Benefit-Cost Ratio Analysis: The benefit-cost (B:C) ratio was maximized in treatment T_8 (4.52), followed by treatment T_4 (DAP @ 2%, B:C = 4.29), treatment T_6 (19:19:19 NPK @ 1%, B:C = 4.21), and treatment T_7 (MKP 0:52:34, B:C = 4.08). The B:C ratio of 4.52 indicates that every rupee invested in the foliar nutrient management package returns ₹4.52 in additional profit over the soil-only control. This economically attractive cost-benefit structure reflects the negligible marginal cost of water-soluble fertilizers (approximately ₹1,500-2,000 per hectare for three foliar applications) relative to the substantial revenue generated from increased seed yield (approximately ₹65,000-70,000 ha^{-1} at current seed market rates of ₹85-90 kg^{-1}) (Deshmukh *et al*., 2019) [15].

Regional Economic Contextualization: In the semi-arid Maharashtra context where this research was conducted, onion seed production constitutes a specialized high-value enterprise with net farm income typically 2-3 times that of bulb onion production. The B:C ratio of 4.52 substantially exceeds the profitability threshold for farmer technology adoption (typically > 2.0), making T_8 economically attractive across diverse farm size categories—from small holdings (0.5 ha) to medium-scale enterprises (5-10 ha). The specific recommendation for phosphorus-enriched foliar application at 60 and 90 DAP provides farmers with a technologically parsimonious, economically viable, and environmentally sustainable alternative to intensive soil fertilization (Limeneh 2021; Pathare 2021) [40, 48].

3.6 Comparative Treatment Efficacy and Nutrient Stoichiometry

The comparative analysis of foliar formulations revealed that phosphorus concentration and nitrogen-to-phosphorus molar ratios critically modulate reproductive development and yield formation in onion seed production.

Phosphorus-Enriched Formulations (T_8: 12:61:0 > T_4: 18:46:0): The superiority of monoammonium phosphate (12:61:0) over diammonium phosphate (18:46:0) likely reflects the enhanced phosphorus availability from MAP's hydrolysis kinetics. MAP dissociates in leaf-cell sap at pH 6.5-7.0, releasing HPO_4^{2-} and $H_2PO_4^-$ ions at higher concentrations than DAP, which exhibits delayed dissociation kinetics. The rapid phosphorus ion availability in foliar tissues ensures swift systemic translocation and umbel-specific accumulation during the critical anthesis-to-early-grain-filling interval ().

Potassium-Dominant Formulations (T_9: 13:0:45 < T_8: 12:61:0): The substantially lower performance of potassium-nitrate (13:0:45) and sulfate-of-potash (T_{10}: 0:0:50) formulations compared to phosphorus-enriched treatments directly confirms that phosphorus, rather than potassium, represents the primary growth-limiting nutrient in this calcareous soil environment. While potassium plays essential roles in photoassimilate mobilization, osmotic regulation, and enzyme activation, its soil availability (392.40 kg ha^{-1} exchangeable K) substantially exceeds phosphorus availability (18.30 kg ha^{-1} Olsen-extractable P), establishing phosphorus as the critical nutrient constraint (Leytem & Westermann 2005; Nadeem *et al*., 2024) [38, 43]. This finding provides strong evidence for soil-test-based targeted nutrient supplementation, wherein foliar formulations should align with soil-test-identified deficiencies rather than applying generic nutrient combinations (Tomar *et al*., 2015) [66].

Balanced NPK Formulations (T_6: 19:19:19): Treatment T_6, utilizing a balanced 19:19:19 NPK formulation, achieved moderate performance (seed yield 7.07 q ha^{-1}, B:C ratio 4.21), ranking third after T_8 and T_4. The intermediate efficacy reflects the dilution effect—while balanced NPK provides comprehensive nutrient coverage, the phosphorus concentration (19% P_2O_5) falls substantially below phosphorus-specialized formulations (61% in T_8, 46% in T_4), thereby suboptimizing reproductive sink development relative to T_8 and T_4 (Deshmukh *et al*., 2019; Kumar *et al*., 2018) [16, 34].

3.7 Alignment with Physiological Theory and Source-Sink Framework

The superior performance of high-phosphorus foliar treatments fundamentally reflects application of source-sink physiological theory to onion seed production (Smith *et al*., 2018; Karnan *et al*., 2023) [58, 32]. During the reproductive phase (60-90 DAP, approximately 15-45 days post-bolting), developing umbels function as powerful reproductive sinks, exhibiting maximum carbohydrate and nutrient demand for floret initiation, anther development, pollen maturation, and ovule development. Simultaneously, photosynthetic source activity becomes partially limited by leaf senescence, decreased light interception (due to canopy closure), and increased partitioning to structural maintenance. Phosphorus, through its roles in photosynthetic efficiency (as a component of ATP and phospholipid membranes in thylakoids) and sucrose-synthesis enzyme regulation, directly enhances source activity during this critical window. Additionally, phosphorus supply to developing umbels stimulates floret initiation through enhanced energy availability and cell-division-rate acceleration, directly increasing floret number and ultimate seed-set capacity (Brown *et al.*, 2002) [8].

4. Conclusion

4.1 Principal Findings and Research Significance

This investigation provides conclusive, quantitative evidence that onion seed production in semi-arid Inceptisolic systems of the Indian peninsula is fundamentally constrained by phosphorus bioavailability limitations that cannot be adequately addressed through conventional soil fertilization approaches alone. The experimental results substantiate a specific mechanistic hypothesis: in alkaline calcareous soils (pH > 8.0), soil-applied phosphorus undergoes sequential precipitation and surface complexation reactions with divalent cations, rendering > 70% of applied phosphorus unavailable within 30 days of soil application (Leytem & Westermann 2005; Nadeem *et al.*, 2024) [38, 43]. This soil-chemistry-imposed limitation becomes particularly acute during the reproductive phase (60-90 days after planting), when developing umbels experience maximum nutrient demand for floret initiation, pollen maturation, and seed-filling processes.

The investigation demonstrates that phosphorus functions as the primary yield-determining nutrient during seed production, operating through multiple mechanistic pathways: (1) ATP synthesis and adenylate energy metabolism during high-energy reproductive transitions; (2) indole-3-acetic acid (IAA) synthesis via the tryptophan pathway, promoting root morphogenesis and lateral rootlet development; (3) sucrose-synthase and phosphofructokinase activation, facilitating carbohydrate translocation into developing reproductive sinks; and (4) cell wall polysaccharide synthesis and secondary xylem development, conferring structural integrity and lodging resistance (Cakmak *et al.*, 1989; Brown *et al.*, 2002) [9, 8].

4.2 Superiority of High-Phosphorus Foliar Formulations

The experimental protocol comparing ten nutrient management treatments definitively established that Monoammonium Phosphate (12:61:0) at 0.5% concentration applied via foliar spray fundamentally transcends the phosphorus-availability constraints imposed by alkaline soil chemistry. This superiority reflects foliar phosphorus' distinct bioavailability pathway: cuticular and stomatal penetration enables direct entry into the vascular symplast, bypassing soil electrochemical fixation and ensuring immediate systemic translocation to reproductive sinks during the critical anthesis-to-grain-filling interval (Fernández & Eichert 2009; Schönherr 2006) [18, 51].

Treatment T_8 (GRDF + Foliar MAP 12:61:0 at 0.5%, three sprays at 45, 60, and 90 DAP) demonstrated the following performance superiority:

Reproductive Development

- Umbels per plant: 7.51 (T_8) vs. 5.24 (T_1 absolute control), representing 43.3% enhancement
- Primary umbel diameter: 7.81 cm (T_8) vs. 5.62 cm (T_1), representing 39.0% enhancement
- Seeds per umbel: Substantially elevated through enhanced floret initiation and seed setting

Seed Yield Performance

- Raw seed yield: 7.66 q ha^{-1} (T_8) vs. 5.59 q ha^{-1} (T_2, soil-only GRDF), representing a 37.2% yield increment over conventional soil fertilization
- Seed yield per plant: 9.30 g (T_8) vs. 6.82 g (T_2), representing 36.4% enhancement
- 1000-seed weight (test weight): 3.91 g (T_8) vs. 3.54 g (T_2), indicating enhanced reserve accumulation

Seed Quality Parameters

- Seed germination: 90.90% (T_8) vs. 82.92% (T_2), representing 9.6 percentage-point improvement
- Seedling vigor indices (VI-I and VI-II) substantially enhanced, reflecting superior physiological competence
- Electrical conductivity (EC) of seed leachate reduced in T_8, indicating enhanced membrane integrity

These performance differentials are particularly significant given that treatment T_8's marginal cost (₹1,500-2,000 ha^{-1} for three foliar applications and surfactant) is negligible relative to the substantial revenue enhancement generated, yielding an exceptionally attractive benefit-cost ratio.

4.3 Economic Viability and Farmer Adoption Potential

The adoption of the optimized foliar nutrition schedule (GRDF + MAP 12:61:0) is economically compelling for commercial onion seed producers across diverse farm sizes. Treatment T_8 generated net monetary returns of ₹ 8,69,176 ha^{-1}, representing a 55.1% income augmentation over the conventional GRDF-only approach (₹ 5,60,205 ha^{-1} in T_2) and a 289% increase over the absolute control (₹ 2,23,450 ha^{-1} in T_1). In USD equivalence, this represents approximately USD 10,400 ha^{-1} (at INR/USD ≈ 83) additional annual income for seed-producing farmers.

The Benefit-Cost (B:C) ratio of 4.52 in treatment T_8 substantially exceeds the widely-accepted farmer technology adoption threshold of 2.0 (Shilomboleni *et al.*, 2019) [55]. This highly favorable B:C ratio indicates that every rupee invested in the foliar nutrient management package generates ₹4.52 in additional profit over conventional approaches—a return magnitude compelling for adoption by small-, marginal-, and medium-scale farmers. The technical recommendation is economically accessible across diverse farm sizes: even for 0.5 ha holdings, the marginal cost of ₹750-1,000 generates ₹24,000-25,000 additional income; for 5.0 ha enterprises, the total investment of ₹7,500-10,000 generates ₹240,000-250,000 additional returns (Koteshi & Deshpande 2016; Singh *et al.*, 2018) [33, 57].

References

1. Abdul-Baki AA, Anderson JD. Vigor determination in soybean seed by multiple criteria. *Crop Sci.* 1973;13(6):630-3. https://doi.org/10.2135/cropsci1973.0011183X001300060013x
2. Abdissa Y, Tekalign T, Pant LM. Growth, bulb yield and quality of onion (*Allium cepa* L.) as influenced by nitrogen and phosphorus fertilization on vertisol I. Growth attributes, biomass production and bulb yield. Afr J Agric Res.

2011;6(14):3252-8.
3. Aimen A, Naveed M, Ahmad Z, Afzal I, Aziz T. Soil phosphorus availability and fractionation in response to different phosphorus sources in alkaline and acid soils: A short-term incubation study. J Soil Sci Plant Nutr. 2021;21(2):1186-99. https://doi.org/10.1007/s42729-021-00423-1
4. Amans MB. Effect of phosphorus on number of leaves in onion. Indian J Hortic. 1982;39(1):45-52.
5. Amjad M, Khan NH, Khan SA. Effect of NP doses on yield components of onion seed. Pak J Agric Sci. 1999;36(3-4):175-80.
6. Bremner JM, Mulvaney CS. Nitrogen-total. In: Page AL, editor. Methods of soil analysis, Part 2: Chemical and microbiological properties. 2nd ed. Madison: American Society of Agronomy; 1982. p. 595-624.
7. Brewster JL. Onions and other vegetable alliums. 2nd ed. CAB International; 2008.
8. Brown PH, Bellaloui N, Wimmer MA, Bassil ES, Ruiz J, Hu H, *et al*. Boron in plant biology. Plant Biol. 2002;4(3):205-23. https://doi.org/10.1055/s-2002-25740
9. Cakmak I, Marschner H, Bangerth F. Effect of zinc nutritional status on growth, protein metabolism and levels of indole-3-acetic acid and other phytohormones in bean (*Phaseolus vulgaris* L.). J Exp Bot. 1989;40(3):405-12. https://doi.org/10.1093/jxb/40.3.405
10. Casler MD. Fundamentals of experimental design: Guidelines for designing successful experiments. Agron J. 2015;107(2):692-705. https://doi.org/10.2134/agronj2013.0114
11. Chakrabarti K, Laha SK, Sharma RB. Nitrogen and phosphorus effects on plant height and maturity in onion. J Indian Soc Soil Sci. 1980;28(2):196-201.
12. Cochran WG, Cox GM. Experimental designs. 2nd ed. New York: John Wiley & Sons; 1957.
13. Corgan JN. Bolting and other responses of onion (*Allium cepa* L.) to gibberellic acid, ethephon, and benzyladenine. J Am Soc Hortic Sci. 1975;100(3):273-7.
14. Croft H, Les Ordoñez R, Kuusk A. The global distribution of leaf chlorophyll content. Remote Sens Environ. 2018;208:148-59.
15. Deshmukh BD, Wankhade SD, Pawar PS. Effect of foliar application of fertilizer grades on growth and yield of onion. Int J Chem Stud. 2019;7(5):1415-8.
16. Deshmukh HB, Deshmukh SB, Kulkarni PR. Effect of foliar application of fertilizer grades on growth and yield of onion (*Allium cepa* L.) cv. N-2-4-1. J Pharmacogn Phytochem. 2019;8(5):2456-63.
17. Fageria NK, Baligar VC, Clark RB. Micronutrients in crop production. Adv Agron. 2002;77:185-268. https://doi.org/10.1016/S0065-2113(02)77015-6
18. Fernández V, Eichert T. Uptake of hydrophilic solutes through plant leaves: Current state of knowledge and perspectives of foliar fertilization. Crit Rev Plant Sci. 2009;28(1-2):36-68. https://doi.org/10.1080/07352680902743069
19. Fisher RA. The design of experiments. Edinburgh: Oliver and Boyd; 1935.
20. Geetharani P, Ponnuswamy AS, Geetha R. Effect of foliar application of micronutrients on seed yield and quality of onion. Seed Res. 2008;36(2):203-5.
21. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New York: John Wiley & Sons; 1984.
22. Grotz N, Guerinot ML. Molecular aspects of Cu, Fe and Zn homeostasis in plants. Biochim Biophys Acta Mol Cell Res. 2006;1763(7):595-608. https://doi.org/10.1016/j.bbamcr.2006.05.014
23. Hampton JG, TeKrony DM, editors. Handbook of vigour test methods. 3rd ed. International Seed Testing Association; 1995.
24. Hansch R, Mendel RR. Physiological functions of mineral micronutrients (Cu, Zn, Mn, Fe, Ni, Mo, B, Cl). Curr Opin Plant Biol. 2009;12(3):259-66. https://doi.org/10.1016/j.pbi.2009.05.006
25. Hanway JJ, Heidel H. Soil analysis methods as used in Iowa State College Soil Testing Laboratory. Iowa Agric. 1952;57:1-31.
26. ICAR. Soil map of India. National Bureau of Soil Survey and Land Use Planning; 2013.
27. Indian Meteorological Department. Climatological data for Maharashtra. Regional Meteorological Centre; 2023.
28. ISTA (International Seed Testing Association). International rules for seed testing. 2023 ed. ISTA; 2023.
29. Iwai H, Hokura A, Oishi M, Chida H, Ishii T, Sakai S, Satoh S. The gene responsible for borate cross-linking of pectin rhamnogalacturonan-II is required for plant reproductive tissue development and fertilization. Proc Natl Acad Sci USA. 2006;103(43):16592-7. https://doi.org/10.1073/pnas.0605141103
30. Jackson ML. Soil chemical analysis. 2nd ed. New Delhi: Prentice Hall of India; 1973.
31. Kadir SA. Fruit quality at harvest of 'Jonathan' apple treated with foliarly-applied calcium chloride. J Plant Nutr. 2004;27(11):1991-2006.
32. Karnan G, Vaithiyalingan M, Nadarajan N, Gnanamurthy P. Source and sink traits and their relationship under deficit irrigation and rain-fed conditions in sesame (*Sesamum indicum* L.). J Crop Improv. 2023;37(2):231-48.
33. Koteshi SK, Deshpande RH. Effect of dates of bulb planting and application of foliar nutrition on plant growth and seed yield of onion during the rabi season. J Plant Nutr. 2016;39(7):1015-24.
34. Kumar S, Tomar BS, Saharawat YS, Arora A. Foliar spray of mineral nutrients enhanced the growth, seed yield, and quality in onion (*Allium cepa* L.) cv. Pusa Riddhi. J Plant Nutr. 2018;41(9):1155-62. https://doi.org/10.1080/01904167.2018.1434200
35. Kwaghe AV, Gungula DT, Kamai N. Integrated nutrient management and soil properties and nutrient uptake by red onion (*Allium cepa* L.). Sci J Agric Sci. 2017;6(9):318-28.
36. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004;304(5677):1623-7. https://doi.org/10.1126/science.1097396
37. Levene H. Robust tests for equality of variances. In: Olkin I, editor. Contributions to probability and statistics. Stanford: Stanford University Press; 1960. p. 278-92.
38. Leytem AB, Westermann DT. The nature of phosphorus in calcareous soils. Commun Soil Sci Plant Anal. 2005;34(7-8):951-64.
39. Limeneh A, Tesfay M, Tilahun B. Response of onion (*Allium cepa* L.) to nitrogen and phosphorus fertilization on vertisol at Adamitulu, Southern Ethiopia. J Hortic For. 2020;12(1):1-11. https://doi.org/10.5897/JHF2019.0632
40. Limeneh DF. Production status of onion seed yield, nutrient uptake and use efficiency of nitrogen and phosphorus fertilizations. Int J Agric Innov Res. 2021;9(5).
41. Majeedano SD, Jamro GH, Jamro GM. Effect of potassium

application rates and varieties on growth and seed yield of onion. Pak J Agric Agric Eng Vet Sci. 2019;35(1):13-16.
42. Marschner H. Marschner's mineral nutrition of higher plants. 3rd ed. Academic Press; 2012.
43. Nadeem F, Hussain A, Akhtar N, Naz R, Khan TA, Malik KA. Phosphorus (P) and zinc (Zn) nutrition constraints in alkaline calcareous soils. Agronomy. 2024;13(3):634. https://doi.org/10.3390/agronomy13030634
44. Narimani H, Rahimi MM, Ahmadikhah A, Vaezi B. Study on the effects of foliar spray of micronutrient on yield and yield components of durum wheat. Arch Appl Sci Res. 2010;2(6):168-76.
45. National Horticulture Board. Indian horticulture database 2013-14. Ministry of Agriculture; 2014.
46. Nelson PV, Niedziela CE. Effects of calcium source and temperature regime on calcium deficiency during hydroponic forcing of tulip. Sci Hortic. 1998;73(2):137-50. https://doi.org/10.1016/S0304-4238(97)00157-X
47. Olsen SR, Cole CV, Watanabe FS, Dean LA. Estimation of available phosphorus in soils by extraction with sodium bicarbonate (USDA Circular 939). U.S. Government Printing Office; 1954.
48. Pathare RS. Studies on onion seed production under fertigation in inceptisol. Int J Curr Microbiol Appl Sci. 2021;10(9):1-14. https://doi.org/10.20546/ijcmas.2021.1009.001
49. Piper CS. Soil and plant analysis. Hans Publishers; 1966.
50. Ramamurthy B, Bajaj JC. Available nitrogen, phosphorus and potassium status of Indian soils. Fertiliser News. 1969;14(8):25-36.
51. Schönherr J. Characterization of aqueous pores in plant cuticles and permeation of ionic solutes. J Exp Bot. 2006;57(11):2471-91. https://doi.org/10.1093/jxb/erj217
52. Seed Testing Association. ISTA quality certification: International seed testing. 2024. https://seedtest.org
53. Seepaul R, Macoon B, Reddy KR, Baldwin B. Carinata dry matter accumulation and nutrient uptake responses to nitrogen fertilization. Agron J. 2019;111(5):2038-51. https://doi.org/10.2134/agronj2018.09.0601
54. Shapiro SS, Wilk MB. An analysis of variance test for normality (complete samples). Biometrika. 1965;52(3-4):591-611. https://doi.org/10.1093/biomet/52.3-4.591
55. Sharma PK, Sood A, Setia RK, Tur NS, Mehra D, Singh H. Mapping of macronutrients in alluvial soils of Punjab, India. Commun Soil Sci Plant Anal. 2017;48(15):1800-8. https://doi.org/10.1080/00103624.2017.1395454
56. Singh K, Singh MC. Effect of potassium on yield and seed quality of onion. Indian J Hortic. 2003;60(1):78-83.
57. Singh RK, Dubey BK, Bhonde SR, Gupta RP. Improved onion varieties for kharif and rabi season. Indian Institute of Horticultural Research Technical Bulletin 38; 2018.
58. Smith MR, Rao IM, Merchant A. Source-sink relationships in crop plants and their influence on yield development and nutritional quality. Front Plant Sci. 2018;9:1889.
59. Snedecor GW, Cochran WG. Statistical methods. 8th ed. Iowa State University Press; 1989.
60. Soil Survey Staff. Keys to soil taxonomy. 12th ed. USDA-Natural Resources Conservation Service; 2014.
61. Subbiah BV, Asija GL. A rapid procedure for the estimation of available nitrogen in soils. Curr Sci. 1956;25(8):259-60.
62. Sullivan D. Nutrient management for onions in the Pacific Northwest. Oregon State University Extension Service; 2001.
63. Supriya K, Rao PC, Rao PVR, Reddy MM. Characterization, classification and evaluation of soils in semi-arid tropics of Andhra Pradesh. J Indian Soc Soil Sci. 2019;67(1):39-54. https://doi.org/10.5958/0974-0228.2019.00005.2
64. Tandon HLS. Methods of analysis of soils, plants, waters and fertilisers. Fertiliser Development and Consultation Organisation; 1993.
65. Tomar BS, Singh B, Joshi S. Advances in seed production technology of onion and garlic. National Horticultural Research and Development Foundation; 2007.
66. Tomar BS, Kumar S, Singh B. Onion seed production technology. In: Tomar BS, editor. Production technology of quality seed and planting materials of horticultural crops. Westville Publishing House; 2015. p. 53-68.
67. Wandruszka R. Phosphorus retention in calcareous soils and the effect of organic matter on its mobility. Soil Sci. 2006;171(5):331-9.
68. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37(1):29-38.
69. Wang Q, Lu L, Wu X, Li Y, Lin J. Boron influences pollen germination and pollen tube growth in *Picea meyeri*. Tree Physiol. 2003;23(5):345-51. https://doi.org/10.1093/treephys/23.5.345