Original Article

Role of Variety, Fertilizer Composition, and Planting Density and Its Interaction on the Agronomic Traits of Shallots

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Abstract

The productivity of shallot from true seed (*Allium ascalonicum* L.) is influenced by the interaction of genetic, nutritional, and spatial factors. This study aimed to evaluate the combined effects of variety, foliar fertilizer composition, and planting density on shallot growth and yield. The experiment was conducted from June to September 2024 at the Hasanuddin University Experimental Farm, Makassar, Indonesia (5°7′40.07″ S, 119°28′48.94″ E), using a split-split plot design with three varieties (Lokananta, Merdeka F1, Sanren F1), three foliar fertilizer packages, and two planting densities (single and double seedlings per hole). Analysis of variance showed significant ($p < 0.05$) three-way interactions among variety, fertilizer, and density for plant height, dry biomass, and bulb weight. The maximum plant height (58.41 cm) was recorded in Merdeka F1 with fertilizer package A and double seedlings, while the greatest dry biomass (54.30 g) occurred in Sanren F1 with fertilizer package C and single seedlings. The maximum bulb fresh weight (41.72 g) was achieved in Lokananta under package A with single seedlings. Fertilizer package C produced the highest bulb dry weight (33.09 g) and yield (22.06 g per plant), representing a 35% increase over package A. Single-seedling planting yielded 21.34 g compared with 16.39 g under double planting. A strong positive correlation ($r = 0.95$) was found between bulb dry weight and total yield. These results confirm that optimal combinations of variety, fertilizer composition, and planting density substantially enhance shallot productivity under controlled conditions.

Keywords: Allium ascalonicum L., fertilizer, foliar, seedling

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Introduction

Shallots, scientifically known as *Allium ascalonicum*, are one of the most significant horticultural crops in Indonesia. This bulbous vegetable is highly esteemed not only for its rich flavor and versatility in culinary applications but also for its myriad health benefits, which contribute to its status as a staple in the local diet. It is often used to enhance the taste of various traditional Indonesian dishes, adding depth and complexity to flavors integral to Indonesian cuisine (4, 31). Beyond its culinary importance, shallots are recognized for their nutritional value, containing essential vitamins and minerals, as well as antioxidants that support overall health. These properties have made shallots a popular choice for health-conscious consumers, further embedding them into the cultural and economic fabric of the region. The cultivation of shallots plays a crucial role in Indonesia's agricultural landscape, providing livelihoods for numerous farmers and contributing significantly to the local economy. As demand continues to grow, shallots not only support dietary practices but also contribute to economic stability, underscoring their importance in both health and commerce within the Indonesian context **(29, 32)**.

One effective strategy that can be implemented is to significantly increase the number of shallot plants in each area. Nevertheless, the details concerning the rise in production stemming from the expanding population of shallot plants have not been extensively researched. In various vegetable crops, increased planting density significantly boosts yield per unit area by optimizing light interception and nutrient utilization efficiency, ultimately resulting in a more profitable harvest and contributing to regional food security. Higher planting densities increase the number of plants per unit area, which directly boosts the total yield per hectare. For instance, in Brussels sprouts, the maximum yield per hectare was achieved at a planting density of 0.49 m^2 per plant **(38)**. Similarly, in onions, higher densities reduced bulb diameter and fresh mass but increased total yield **(8)**.

Furthermore, in semi-bush tropical pumpkins, higher planting densities were linked to improved yields **(41)**. Likewise, in winter canola, greater densities enhanced sunlight capture and yield, with ideal densities noted at 60-80 plants per square meter, balancing yield with resistance to lodging **(40)**. In winter wheat, combining higher plant density with wide seedling strip planting significantly increased grain yield by enhancing dry matter production and light interception **(44)**. For rice, a high-density planting method raised yields by up to 20.17% for specific varieties, highlighting the potential of density management in rice farming **(21)**.

However, it is important to consider the potential disadvantages of high-density planting, including intensified competition for resources among plants and increased vulnerability to pests and diseases. In maize, increasing plant density significantly increased grain yield per hectare, although it reduced yield per plant. The best results were achieved with high-density planting combined with high nitrogen levels **(3)**. In cannabis, higher density increased yield per area but reduced cannabinoid uniformity, highlighting a trade-off between yield and product quality **(7)**. Balancing these factors is essential for optimizing crop production, as farmers must carefully assess the specific needs of each crop and their growing conditions to achieve sustainable yields without compromising quality.

In Indonesia, the development and use of true shallot seed (TSS) have gained increasing attention as an efficient and disease-free propagation method compared to traditional bulb planting. Several TSS varieties exhibit distinct agronomic characteristics that influence their adaptability and yield potential. In this study, Lokananta, Merdeka F1, and Sanren F1 were selected because they represent the commercially available TSS varieties currently distributed to farmers.

Fertilization practices also play a vital role in determining shallot productivity, particularly under intensive cultivation systems. In this study, foliar fertilizers with varying nutrient compositions were applied to represent different nutrient balance strategies. These formulations contained major macronutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium, along with essential micronutrients including sulfur, iron, boron, zinc, and copper. The variation among fertilizer compositions was designed to examine how different nutrient balances influence growth, bulb development, and yield potential when interacting with variety and planting density.

To prove this phenomenon, an interaction study was conducted on plant density, variety, and fertilizer packages to examine their effects on shallot productivity. This study aims to provide insights into how different combinations of plant density, variety selection, and fertilizer application can influence the overall productivity of shallots, ultimately guiding farmers in making informed decisions to enhance their agricultural practices. The results of this study will not only highlight the optimal conditions for shallot growth but also contribute to a broader understanding of how precision agriculture techniques can be employed to maximize both yield and quality in various crops.

Materials and Methods

Plant Materials

The experiment was conducted from June to September 2024 at the Hasanuddin University Experimental Farm, located at 5°7'40.07" S latitude and 119°28'48.94" E longitude, at an elevation of 9 meters above sea level. A 120 m^2 net house utilized for this research was equipped with a 50-mesh anti-aphid screen on its sides and roof and supported by an aluminum frame. Its west-southwest orientation was selected to optimize sunlight exposure while reducing excess heat, offering a semi-controlled microclimate that ensured homogeneity across the experimental plots.

The soil used in the experiment had a pH of 6.58 and contained 3.52% organic carbon and 0.28% total nitrogen, with a C/N ratio of 13. The available phosphorus (P_2O_5) content was 12.28 ppm, and the exchangeable potassium was 0.28 cmol kg^{-1}. The soil also showed a cation exchange capacity (CEC) of 19.65 cmol kg^{-1}, indicating a moderate nutrient-holding capacity.

Experimental Design and Procedures

The study followed a split-split plot design involving three factors: shallot variety, fertilizer package, and seedling number per planting hole. The main plots consisted of three shallot varieties: Lokananta, characterized by deep green leaves and purple bulbs (4–6 bulbs per plant); Merdeka F1, with green foliage and red-purple bulbs (4–8 bulbs per plant); and Sanren F1, featuring dark green leaves and red bulbs (2–4 bulbs per plant). The subplot factor was the fertilizer composition, with three packages (A, B, and C) containing different concentrations of macronutrients and micronutrients (**Table 1**).

Table 1. Fertilizer composition of the shallot experiments

Nutrients	Fertilizer Package (%)		
	A	B	C
N	24.64	18.60	24.96
P	5.40	5.60	4.63
K	35.50	28.80	35.49
Ca	18.45	13.00	15.43
Mg	5.38	5.60	7.33
S	10.05	9.60	11.57
Fe	0.31	0.09	0.31
B	0.08	0.02	0.08
Zn	0.03	0.02	0.02
Cu	0.03	0.04	0.01
Mo	0.03	0.001	0.01
Na	0.01	-	-
Cl	-	-	0.10

The nutrients in the foliar fertilizer packages were derived from commonly used analytical-grade salts. Nitrogen (N) was supplied from urea and ammonium nitrate, while phosphorus (P) originated from mono-potassium phosphate (KH_2PO_4). Potassium (K) was provided through potassium nitrate (KNO_3) and potassium sulfate (K_2SO_4), depending on the formulation. Calcium (Ca) was derived from calcium nitrate [$Ca(NO_3)_2$], and magnesium (Mg) from magnesium sulfate ($MgSO_4 \cdot 7H_2O$). Sulfur (S) was contributed by ammonium sulfate and magnesium sulfate. Micronutrients were added in soluble or chelated forms: iron (Fe) as Fe-EDTA, boron (B) as boric acid (H_3BO_3), zinc (Zn) as zinc sulfate ($ZnSO_4 \cdot 7H_2O$), copper (Cu) as copper sulfate ($CuSO_4 \cdot 5H_2O$), and molybdenum (Mo) as sodium molybdate ($Na_2MoO_4 \cdot 2H_2O$). Sodium (Na) was provided in trace amounts from sodium nitrate ($NaNO_3$), and chlorine (Cl) from potassium chloride (KCl) in Package C. These ingredients were precisely mixed and dissolved in water to produce foliar solutions reflecting the specific nutrient ratios for each fertilizer package.

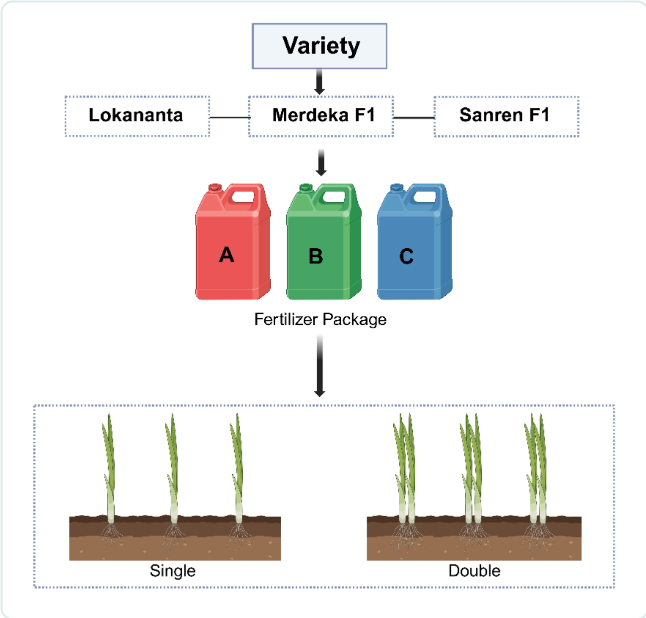

Figure 1. Experimental model

The sub-subplot consisted of seedling numbers per planting hole: single (90 plants per plot) or double (180 plants per plot). Each treatment combination was replicated three times, resulting in a total of 54 experimental units (**Fig. 1**).

Seedlings were grown from true shallot seeds and sown in a nursery tank filled with a growth medium composed of equal parts soil, compost, and biochar (1:1:1) (v/v/v). Furrows were made 0.5 cm deep with 10 cm spacing, and seeds were irrigated twice daily. Leaf pruning was conducted 20, 25, and 30 days after sowing by removing a quarter of the leaf length, a method adapted from Faried et al. (2024) to encourage robust root development. After 45 days, the seedlings were ready for transplanting into field plots.

Each plot measured 1 × 1 meter with a bed height of 30 cm and 50 cm spacing between beds. Black plastic mulch was applied to suppress weed growth and retain soil moisture. Planting holes were arranged in a 10 × 15 cm grid pattern, totaling 90 holes per plot. Transplanting was done in the afternoon to reduce transplant stress. Post-transplant management included twice-daily irrigation and biweekly application of insecticides and fungicides for pest and disease control.

Fertilizers were applied through foliar spraying at three intervals of 15, 30, and 45 days after transplanting. The volume of application increased with each stage, beginning with 750 mL per plot at the first application, followed by 1000 mL and 1250 mL for the second and third applications, respectively. Morning applications ensured higher absorption efficiency and minimized nutrient loss due to evaporation. Foliar feeding was selected to enhance nutrient uptake in the plastic-mulched environment, allowing precise control over dosage and timing.

Assessments and Data Analysis

The shallots were harvested once physiological maturity was evident, indicated by leaf senescence and bulb protrusion above the soil. Plants were manually uprooted and sun-dried for one week to determine dry biomass and bulb dry weight. The following agronomic traits were measured: plant height (cm) at 45 days after transplanting; number of bulbs per plant; fresh biomass (g); dry biomass (g); bulb fresh weight (g); bulb dry weight (g); bulb diameter (mm); and yield (g per plot). Measurements were taken from ten representative plants per plot, avoiding border rows to prevent edge effects.

Data were analyzed using analysis of variance (ANOVA), a suitable statistical test for a split-split plot design, to identify significant main effects and interactions. Duncan's multiple range test (DMRT) was applied at a significance level of $p < 0.05$ for pairwise comparisons among treatment means. RStudio version 4.4.1 **(28)** was employed for all statistical analyses and data visualization. Additionally, Pearson correlation analysis was performed to explore relationships among vegetative growth traits and yield parameters, with particular emphasis on identifying predictive traits for yield enhancement.

Results and Discussion

Results

The analysis of variance reveals the significance of the interaction effects between varieties, fertilizer package, and seedling number on several agronomic traits of shallot plants (Table 2). The p-values indicate that plant height, fresh biomass, dry biomass, bulb fresh weight, bulb dry weight, and yield were significantly affected by the different factors and their interactions. The interactions between variety, fertilizer package, and seedling number had significant effects on plant height ($p \leq 0.05$), dry biomass ($p \leq 0.01$), and bulb fresh weight ($p \leq 0.05$), indicating that treatment combinations have a crucial role in optimizing plant growth and productivity.

Table 2. Analysis of variance for agronomic traits for tested shallot varieties, fertilizer package and planting density

Treatment	P-Value							
	PH	NOB	FB	DB	BFW	BDW	BD	Y
V	<0.01	0.01	0.37	<0.01	0.05	0.08	<0.01	0.08
F	0.13	0.09	<0.01	<0.01	<0.01	<0.01	0.36	<0.01
V × F	<0.01	0.47	0.04	<0.01	<0.01	0.47	0.16	0.47
S	0.95	0.94	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
S × V	<0.01	0.01	0.26	<0.01	0.25	0.14	0.10	0.14
S × F	<0.01	0.32	<0.01	<0.01	0.03	0.45	0.21	0.45
S × V × F	0.05	0.06	0.22	<0.01	0.02	0.81	0.68	0.81

Note: (**) p-value≤0.01; (*) 0.01>p-value≤0.05; (ns) p-value>0.05. Plant height (PH), number of bulbs (NOB), fresh biomass (FB), dry biomass (DB), bulb fresh wight (BFW), bulb dry weight (BDW), bulb diameter (BD), and Y (yield).

Plant Height

Table 3 presents the results of plant height measurements based on the interaction between variety, fertilizer package, and seedling number. The maximum plant height was observed in the Merdeka F1 variety with a double seedling number under fertilizer package A (58.41 cm), followed by Sanren F1 with a double seedling number under fertilizer package C (57.16 cm). Meanwhile, the lowest height was for the Lokananta variety with a double seedling number under fertilizer package A (47.50 cm). These results indicate that different treatment combinations produced varying plant heights. The Merdeka F1 variety generally produced greater plant heights across all treatment combinations compared to Lokananta and Sanren F1. The double seedling number resulted in higher plant heights than the single seedling ones in most treatments. Fertilizer package A tended to produce higher plant heights, especially in the Merdeka F1 variety.

Table 3. Effect of interaction between varieties, fertilizer package, and seedling number on plant height

Variety	Fertilizer package	Seedling number	
		Single	Double
Lokananta	A	50.83efg	47.5fh
	B	53.91bcd	49.75fgh
	C	53.16cde	49.00gh
Merdeka F1	A	53.33cde	**58.41a**
	B	50.33efgh	50.67efg
	C	52.33def	55.91abc
Sanren F1	A	50.91defg	53.00cde
	B	56.25ab	51.67defg
	C	52.25def	57.16a

Note: means followed by the same letter are not significantly different at p < 0.05 according to Duncan's multiple range test (DMRT).

Number of Bulbs

The number of bulbs per plant varied significantly across different shallot varieties and seedling numbers. The Sanren F1 and Merdeka F1 varieties produced the highest numbers, averaging 4.89 and 4.80 bulbs per plant, respectively, compared to the Lokananta's 4.11 bulbs per plant. Under single seedling planting, Merdeka F1 produced significantly more bulbs at 5.33 than under double seedling planting (4.27 bulbs), indicating that reducing intra-plant competition can enhance bulb multiplication. **(Table 4)**

Table 4. Effect of varieties and its interaction with seedling number on number of bulbs per plant

Variety	Number of bulbs
Lokananta	4.11b
Merdeka F1	4.80a
Sanren F1	**4.89a**
Variety × Seedling Number	**Number of bulbs**
Lokananta × single	3.67c
Lokananta × double	4.55abc
Merdeka F1 × single	**5.33a**
Merdeka F1 × double	4.27bc
Sanren F1 × single	4.83ab
Sanren F1 × double	4.94ab

Note: means followed by the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test (DMRT).

Fresh Biomass

Fresh biomass production was significantly influenced by both the fertilizer package and the number of seedlings, with the highest (43.43 g) observed for the package A fertilizer and single seedling planting combination. The application of fertilizer package C resulted in higher fresh biomass, likely due to its role in improving soil fertility and nutrient availability. Single seedling planting consistently yielded higher fresh biomass compared to double seedlings, with a difference of more than 8 g, indicating that reduced competition allows plants to allocate more resources to vegetative growth. **(Table 5)**

Table 5. Effect of fertilizer package, seedling number and its interaction on fresh biomass per plant

Fertilizer package	Fresh biomass
A	35.69b
B	34.27b
C	39.36a
Seedling number	**Fresh biomass**
Single	40.58a
Double	32.30b
Seedling number × fertilizer package	**Fresh biomass**
Single × A	**43.43a**
Single × B	38.64a
Single × C	39.67a
Double × A	27.95b
Double × B	29.90b
Double × C	39.05a

Note: means followed by the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test (DMRT).

Dry Biomass

Dry biomass was significantly affected by the interaction between variety, fertilizer package, and seedling number. The highest dry biomass (54.30 g) was recorded in Sanren F1 under fertilizer package C and single seedling planting method, while the lowest was in Lokananta under the fertilizer package A and double seedling planting method. This suggests that these treatments enhance the accumulation of dry matter in shallot plants. Single seedling planting generally produced higher dry biomass, reinforcing the positive effect of reduced competition on biomass production. **(Table 6)**

Table 6. Effect of fertilizer package, seedling number and its interaction on dry biomass per plant

Variety	Fertilizer package	Seedling number	
		Single	Double
Lokananta	A	42.64bc	16.55g
	B	31.96ef	32.40ef
	C	35.17cde	23.87fg
Merdeka F1	A	44.14b	31.10ef
	B	28.05ef	19.31g
	C	27.51ef	46.57b
Sanren F1	A	34.08de	31.69ef
	B	40.54bcd	27.67ef
	C	44.67b	**54.30a**

Note: means followed by the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test (DMRT).

Bulb Fresh Weight

The interaction of variety, fertilizer package, and seedling number influenced bulb fresh weight. The highest bulb fresh weight (41.72 g) was observed in Lokananta under fertilizer package A with single seedling planting, while the lowest bulb fresh weight (18.13 g) was recorded in Merdeka F1 under fertilizer package B with double seedling planting. This outcome suggests that fertilizer package C promotes bulb development and water retention, both of which are essential for achieving a marketable yield. Double-seedling planting consistently produced lower bulb fresh weights, due possibly to competition for water and nutrients. **(Table 7)**

Table 7. Effect of interaction between varieties, fertilizer package, and seedling number on bulb fresh weight

Variety	Fertilizer package	Seedling number	
		Single	Double
Lokananta	A	41.72a	23.19ef
	B	32.47bcd	26.76cde
	C	31.41bcd	24.80def
Merdeka F1	A	27.54cde	25.99cde
	B	31.19bcd	18.13f
	C	33.03bc	28.11bcde
Sanren F1	A	31.24bcd	20.78ef
	B	35.92ab	26.21cde
	C	35.77ab	41.10a

Note: means followed by the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test (DMRT).

Bulb Diameter

Bulb diameter was significantly affected by both variety and the number of seedlings. Larger bulbs were associated with Lokananta (35.00 mm) and Sanren F1 (33.00 mm), particularly under single seedling planting (28.87 mm) as against double seedlings (25.34 mm), suggesting that less competition enables plants to allocate more resources to bulb expansion. **(Table 8)**

Table 8. Effect of varieties and seedling number on bulb diameter per plant

Variety	Bulb diameter
Lokananta	35.00a
Merdeka F1	13.32b
Sanren F1	33.00a
Seedling number	**Bulb diameter**
Single	28.87a
Double	25.34b

Note: means followed by the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test (DMRT).

Bulb Dry Weight

Bulb dry weight and yield were significantly influenced by fertilizer package and seedling number. The highest bulb dry weight (33.09 g) and yield (22.06 g) were recorded under fertilizer package C with single seedling planting, indicating their positive effect on shallot productivity. Single-seedling planting consistently produced higher bulb dry weight and yield compared to double-seedling planting, emphasizing the importance of planting density in optimizing yield outcomes. **(Table 9)**

Table 9. Effect of fertilizer package and seedling number on bulb dry weight and yield

Fertilizer Package	Bulb Dry Weight	Yield
A	25.33b	16.89b
B	26.48	17.65b
C	33.09a	22.06a
Seedling Number	**Bulb Dry Weight**	**Yield**
Single	32.02a	21.34a
Double	24.58	16.39b

Note: means followed by the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test (DMRT).

Correlation Analysis among Seedling Traits

The correlation analysis among seedling traits revealed significant positive relationships between plant height, fresh biomass, dry biomass, bulb fresh weight, bulb dry weight, and yield. The strongest correlation was observed between bulb dry weight and yield ($r = 0.95$), suggesting that improvements in vegetative growth parameters contribute to higher bulb yield. This finding highlights the interconnectedness of agronomic traits in shallot production, underscoring the importance of integrated management strategies.

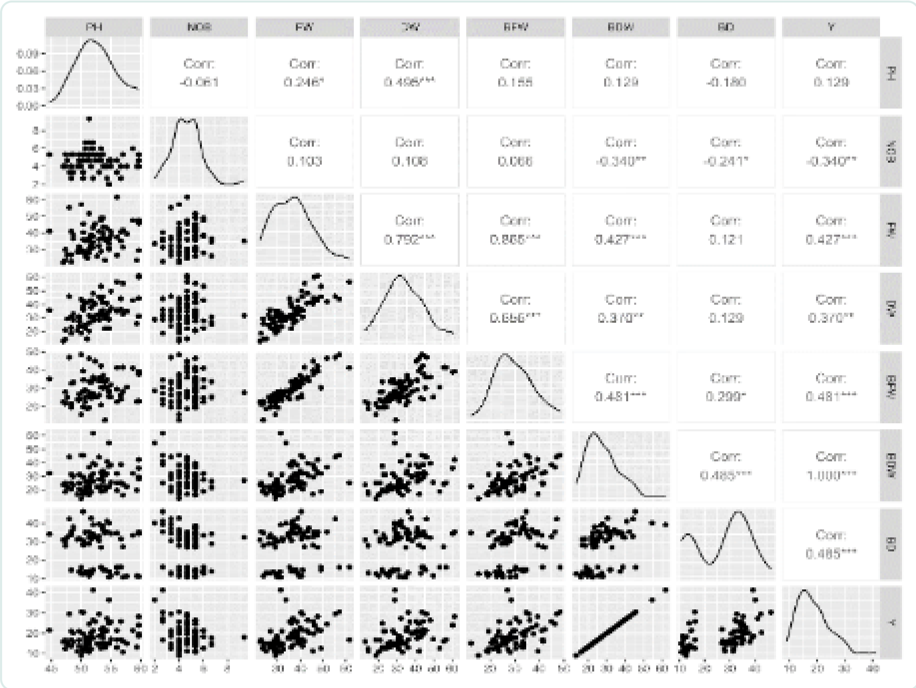

Figure 2. Correlation analysis among seedling traits. Plant height (PH), number of bulbs (NOB), fresh biomass (FB), dry biomass (DB), bulb fresh wight (BFW), bulb dry weight (BDW), bulb diameter (BD), and Y (yield).

Discussion

Influence of Variety on Growth and Yield Attributes

The shallot varieties under study exhibited significant differences in growth and yield traits, highlighting the pivotal role of genotype in determining agronomic performance. Merdeka F1 exhibited greater vegetative vigor, particularly in terms of plant height, suggesting enhanced early growth potential, possibly due to superior photosynthetic efficiency or increased shoot vigor. Nevertheless, this vegetative advantage did not consistently translate into higher yields, indicating a potential trade-off between shoot biomass and bulb development. In contrast, Lokananta and Sanren F1 demonstrated superior bulb attributes, including greater fresh weight and diameter.

These genotype-specific responses underline the need to align varietal traits with specific production goals. For example, Lokananta may be better suited to systems emphasizing bulb size and uniformity, while Merdeka F1 could be advantageous in high-density plantings requiring rapid canopy coverage to suppress weeds or maximize light interception. This variation aligns with the broader understanding of genotype-based resource allocation strategies in crops.

Genotypic differences influence yield potential through traits such as drought resilience, nutrient uptake efficiency, and environmental adaptability. In wheat, for instance, specific genotypes have been demonstrated to outperform others under drought stress, resulting in higher biomass and grain yields **(1, 15)**. The presence of genetic diversity within crop populations supports improved adaptation and yield stability across variable environments **(23, 39)**. Traits like plant height and root architecture have been positively linked to seed yield in sesame and cowpea **(2, 16)**, while stress-tolerant genotypes in other species show increased yield stability under heat or drought conditions **(11, 13)**.

Effects of Seedling Number on Competition and Yield Efficiency

The comparison between single and double seedling plantings clearly showed that increasing intra-specific competition hurt shallot performance. Across all varieties and fertilizer treatments, single-seedling plots consistently yielded higher fresh and dry biomass, larger bulb diameters, and greater total yields. This reflects a classical density-dependent growth response, where excessive plant density reduces the availability of essential resources such as light, water, and nutrients for each individual.

Although double seedling planting sometimes led to increased plant height, particularly in Merdeka F1, this was likely a stress-induced elongation response rather than an indicator of increased productivity. The superior performance of single seedlings emphasizes the importance of optimized plant spacing for maximizing resource use efficiency and marketable yield. These findings are consistent with studies on other crops, such as cotton, pumpkin, and winter wheat, where moderate density achieved higher area-based yields without compromising individual plant output.

Plant spacing has a significant impact on growth dynamics, affecting light interception, nutrient uptake, and plant interactions. For example, reducing row spacing in maize can increase yield by enhancing light capture **(22, 42)**, whereas in soybean, increased density can reduce yield components **(33, 34)**. Excessive density may result in yield penalties due to shading and nutrient competition **(35)**.

Optimal spacing has been shown to enhance light absorption and promote uniform growth, as observed in chickpeas and other crops **(17, 20)**. However, overly dense stands can suppress growth through decreased nutrient uptake and light availability **(6, 20)**. Therefore, strategic management of plant density is crucial to achieving sustainable productivity.

Role of Fertilizer Composition in Enhancing Productivity

Among the fertilizer regimes evaluated, Package C consistently supported the highest dry biomass, bulb dry weight, and total yield. Its composition, featuring higher levels of magnesium, sulfur, and a balanced array of micronutrients, creates a nutrient-rich environment conducive to both vegetative and reproductive development. Potassium facilitates carbohydrate translocation, cell expansion, and stress resistance; calcium strengthens cell walls; and sulfur promotes protein synthesis, all of which are vital for bulb growth and plant metabolism.

Foliar nutrient application likely further improved nutrient use efficiency, particularly under mulched conditions that may restrict soil nutrient mobility. These findings support precision nutrient management approaches that align application timing and composition with plant demand, which is particularly beneficial in high-value horticultural systems.

Magnesium, a central element in chlorophyll synthesis and enzyme activation, significantly impacts photosynthetic efficiency and carbohydrate metabolism **(14, 45)**. Adequate magnesium enhances energy production and nutrient uptake, especially in interaction with calcium **(26)**, while its deficiency can lead to chlorosis and impaired plant development **(5, 14)**, highlighting its importance for productivity **(36)**.

Sulfur is equally critical, as it is a component of essential amino acids and coenzymes involved in growth and metabolism **(14)**. It contributes to chloroplast development, hormonal regulation, and nitrogen use efficiency while improving root development and oxidative stress tolerance. Sulfur fertilization can enhance plant growth, improve resistance to diseases, and increase the nutritional quality of **(10, 18, 25)**.

Chlorine, though required in trace amounts, is vital for photosynthesis via its role in photosystem II and for osmotic regulation under water stress **(1, 15)**. It activates enzymes in nitrogen metabolism and facilitates potassium uptake, enhancing plant function and resilience **(23, 39)**. A chlorine deficiency can reduce chlorophyll synthesis and overall productivity **(16)**.

Interactions among Variety, Fertilizer, and Density

Significant three-way interactions observed in plant height, biomass accumulation, and bulb weight underscore the complex interplay between genotype, nutrition, and density. While Merdeka F1 showed enhanced vegetative growth under higher fertilizer input, it was outperformed in bulb traits by Lokananta and Sanren F1 under double seedling conditions. Notably, Sanren F1 achieved optimal yield under Package C combined with single seedling planting, indicating a highly favorable genotype–nutrient–density synergy.

These results support the view that crop performance is not solely dictated by individual factors but rather by their interaction. Thus, aligning genetic potential with suitable agronomic practices, especially nutrient management and planting density is key to optimizing productivity. Practical implications include adopting tailored cultivation strategies based on varietal characteristics and the environmental context.

Correlation Between Vegetative Traits and Yield

Strong positive correlations were observed between vegetative traits (e.g., plant height, dry biomass) and yield parameters (e.g., bulb dry weight and total yield).

The exceptionally high correlation between bulb dry weight and total yield (r = 0.95) reinforces the utility of dry biomass as a predictive marker for productivity.

These findings emphasize the importance of integrated, trait-based monitoring during the crop cycle. Early identification of vegetative vigor may serve as an indicator of reproductive success and guide timely agronomic interventions. This is consistent with crop modeling approaches that prioritize early biomass accumulation as a key determinant of yield.

Dry weight has been widely validated as a predictor of yield, reflecting overall plant growth and photosynthetic capacity **(43)**. Its accumulation is critical for reproductive development, including grain or bulb formation **(19)**. In crops such as maize and beans, dry matter accumulation is positively correlated with yield components, including grain number and pod development **(27, 30, 37)**. Additionally, early-season dry weight has been used to predict final yield and inform nutrient and irrigation strategies **(24, 42)**.

Conclusion

This study demonstrated that the interaction between variety, nutrition, and planting density can significantly influence the agronomic optimization of shallot from true seed. Among the tested genotypes, Merdeka F1 exhibited strong vegetative traits, while Lokananta and Sanren F1 achieved superior bulb attributes, confirming that varietal selection must align with agronomic goals. Single-seedling planting outperformed double-seedling treatments in terms of biomass and yield, underlining the importance of managing intra-specific competition. Fertilizer Package C, enriched with magnesium, sulfur, and chlorine, proved most effective in enhancing dry biomass, bulb dry weight, and total yield, highlighting the crucial role of secondary nutrients in high-value horticultural crops.

The strong correlation between vegetative growth and bulb yield (r = 0.95) confirms that early vigor is a reliable predictor of productivity. This research provided valuable insights into precision agronomy for shallot cultivation, supporting tailored recommendations for maximizing yield. Future studies should explore genotype-specific nutrient efficiency and long-term field validation under variable environmental conditions.

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مقالة أصيلة

دور الصنف وتركيبة السماد وكثافة الزراعة وتفاعلها على الصفات الزراعية للكراث

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الخلاصة

تتأثر إنتاجية الكراث من البذور الحقيقية (*Allium ascalonicum* L.) بتفاعل العوامل الوراثية والتغذوية والمكانية. هدفت هذه الدراسة إلى تقييم التأثيرات المشتركة للصنف وتركيب السماد الورقي وكثافة الزراعة على نمو وإنتاجية الكراث. أجريت التجربة من يونيو إلى سبتمبر 2024 في المزرعة التجريبية لجامعة حسن الدين في ماكاسار، إندونيسيا (خط العرض 5°7′40.07″ جنوباً، خط الطول 119°28′48.94″ شرقاً، باستخدام تصميم القطع المنشقة-المنشقة بثلاثة أصناف (Lokananta, Merdeka F1, Sanren F1)، وثلاث حزم من الأسمدة الورقية، وكثافتين زراعيتين (شتلة واحدة وشتلتان في كل حفرة). أظهر تحليل التباين وجود تفاعلات ثلاثية معنوية ($p < 0.05$) بين الصنف والسماد والكثافة فيما يتعلق بارتفاع النبات والكتلة الحيوية الجافة ووزن الأبصال. تم تسجيل أعلى ارتفاع للنبات 58.41 سم في صنف Merdeka F1 مع الحزمة السمادية A وزراعة مزدوجة، بينما سُجلت أعلى كتلة حيوية جافة 54.30 غم في صنف Sanren F1 مع الحزمة السمادية C وزراعة مفردة. وحقق صنف Lokananta أعلى وزن طازج للأبصال 41.72 غم تحت الحزمة A مع الزراعة المفردة. أنتجت الحزمة السمادية C أعلى وزن جاف للأبصال 33.09 غم وأعلى محصول 22.06 غم للنبات الواحد، أي بزيادة قدرها 35٪ مقارنة بالحزم.A أعطت الزراعة المفردة إنتاجية قدرها 21.34 غم مقارنة بـ 16.39 غم في الزراعة المزدوجة. وُجد ارتباط موجب قوي ($r = 0.95$) بين الوزن الجاف للأبصال والمحصول الكلي. تؤكد هذه النتائج أن الجمع الأمثل بين الصنف وتركيب السماد وكثافة الزراعة يعزز بشكل كبير إنتاجية الكراث في الظروف المتحكم بها

الكلمات المفتاحية: الآليوم أسكالونيكوم، سماد، ورقي، شتلة