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Effect of NPK Slow-Release Fertilizer Diameter and Zeolite Particle Size on Phosphorus Uptake and Yield Quality of Shallot (*Allium ascalonicum* L.) Grown in Inceptisol

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Abstract— *Shallot (Allium ascalonicum L.) is a high-value horticultural crop with increasing demand due to population growth. However, the availability of productive agricultural land to expand shallot cultivation is declining. Inceptisols are widely distributed and have potential for cultivation, but their physical and chemical limitations often restrict crop productivity. The application of slow-release NPK fertilizer (NPK-SR) combined with natural zeolite is expected to improve nutrient availability and enhance soil quality in Inceptisol. This study aimed to determine the optimal diameter of NPK-SR fertilizer and zeolite particle size, as well as their interaction effects on phosphorus (P) uptake and yield quality of shallot. The experiment was conducted in pots using a randomized complete block design (RCBD) with two factors: NPK-SR diameter (control, 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm) and zeolite particle size (60 mesh and 100 mesh), each with three replications. Observed variables included P uptake, bulb diameter, bulb volume, bulb firmness, bulb color, bulb aroma, vitamin C content, and bulb water content. The results showed that different diameters of NPK-SR fertilizer did not significantly affect all observed variables. Zeolite particle size significantly affected bulb firmness. A significant interaction between NPK-SR diameter and zeolite particle size was observed for vitamin C content, with the best combination obtained from 5 mm NPK-SR fertilizer and 60 mesh zeolite, producing the highest vitamin C content of 0.96%.*

Keywords— Shallot, slow-release fertilizer, zeolite, phosphorus uptake, Inceptisols.

I. INTRODUCTION

Shallot (*Allium ascalonicum* L.) is an economically important horticultural crop widely cultivated in tropical and subtropical regions. It plays a significant role in food security and agro-based economies due to its high market value and its use as a culinary spice and medicinal plant (1). Increasing demand for shallots, driven by population growth and expanding food industries, requires sustainable intensification strategies, particularly in areas where fertile agricultural land is limited. However, the expansion of productive agricultural land is limited, necessitating the optimization of marginal soils to sustain crop productivity.

Inceptisols are among the most widely distributed soil orders globally and are commonly used for crop production (2). These soils are characterized by weak horizon development and moderate weathering. Although generally considered productive, their agricultural performance is often constrained by moderate organic matter content, suboptimal structure, and nutrient limitations (2,3). Inceptisols are widely distributed agricultural soils characterized by moderate development and high phosphorus fixation capacity due to the presence of Fe and Al oxides (4,5). In such soils, applied phosphorus rapidly becomes unavailable, reducing fertilizer use efficiency and increasing production costs (6). One of the major constraints in Inceptisols is low phosphorus (P) availability due to adsorption and fixation by iron (Fe) and aluminum (Al) oxides, particularly under acidic conditions (3,7). Phosphorus plays a critical role in plant metabolism, including energy transfer (ATP), root

development, and bulb formation in shallots. However, the efficiency of applied P fertilizer rarely exceeds 20–30% because of rapid immobilization and precipitation reactions in soil (7).

Improving nutrient use efficiency through controlled-release fertilizers has received increasing attention in sustainable agriculture (8). Slow-release NPK fertilizers (NPK-SR) are designed to release nutrients gradually in synchrony with crop demand, thereby reducing nutrient losses and enhancing fertilizer efficiency (8,9). The physical properties of fertilizer granules, particularly granule diameter, may significantly influence dissolution kinetics and nutrient diffusion in soil. Larger granules generally exhibit slower nutrient release rates due to lower surface area-to-volume ratios, potentially improving synchronization between nutrient availability and plant uptake (9).

Zeolite, a naturally occurring aluminosilicate mineral with high cation exchange capacity (CEC) and adsorption properties, has been widely studied as a soil amendment (7). Its porous structure enhances nutrient retention, reduces leaching losses, and improves soil moisture dynamics (10,11). In addition, zeolite particle size may influence its reactivity and effectiveness. Smaller particle sizes provide greater specific surface area, potentially enhancing adsorption capacity and nutrient exchange processes (11). The integration of zeolite with controlled-release fertilizers has been reported to improve nutrient retention and increase fertilizer efficiency under various soil conditions (12).

Although numerous studies have examined controlled-release fertilizers or zeolite individually, limited information is available regarding the interaction between fertilizer granule diameter and zeolite particle size under Inceptisol conditions. Understanding this interaction is important to optimize nutrient-use efficiency and improve horticultural crop quality. Therefore, this study aimed to: (1) determine the optimal granule diameter of NPK slow-release fertilizer; (2) evaluate the effect of zeolite particle size; and (3) analyze their interaction on phosphorus uptake and yield quality of shallot cultivated in Inceptisol.

II. MATERIALS AND METHODS

2.1 Study Site and Experimental Period:

The experiment was conducted in a screen house at the Experimental Farm and Soil Science Laboratory, Faculty of Agriculture, Jenderal Soedirman University, Purwokerto, Indonesia (7°15'05"–7°37'10" S; 108°39'17"–109°27'15" E). The study was carried out from December 2021 to July 2022.

2.2 Soil and Plant Materials:

The soil used in this study was classified as Inceptisol. The soil was air-dried, homogenized, and sieved (2 mm) prior to use. Initial soil chemical properties (pH, organic matter, available P, and CEC) were analyzed before treatment application.

Shallot (*Allium ascalonicum* L.) bulbs of the Bima variety were used as planting material. Each polybag (45 cm × 45 cm) was filled with homogenized soil and planted with four uniform bulbs.

Natural zeolite was applied in two particle sizes:

- 60 mesh (Z1)
- 100 mesh (Z2)

The slow-release NPK fertilizer (NPK-SR) was prepared in different granule diameters (1–5 mm). Other fertilizers used included urea, KCl, and BFA (phosphate fertilizer), adjusted according to treatment design.

2.3 Experimental Design:

The experiment was arranged in a 6 × 2 factorial design using a randomized complete block design (RCBD) with three replications.

Factor 1: NPK-SR granule diameter

- P0: Control (no NPK-SR application)
- P1: 1 mm
- P2: 2 mm
- P3: 3 mm

- P4: 4 mm
- P5: 5 mm

Factor 2: Zeolite particle size

- Z1: 60 mesh
- Z2: 100 mesh

A total of 12 treatment combinations were obtained, resulting in 36 experimental units (12 treatments × 3 replications). Each experimental unit consisted of four plants grown in a polybag.

2.4 Treatment Application:

Fertilizer treatments (NPK-SR combined with zeolite) were applied every 7 days for 6 weeks according to the predetermined dosage for each treatment. Zeolite was thoroughly mixed with soil prior to planting to ensure uniform distribution.

Irrigation and crop management practices were carried out uniformly for all treatments throughout the experimental period.

2.5 Observed Variables:

2.5.1 Plant and Yield Parameters:

The following variables were measured:

- Phosphorus uptake (mg P clump^{-1})
- Bulb diameter (mm)
- Bulb volume (cm^3)
- Bulb firmness (kg cm^{-2})
- Bulb color (visual scoring on a scale of 1-5)
- Bulb aroma (organoleptic assessment on a scale of 1-5)
- Vitamin C content (%)
- Bulb water content (%)

Phosphorus uptake was determined at the end of the vegetative phase (±35 days after planting, DAP). Leaf samples were collected and subjected to wet digestion using H_2SO_4 and H_2O_2. Phosphorus concentration was measured using a spectrophotometer at 889 nm following the molybdenum blue method (Soil Research Institute, 2009). P uptake was calculated by multiplying tissue P concentration by plant dry weight.

Yield quality analysis (vitamin C content, firmness, water content, and other parameters) was performed after harvest. Vitamin C content was determined using titration method.

2.5.2 Environmental Parameters:

Environmental variables recorded during the experiment included:

- Air temperature (°C)
- Relative humidity (%)
- Light intensity (Lux)
- Soil pH

Temperature, humidity, and light intensity were measured daily (morning, midday, and afternoon) using thermohygrometers and lux meters. Soil pH was measured at the end of the experiment using a pH meter in a soil–water suspension (1:2.5 ratio).

2.6 Statistical Analysis:

Data were analyzed using analysis of variance (ANOVA) at a 5% significance level to evaluate the effects of NPK-SR granule diameter, zeolite particle size, and their interaction. When significant differences were detected, mean separation was

performed using Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$. Data from sensory analysis (organoleptic variables) were followed by an effectiveness index test to determine the best treatment. The treatment that shows the highest observed results significantly compared to other treatments is considered the best treatment.

All statistical analyses were conducted using appropriate statistical software.

III. RESULTS AND DISCUSSION

The analysis of variance showed that NPK-SR granule diameter did not significantly affect phosphorus (P) uptake, bulb diameter, bulb volume, firmness, color, aroma, vitamin C content, or water content. Zeolite particle size significantly influenced bulb firmness, whereas a significant interaction between NPK-SR granule diameter and zeolite particle size was observed only for vitamin C content.

TABLE 1
ANALYSIS OF VARIANCE (ANOVA) FOR EFFECTS OF NPK-SR GRANULE DIAMETER AND ZEOLITE PARTICLE SIZE ON SHALLOT PARAMETERS

No.	Variable	Fertilizer Diameter (P)	Zeolite Size (Z)	Interaction (P × Z)
1	P Uptake	ns	ns	ns
2	Bulb Diameter	ns	ns	ns
3	Bulb Volume	ns	ns	ns
4	Bulb Firmness	ns	s	ns
5	Bulb Color	ns	ns	ns
6	Bulb Aroma	ns	ns	ns
7	Bulb Water Content	ns	ns	ns
8	Vitamin C Content	ns	ns	s

Note: s = significant (p<0.05); ns = not significant

The limited response of most variables suggests that under Inceptisol conditions, modifications in fertilizer physical size alone were insufficient to significantly alter nutrient availability dynamics. In highly buffered soils, nutrient release rate may be overridden by fixation and adsorption processes (13,14).

3.1 Effect of NPK-SR Granule Diameter on P Uptake and Quality of Shallot:

TABLE 2
EFFECT OF NPK-SR GRANULE DIAMETER ON PHOSPHORUS UPTAKE AND YIELD QUALITY OF SHALLOT

Fertilizer Diameter (mm)	P Uptake (mg P/clump)	Bulb Diameter (mm)	Bulb Volume (cm^3)	Bulb Firmness ($kg\ cm^{-2}$)	Bulb Color (1-5)	Bulb Aroma (1-5)	Bulb Water Content (%)	Vitamin C Content (%)
P0 (control)	0.13a	15.23a	2.67a	6.11a	3.43a	2.37a	88.78a	0.49a
P1 (1 mm)	0.12a	12.81a	2.15a	6.19a	3.87a	2.59a	86.27a	0.59a
P2 (2 mm)	0.13a	14.54a	2.74a	6.08a	3.77a	2.82a	88.74a	0.55a
P3 (3 mm)	0.14a	13.96a	2.43a	5.89a	3.21a	2.55a	87.70a	0.48a
P4 (4 mm)	0.12a	14.14a	2.58a	6.10a	3.64a	2.87a	88.78a	0.54a
P5 (5 mm)	0.13a	15.16a	2.44a	5.86a	3.71a	2.61a	86.07a	0.69a
F count	0.24	1.42	0.82	0.24	0.38	1.64	0.39	0.89
F table (5%)	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53
C.V. (%)	24.57	12.91	22.99	10.74	5.71	35.71	5.71	35.71

Note: Numbers followed by the same letter in the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at 5% level. P1 = NPK-SR diameter 1 mm, P2 = NPK-SR diameter 2 mm, P3 = NPK-SR diameter 3 mm, P4 = NPK-SR diameter 4 mm, P5 = NPK-SR diameter 5 mm.*

3.1.1 Phosphorus Uptake (mg P/clump):

The results showed that the application of NPK-SR fertilizer with various diameters (1-5 mm) did not have a significant effect on the P uptake of shallots (Table 2). This finding indicates that variations in granule size did not substantially modify P

dissolution or plant availability during the cropping period. In Inceptisols, phosphorus is prone to fixation by Fe and Al oxides, which limits mobility regardless of release kinetics (15). Recent studies on controlled-release fertilizers indicate that physical modification of granule size influences nutrient release rate; however, its agronomic effectiveness depends strongly on soil chemical properties (16,17). Therefore, soil buffering capacity may have neutralized potential differences in release patterns among granule sizes.

3.1.2 Bulb Diameter (mm):

The application of NPK-SR fertilizer with various diameters did not have a significant effect on shallot bulb diameter (Table 2). This is because bulb formation depends on cumulative nutrient uptake, particularly nitrogen and potassium during the vegetative-to-bulbing transition (18). Since P uptake did not differ significantly, bulb growth response remained uniform. This suggests that granule size variation alone is insufficient to enhance macronutrient use efficiency unless accompanied by improved soil nutrient retention mechanisms.

3.1.3 Other Quality Traits:

The results of the analysis of variance showed that the application of NPK-SR fertilizer with different diameters did not have a significant effect on shallot quality variables including bulb volume, bulb firmness, bulb color, bulb aroma, vitamin C content, and bulb water content (Table 2). This is because quality traits are influenced by nutrient balance and physiological stability rather than solely by nutrient release rate (19). Nitrogen metabolism and stress regulation play major roles in vitamin C biosynthesis (20). Similar nutrient availability across treatments likely resulted in comparable metabolic responses.

3.2 Effect of Zeolite Particle Size on P Uptake and Yield Quality of Shallot:

TABLE 3
EFFECT OF ZEOLITE PARTICLE SIZE ON PHOSPHORUS UPTAKE AND YIELD QUALITY OF SHALLOT

Zeolite Size (mesh)	P Uptake (mg P/clump)	Bulb Diameter (mm)	Bulb Volume (cm^3)	Bulb Firmness (kg cm^{-2})	Bulb Color (1-5)	Bulb Aroma (1-5)	Bulb Water Content (%)	Vitamin C Content (%)
Z1 (60 mesh)	0.13a	14.25a	2.55a	6.28a	3.72a	2.63a	88.84a	0.58a
Z2 (100 mesh)	0.13a	14.36a	2.45a	5.80b	3.49a	2.64a	86.61a	0.53a
F count	0.01	0.03	0.27	5.02*	0.53	0.01	1.79	0.59
F table (5%)	4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13
C.V. (%)	24.57	12.91	22.99	10.74	5.71	35.71	5.71	35.71

Note: Numbers followed by different letters in the same column are significantly different according to Duncan's Multiple Range Test (DMRT) at 5% level. Z1 = 60 mesh zeolite, Z2 = 100 mesh zeolite. * = significant at p<0.05.*

3.2.1 Phosphorus Uptake (mg P/clump):

The application of zeolite with different sizes did not give significant results on plant P uptake (Table 3). Although finer particles provide greater surface area and higher cation exchange capacity, excessive fineness may reduce macroporosity and alter soil physical structure (21). Improvements in nutrient retention do not always directly translate into higher plant uptake (22).

3.2.2 Bulb Firmness (kg cm^{-2}):

The sizing treatment of natural zeolite showed significant results on bulb firmness. The 60 mesh zeolite showed higher firmness (6.28 kg cm^{-2}) than the 100 mesh zeolite (5.80 kg cm^{-2}) (Table 3). The size of the zeolite can affect the bulk density which is related to ion absorption. Moderately coarse zeolite likely improved soil water regulation and structural stability without excessively reducing pore space. Previous research has demonstrated that zeolite amendments can enhance soil moisture retention and mechanical support for root systems, leading to improved crop quality (23,24). Excessively fine particles may compact soil microstructure, reducing oxygen diffusion and root expansion, which indirectly affects bulb firmness.

3.2.3 Other Quality Traits:

The application of zeolite with different sizes did not have a significant effect on other quality traits including bulb diameter, bulb volume, bulb color, bulb aroma, vitamin C content, and bulb water content (Table 3). This indicates that within the tested range, zeolite size had limited influence on nutrient dynamics sufficient to alter overall yield formation. Similar results showed that administration of zeolite with differences in size did not make a difference in the moisture content of shallot bulbs (25).

3.3 Interaction of NPK-SR Fertilizer Diameter and Zeolite Particle Size on P Uptake and Shallot Quality:

TABLE 4
INTERACTION EFFECTS OF NPK-SR GRANULE DIAMETER AND ZEOLITE PARTICLE SIZE ON SHALLOT PARAMETERS

Treatment	P Uptake (mg P/clump)	Bulb Diameter (mm)	Bulb Volume (cm^3)	Bulb Firmness ($kg\ cm^{-2}$)	Bulb Color (1-5)	Bulb Aroma (1-5)	Bulb Water Content (%)	Vitamin C Content (%)
P0Z1	0.13a	14.98a	2.48a	6.44a	3.43a	2.19a	85.94a	0.52b
P0Z2	0.13a	15.49a	2.85a	5.78a	3.43a	2.56a	91.61a	0.47b
P1Z1	0.12a	14.09a	2.81a	6.71a	3.96a	2.56a	90.81a	0.63ab
P1Z2	0.12a	11.52a	1.48a	5.67a	3.79a	2.63a	81.73a	0.54b
P2Z1	0.12a	13.68a	2.54a	6.18a	3.51a	3.12a	91.45a	0.45b
P2Z2	0.13a	15.39a	2.94a	5.98a	4.04a	2.52a	86.03a	0.66ab
P3Z1	0.12a	13.66a	2.39a	6.11a	3.69a	2.56a	89.41a	0.49b
P3Z2	0.15a	14.26a	2.46a	5.68a	2.73a	2.53a	85.99a	0.47b
P4Z1	0.14a	15.25a	2.85a	6.21a	4.08a	2.88a	89.39a	0.45b
P4Z2	0.11a	13.02a	2.31a	5.99a	3.20a	2.87a	88.17a	0.63ab
P5Z1	0.14a	13.84a	2.22a	6.03a	3.67a	2.48a	86.04a	0.96a
P5Z2	0.12a	16.48a	2.65a	5.69a	3.75a	2.73a	86.11a	0.42b
F count	0.74	1.93	2.27	0.37	0.55	1.37	1.52	2.78*
F table (5%)	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53
C.V. (%)	24.57	12.91	22.99	10.74	5.71	35.71	5.71	35.71

Note: Numbers followed by different letters in the same column are significantly different according to Duncan's Multiple Range Test (DMRT) at 5% level. P1 = NPK-SR diameter 1 mm, P2 = NPK-SR diameter 2 mm, P3 = NPK-SR diameter 3 mm, P4 = NPK-SR diameter 4 mm, P5 = NPK-SR diameter 5 mm, Z1 = 60 mesh zeolite, Z2 = 100 mesh zeolite. * = significant interaction at $p<0.05$.*

A significant interaction between NPK-SR granule diameter and zeolite particle size was observed only for vitamin C content. The combination of 5 mm granules and 60 mesh zeolite (P5Z1) produced the highest vitamin C concentration (0.96%), which was significantly different from other treatment combinations. This suggests that gradual nutrient release from larger granules combined with optimized nutrient retention by moderately coarse zeolite may have improved nitrogen synchronization during critical metabolic stages. Controlled nutrient availability has been shown to influence secondary metabolite accumulation, including ascorbic acid (26,27). Although primary yield components were not significantly affected, this interaction indicates that physical optimization of fertilizer and soil amendment characteristics may influence metabolic quality traits rather than biomass production.

IV. CONCLUSION

1. Variation in NPK-SR granule diameter (1–5 mm) did not significantly influence phosphorus uptake or yield parameters of shallot grown in Inceptisol. Zeolite particle size significantly affected bulb firmness, with 60 mesh providing superior quality compared to 100 mesh.
2. A significant interaction between fertilizer granule diameter and zeolite particle size was observed for vitamin C content, indicating that combined physical optimization of fertilizer and soil amendment characteristics may enhance

nutritional quality traits. The best treatment interaction was the P5Z1 treatment (NPK-SR fertilizer 5 mm and 60 mesh natural zeolite), which produced the highest vitamin C content of 0.96%.

3. Overall, while granule size modification alone did not improve nutrient uptake efficiency, integration of controlled-release fertilizer with appropriately sized zeolite demonstrates potential for improving crop quality in highly buffered soils.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript

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