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Integrating water management and organic amendments to enhance shallot yield and irrigation water productivity

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ABSTRACT

This study evaluated the effects of watering regime and fertilizer composition on shallot (*Allium cepa* L. var. aggregatum) growth, yield, soil physical properties, and irrigation water productivity (IWP) under sandy loam conditions. A split-plot design was used, with watering as the main factor and fertilizer as the subplot. The watering treatments were: W1 – watering up to field capacity during both vegetative and generative phases; W2 – watering up to field capacity in the vegetative phase and up to allowable depletion in the generative phase; and W3 – watering up to allowable depletion in the vegetative phase and up to field capacity in the generative phase. The fertilizer treatments were F1 (NPK) and F2 (NPK + guano + rice husks). Results showed that F2 significantly improved plant height, leaf number, yield, and IWP compared with F1, primarily due to enhanced soil fertility and structure. The W3 treatment produced high yields while saving up to 13% of water and increasing IWP compared with continuous watering (W1). The combination of F2 with W3 yielded the highest productivity (2.92 kg per plot) and improved soil physical quality by reducing particle and bulk densities. Integrating organic amendments with NPK and applying regulated watering up to the allowable depletion limit during the vegetative phase can enhance shallot yield and water-use efficiency in sandy loam soils.

Keywords: guano, rice husk, shallot, irrigation water productivity, bulk density

INTRODUCTION

Shallot (*Allium cepa* L. Aggregatum group) is one of Indonesia's most important horticultural crops, providing both high market value and essential income for smallholder farmers. Indonesia is among the leading producers in Southeast Asia, with major production centers in Central Java, East Java, and West Nusa Tenggara (Data Center and Agricultural Information System, 2023). Despite its economic significance, shallot productivity remains highly variable due to suboptimal soil conditions, conventional fertilization practices, and inefficient water use during cultivation.

Traditional surface irrigation, which remains dominant in shallot production, often applies water without regard to soil moisture dynamics or crop water requirements. This approach tends to lower irrigation water productivity (IWP) and contributes to nutrient leaching and root stress, which in turn reduces plant growth and bulb yield (Amare et al., 2024; Rajanna et al., 2018; Wudil et al., 2023). At the same time, intensive reliance on inorganic fertilizers – particularly NPK – has improved yields temporarily but caused long-term soil degradation. Continuous use of chemical fertilizers reduces soil organic matter, microbial activity, and cation exchange capacity, leading to compaction and nutrient imbalance (Tahat et al., 2020). These effects diminish both soil fertility and fertilizer-use efficiency.

The use of organic soil amendments, such as guano and rice husks, offers a promising alternative for restoring soil quality and improving water-use efficiency. Guano is rich in nitrogen, phosphorus, and trace elements that support soil microbial activity and enhance nutrient availability (Marwa et al., 2021; Palita et al., 2021). Rice husk, a locally abundant agricultural byproduct, enhances soil aggregation, increases porosity, and reduces bulk density, thereby promoting root growth and improving moisture retention (Islabão et al., 2016). When applied in conjunction with NPK fertilizers, these amendments can enhance the physical and chemical properties of soils, thereby supporting higher plant productivity and more efficient water utilization (J. Wang et al., 2025).

However, despite the known benefits of organic amendments, limited studies have quantified their combined effects on soil physical properties, plant growth, and irrigation water productivity in shallot cultivation under Indonesian conditions. Understanding these interactions is crucial for developing effective and sustainable soil and water management strategies. Therefore, this study investigates the influence of guano and rice husk additions on soil characteristics, shallot growth, and irrigation water productivity to enhance the sustainability and efficiency of shallot production systems.

MATERIALS AND METHODS

Soil and soil amendment characteristics

Sand, silt, and clay fractions were quantified for texture determination using the pipette method (Jackson & Saeger, 1935; Soil and Fertilizer Instrument Testing Laboratory, 2023b). Soil density was determined using the immersion method with a measuring flask (Santos et al., 2022), but ethanol was replaced with boiled distilled water (Soil and Fertilizer Instrument Testing Laboratory, 2023b). Bulk density was obtained using the core or cylinder methods (Food and Agriculture Organization of the United Nations (FAO), 2023). Subsequently, soil pH analysis was conducted through a method including changes in the electrical potential of a glass calomel electrode, measured with a pH/millivolt meter at a specific temperature (25°C), using a soil suspension ratio in water of 1:2.5 (m:v) (Food and Agriculture Organization of the United Nations (FAO), 2021b). Organic carbon was analyzed using the Walkley–Black method (Food and Agriculture Organization of the United Nations (FAO), 2019), while nitrogen was evaluated through the Kjeldahl method (Food and Agriculture Organization of the United Nations (FAO), 2021a). The P available was analyzed using the Olsen method (Olsen et al., 1954). Cation exchange capacity, exchangeable bases, and base saturation were analyzed using ammonium acetate solution (NH_4OAc 1 M) at pH 7 (Nel et al., 2023), followed by atomic absorption spectrophotometry (AAS) to measure the concentration of each element individually (Food and Agriculture Organization of the United Nations (FAO), 2022). Sulfur content was determined by wet ashing using a mixture of concentrated HNO_3 and $HClO_4$ acids (Mico et al., 2007; Soil and Fertilizer Instrument Testing Laboratory, 2023a). The physical and chemical characteristics of soil and soil amendments are presented in Table 1.

Experimental design

The experiment was arranged in a split-plot design. The main plots consisted of different watering regimes applied during the vegetative and generative growth phases of shallots. The treatments were as follows:

- W1: watering up to field capacity during both the vegetative and generative phases (control);
- W2: watering up to field capacity during the vegetative phase and up to the allowable depletion limit during the generative phase;
- W3: watering up to the allowable depletion limit during the vegetative phase and up to field capacity during the generative phase;
- W4: watering up to the allowable depletion limit during both the vegetative and generative phases.

The subplots consisted of fertilizer treatments with two levels:

- F1: inorganic fertilizer (NPK);
- F2: guano + rice husks + inorganic fertilizer (NPK).

In total, there were eight treatment combinations, each replicated four times, resulting in 32 experimental plots.

Research preparation

The experiment was conducted in a screen house constructed with a UV-resistant plastic

Table 1. Soil and soil amendment characteristics

Characteristics	Unit	NPK	NPK + guano + rice husk
Sand	%	59	59
Silt	%	27	27
Clay	%	14	14
Particle density	g/cm^3	2.33	2.00
Bulk density	g/cm^3	1.29	1.14
Porosity	%	44.63	43.00
pH H_2O	-	6.15	6.48
C-organik	%	1.95	2.05
N	%	0.13	0.15
P_2O_5	ppm	10.98	12.24
Ca	cmol(+)kg^{-1}	5.25	5.74
Mg	cmol(+)kg^{-1}	0.95	1.05
K	cmol(+)kg^{-1}	0.35	0.41
Na	cmol(+)kg^{-1}	0.55	0.41
Cation Exchange Capacity	cmol(+)kg^{-1}	19.63	20.74
Base saturation	%	36	37
S	%	0.28	0.19

Soil Amendments	pH H_20	C/N	N	P	K	Ca	Mg	S
	.... %							
Guano	4.58	12	1.65	1.58	1.74	4.25	1.82	1.74
Rice Husk	7.12	11	1.55	0.29	2.5	2.55	0.12	0.61

roof to prevent rainfall from entering, ensuring that the plants received water exclusively from manual watering. The sides of the screen house were enclosed with plastic netting 50 cm in height, allowing air circulation while minimizing external interference. A drainage channel was created along the perimeter of the plots to prevent rainwater runoff from the roof from entering or seeping into the beds.

Air temperature and relative humidity were continuously monitored using measuring instruments placed inside the screen house. Measurements were taken four times daily at 7:00 a.m., 1:00 p.m., 5:00 p.m., and 9:00 p.m. to record microclimatic conditions throughout the experimental period.

Land preparation, fertilization, and planting

The soil was first cleared of weeds and loosened, then divided into plots measuring 2 meters by 1.2 meters. The distance between subplots was maintained at 50 cm, while the distance between main plots and between replicates was 100 cm. For plots receiving organic fertilizer, guano and rice husks were applied immediately after land preparation. The application rate for guano was 10 t ha^{-1}, equivalent to 2.5 kg per plot, while rice husks were applied at a dose of 1 kg per plot. The dosage used in this study was aligned with previous studies, which reported no significant improvement when higher dosages were applied (Elviani et al., 2024; Meutia et al., 2022). Both materials were evenly distributed over the soil surface and lightly incorporated using a rake to ensure uniform mixing.

Following fertilizer application, all plots were watered to saturation every two days and left for two weeks to allow decomposition and stabilization of the organic materials before planting.

After a two-week soil incubation period, shallot bulbs were planted. The variety used in this study was Tajuk. To break dormancy, the bulbs were pretreated by cutting approximately one-third of the tip and soaking them in a fungicide solution for 30 minutes prior to planting. The planting spacing was 20 × 15 cm, resulting in 63 bulbs per plot. After planting, each plot was watered daily with an equal volume of water (approximately 10 L per plot) for one week to ensure uniform germination and seedling establishment.

The inorganic fertilizer used in this study was NPK 16-16-16. Fertilization was applied three times during the growing period at different doses: 250 kg ha^{-1} at 10 days after planting (DAP), 200 kg ha^{-1} at 15 DAP, and 200 kg ha^{-1} at 35 DAP. For the F2 treatment, the NPK rate was reduced by half compared with F1. Fertilizer was evenly broadcast on the soil surface between the plants in the late afternoon, immediately before watering.

Soil moisture measurement and watering

Soil moisture content at field capacity was determined in the laboratory using the gravimetric method. Soil samples were first saturated with water, then drained until gravitational water ceased to percolate. The samples were subsequently oven-dried at 105 °C until a constant weight was reached.

Daily soil moisture measurements were also carried out to monitor soil water availability throughout the experiment. Soil samples for moisture determination were collected from both the center and edges of each plot at 5:00 p.m., prior to watering. The volume and frequency of watering were adjusted according to the daily decrease in soil moisture content and the specific treatment applied. The amount of water supplied was recorded for each plot to calculate irrigation water productivity (IWP).

When the shallots were seven days after planting (DAP), watering was applied according to the experimental design. In W1, irrigation was conducted to maintain field capacity during both the vegetative phase (15–30 DAP) and the generative phase (31–60 DAP). In W2, soil moisture was maintained at field capacity during the vegetative phase, whereas during the generative phase, watering was limited to the allowable depletion (AD) level, equivalent to approximately 35% of available water, as determined in previous studies. In W3, watering was restricted to the AD level during the vegetative phase and increased to field capacity during the generative phase. In W4, water was applied only up to the AD limit throughout both growth phases. Irrigation was stopped entirely two weeks before harvest (61–74 DAP) to facilitate bulb maturation.

Measurement of plant height and crop yield

Plant height was measured four weeks after planting (WAP) from the base of the leaves near the bulb to the tip of the tallest leaf. Crop yield was determined at harvest. The bulbs were carefully cleaned of adhering soil, the tops were cut near the leaf base, and the fresh weight of the bulbs was recorded.

Specific gravity, bulk density, and porosity

The specific gravity and bulk density of the soil were determined after harvest. The analytical methods followed those described previously. Soil porosity was calculated using Equation (1):

$$Porosity = \left(1 - \left(\frac{BD}{PD}\right)\right) x100\% \quad (1)$$

where: *BD* – bulk density ($g \cdot cm^{-3}$), *PD* – particle density ($g \cdot cm^{-3}$).

Irrigation water productivity (IWP)

Irrigation water productivity is calculated using equation (2) (F. Wang et al., 2023):

$$IWP = \frac{Y}{IWA} \quad (2)$$

where: *Y* – yield ($kg \cdot ha^{-1}$), *IWA* – irrigation water applied or total water applied ($m^3 \cdot ha^{-1}$).

Data analysis

Analysis of variance (ANOVA) was performed using a split-plot design with four replicates to assess the effects of treatment factors on the measured parameters. Factors showing significant or highly significant effects were compared using Duncan's Multiple Range Test at a 95% confidence level. All statistical analyses, including ANOVA and post hoc tests, were conducted using SPSS Statistics 27.

RESULTS

Air temperature and relative humidity at the site study

Observations showed that the minimum air temperature (24.9 °C) occurred on Day of Year (DOY) 27, whereas the maximum temperature (36.1 °C) was recorded on DOY 31. Relative humidity ranged from 41% to 91%, with the lowest value observed on DOY 31 and the highest

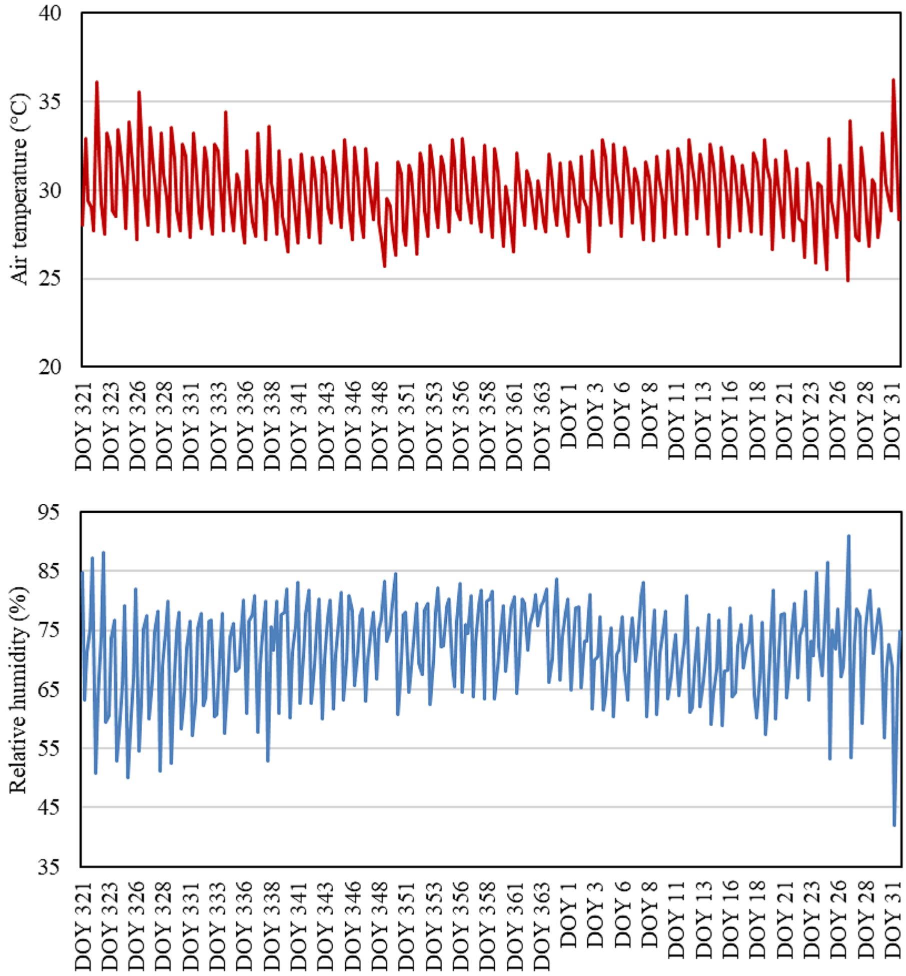

Figure 1. Weather conditions at the study site

on DOY 27. An inverse relationship was evident between air temperature and relative humidity, indicating that temperature increases were associated with decreases in humidity. The highest air temperatures were generally recorded at 1:00 p.m. under clear sky conditions, whereas the lowest temperatures occurred at 7:00 a.m. and 9:00 p.m.

Plant height and number of leaves

Statistical analysis revealed that only the type of fertilizer had a significant effect on plant height and the number of leaves at four weeks after planting (WAP). As presented in Table 2, plants receiving a combination of NPK fertilizer with organic amendments (guano and rice husks) exhibited the most significant average plant height (32.02 ± 1.85 cm), compared with plants receiving NPK fertilizer alone (30.13 ± 4.59 cm). A similar trend was observed for the number of leaves, where the NPK + organic fertilizer treatment produced the highest mean value (21.72 ± 1.80). These results indicate that integrating organic amendments with NPK fertilizer enhances nutrient availability and supports vigorous vegetative growth in shallots.

Yield

Table 3 presents the interaction effects between watering treatment and fertilizer type on shallot yield. The highest average yield was obtained under treatment W3F2 (2.92 ± 0.17 kg per plot), although this value was not significantly different from those of W1F2 (2.53 ± 0.19 kg per plot) and W2F2 (2.77 ± 0.25 kg per plot). Overall, the W3 watering regime produced the highest average yield (2.50 ± 1.65 kg per plot), whereas the lowest yield was recorded under W4 (2.01 ± 0.68 kg per plot). Furthermore, the combination of NPK fertilizer with organic amendments (F2) resulted in higher yields (2.60 ± 1.12 kg per plot) compared with NPK alone (F1). These results indicate that the interaction between watering regime and fertilizer type plays a critical

Table 2. Plant height and number of leaves at 4 weeks after planting (WAP)

Parameter	Fertilizer	Watering				Mean
		W1	W2	W3	W4	
Plant height (cm)	F1	30.08±1.76	31.67±2.40	30.31±3.02	28.44±2.96	30.13±1.32 a
	F2	32.82±3.16	31.73±0.67	31.76±1.54	31.76±4.23	32.02±0.54 b
	Mean	31.45±1.94	31.70±0.05	31.04±1.03	30.10±2.35	
Number of leaves	F1	19.83±2.57	20.33±3.09	18.39±4.10	18.44±3.43	19.25±0.98 a
	F2	21.28±1.88	21.58±1.62	22.47±3.03	21.56±6.36	21.72±0.52 b
	Mean	20.56±1.02	20.96±0.88	20.43±2.89	20.00±2.20	

Note: means within the same column followed by the same letter are not significantly different at $p < 0.05$ (DMRT). W1 – field capacity during vegetative and generative phases; W2 – field capacity during vegetative phase, allowable depletion during generative phase; W3 – allowable depletion during vegetative phase, field capacity during generative phase; W4 – allowable depletion during both phases; F1 – NPK fertilizer; F2 – NPK + guano + rice husks.

Table 3. Yield of shallot (kg/plot)

Fertilizer	Watering				Mean
	W1	W2	W3	W4	
F1	2.35±0.34 bc	1.89±0.23 a	2.09±0.31 ab	1.84±0.29 a	2.04±0.23 a
F2	2.53±0.22 cd	2.77±0.29 d	2.92±0.20 d	2.18±0.20 abc	2.60±0.32 b
Mean	2.44±0.13 b	2.33±0.63 ab	2.50±0.59 b	2.01±0.24 a	

Note: means within the same column followed by the same letter are not significantly different at $p < 0.05$ (DMRT). W1 – field capacity during vegetative and generative phases; W2 – field capacity during vegetative phase, allowable depletion during generative phase; W3 – allowable depletion during vegetative phase, field capacity during generative phase; W4 – allowable depletion during both phases; F1 – NPK fertilizer; F2 – NPK + guano + rice husks.

role in optimizing the water and nutrient supply required for shallot growth during the vegetative and generative phases.

Particle density, bulk density, and porosity

The analysis results indicated that there was no significant interaction between watering treatment and fertilizer type on soil particle density, bulk density, or final soil porosity (Table 4). Among the watering treatments, the highest mean particle density was observed under W3 (2.19 ± 0.35 g cm^{-3}), while W1, W2, and W4 showed slightly lower values of 2.12 ± 0.17, 2.13 ± 0.39, and 2.10 ± 0.39 g cm^{-3}, respectively. The addition of guano and rice husks had a significant influence on the physical properties of the sandy loam soil. Particle density decreased from 2.22 g cm^{-3} under NPK fertilizer alone (F1) to 2.05 g cm^{-3} with the combined application of NPK, guano, and rice husks (F2). Similarly, bulk density declined from 1.22 to 1.16 g cm^{-3}. This reduction suggests that incorporating organic materials with lower intrinsic density than mineral particles effectively altered the soil's composition and improved its structural characteristics.

Irrigation water productivity (kg/m³)

Table 5 shows that there was no significant interaction between watering treatment and fertilizer type on irrigation water productivity (IWP). In general, treatment W4 resulted in the highest mean IWP (4.14 ± 0.88 kg m^{-3}), although this value was not significantly different from those of W2 (3.83 ± 1.83 kg m^{-3}) and W3 (3.84 ± 1.49 kg m^{-3}). The lowest IWP was recorded under W1 (3.24 ± 0.28 kg m^{-3}). With respect to fertilizer type, the highest IWP was obtained from F2 (4.04 ± 1.72 kg m^{-3}), whereas F1 produced a lower value (3.48 ± 1.10 kg m^{-3}). These results indicate that reducing irrigation volume and incorporating organic amendments enhanced irrigation water productivity, suggesting improved water use efficiency under these conditions.

Table 4. Particle density, bulk density, and porosity after harvest

Parameter	Fertilizer	Watering				Mean
		W1	W2	W3	W4	
Particle density ($g \cdot cm^{-3}$)	F1	2.16±0.05	2.23±0.02	2.27±0.02	2.20±0.05	2.22±0.05 a
	F2	2.07±0.04	2.04±0.02	2.10±0.01	2.00±0.09	2.05±0.04 b
	Mean	2.12±0.06 a	2.13±0.14 a	2.19±0.13 b	2.10±0.14 a	
Bulk density ($g \cdot cm^{-3}$)	F1	1.21±0.06	1.24±0.03	1.21±0.04	1.21±0.04	1.22±0.01 a
	F2	1.18±0.02	1.11±0.03	1.18±0.04	1.16±0.06	1.16±0.03 b
	Mean	1.19±0.02	1.17±0.09	1.19±0.02	1.18±0.04	
Porosity (%)	F1	44.12±1.68	44.62±2.08	46.77±1.95	44.93±1.48	45.11±1.16
	F2	43.23±0.88	45.39±2.02	43.82±2.03	41.95±4.94	43.60±1.43
	Mean	43.67±0.62	45.00±0.54	45.30±2.09	43.44±2.11	

Note: means within the same column followed by the same letter are not significantly different at $p < 0.05$ (DMRT). W1 – field capacity during vegetative and generative phases; W2 – field capacity during vegetative phase, allowable depletion during generative phase; W3 – allowable depletion during vegetative phase, field capacity during generative phase; W4 – allowable depletion during both phases; F1 – NPK fertilizer; F2 – NPK + guano + rice husks.

Table 5. Irrigation water productivity

Fertilizer	Watering				Mean
	W1	W2	W3	W4	
F1	3.17±0.49	3.38±0.50	3.47±0.46	3.92±0.32	3.48±0.32 a
F2	3.30±0.47	4.29±0.25	4.21±0.47	4.36±0.44	4.04±0.50 b
Mean	3.24±0.10 a	3.83±0.65 b	3.84±0.53 b	4.14±0.31 b	

Note: means within the same column followed by the same letter are not significantly different at $p < 0.05$ (DMRT). W1 – field capacity during vegetative and generative phases; W2 – field capacity during vegetative phase, allowable depletion during generative phase; W3 – allowable depletion during vegetative phase, field capacity during generative phase; W4 – allowable depletion during both phases; F1 – NPK fertilizer; F2 – NPK + guano + rice husks.

DISCUSSION

The increased plant height and leaf number observed under the F2 treatment can be attributed to the complementary effects of guano and rice husks on soil fertility and structure. Guano provides a slow-release source of essential nutrients, particularly nitrogen, phosphorus, and micronutrients, that sustain plant growth throughout the growing period (Table 1). Rice husks enhance soil aeration, water retention, and microbial activity, thereby promoting root development and nutrient uptake (Hanke et al., 2025; Liu et al., 2023). Moreover, the addition of organic matter from guano and rice husks enhances the soil's cation exchange capacity, soil structure, and nutrient retention, thereby creating a more stable rhizosphere environment (Mutai et al., 2025; Ramos et al., 2018). Improved soil physical conditions also facilitate greater root proliferation, enabling plants to access more nutrients and moisture (Azam et al., 2025). These improvements collectively support higher photosynthetic capacity, as reflected by the increased leaf number and taller plant stature observed in the F2 treatment. These findings are consistent with previous reports indicating that the combined application of organic and inorganic fertilizers promotes a balanced nutrient supply and improves shallot growth compared with sole inorganic fertilization (Lasmini et al., 2015; Sugiono et al., 2021). Therefore, integrating guano and rice husks with NPK represents a promising nutrient management strategy to enhance shallot vegetative growth and potentially increase overall yield in sandy loam soils.

The watering treatment did not significantly affect plant height or leaf number, indicating that a water deficit up to the Allowable Depletion (AD) limit was still adequate to sustain optimal shallot growth. This finding suggests that maintaining soil moisture at field capacity throughout the growing period provides no additional advantage for vegetative development and may instead decrease water-use efficiency. Similar findings were also reported by Ashemi (2021), who observed that moderate water deficit did not significantly affect onion growth parameters.

The interaction between fertilizer type and watering regime had a significant effect on shallot yield per plot. The combined application of NPK fertilizer with guano and rice husks (F2) consistently produced higher yields than NPK alone (F1). Across watering regimes, the mean yield of F2 reached 2.60 kg per plot compared with 2.04 kg per plot for F1. The yield increase under F2 reflects the synergistic effects of integrating organic and inorganic nutrient sources, which enhance soil fertility and structure. Guano supplies readily available nitrogen, phosphorus, and trace elements, while rice husks contribute organic carbon and silica that improve soil aggregation and aeration (Table 1). These amendments also enhance soil moisture retention and root-zone conditions, promoting greater root proliferation and nutrient uptake. Such improvements are particularly advantageous in sandy loam soils, which are susceptible to nutrient leaching and have inherently low water-holding capacity (Meng et al., 2022).

Water availability is a key factor determining shallot yield. A water deficit up to the AD limit during both vegetative and generative phases (W4) reduced yield, although the difference was not statistically significant compared with the W2 treatment. Yields under W4 decreased by 17.6–19.6% relative to the non-deficit treatment (W1) and the treatment with deficit only during the vegetative phase (W3). Although deficit irrigation during both the vegetative and generative phases resulted in the highest irrigation water productivity (IWP), it produced the lowest yield. This occurs because the plants experience continuous water stress throughout their growth cycle, which restricts leaf expansion, photosynthetic activity, bulb development, and the accumulation of assimilates (Pelter et al., 2004; Zheng et al., 2010). As a result, water is used more efficiently, but the plants cannot reach their full yield potential. Similar findings were reported by Igbadun et al. (2012), who observed that suboptimal irrigation decreases shallot yield through impaired carbohydrate translocation (Setter et al., 2001). In contrast, the W3 treatment, which maintained field capacity during the generative phase despite a deficit in the vegetative phase, yielded 2.4% more than the W1 treatment. This result suggests that moderate irrigation sustains soil moisture near the crop's optimal level, thereby supporting continuous nutrient uptake and photosynthetic activity (Amare et al., 2024; Dinh et al., 2019; Xu & Zhou, 2011). Conversely, excessive irrigation can reduce soil aeration and promote nutrient leaching, resulting in lower yield efficiency (Fan et al., 2014; Z. Z. Yu et al., 2024). Overall, applying a controlled water deficit up to the AD limit during the vegetative phase can improve irrigation water productivity (IWP) without adversely affecting shallot yield.

A significant interaction effect was observed between the type of fertilizer and the watering regime. The combination of NPK fertilizer with guano and rice husks under the W3 watering treatment produced the highest yield (2.92 kg per plot). In contrast, NPK alone under W4 resulted in the lowest yield (1.84 kg per plot). The superior performance of the F2 × W3 combination can be attributed to improved nutrient use efficiency and enhanced soil water retention resulting from the addition of organic amendments. Organic materials increase the soil's capacity to retain water, thereby maintaining favorable moisture conditions for crop growth (Jiang et al., 2025). Furthermore, organic amendments stimulate microbial activity, which promotes nutrient mineralization and contributes to the long-term improvement of soil fertility (Song et al., 2022).

The significant increase in soil particle density under W3 (2.19 g cm^{-3}) compared with W1, W2, and W4 indicates that watering management influenced the balance between mineral decomposition and organic matter dynamics in the soil. The alternating moisture conditions in W3—water deficit during the vegetative phase, followed by watering to field capacity during the generative phase – likely accelerated organic matter decomposition and increased the relative proportion of mineral constituents. During the deficit period, limited soil moisture may have suppressed microbial activity and residue incorporation, thereby reducing the accumulation of organic matter. When watering was restored to field capacity in the generative phase, the rewetting effect may have stimulated microbial activity and enhanced mineralization of remaining organic compounds. This process would decrease organic matter content, leading to a higher proportion of mineral material per unit volume and, consequently, greater particle density (Nabayi et al., 2021; Wei et al., 2025). Continuous or balanced watering (W1 and W2) likely maintained more stable organic matter levels, whereas a persistent water deficit (W4) may have reduced microbial activity, limiting both decomposition and mineralization (De Silva et al., 2025; Solly et al., 2025).

The reduction in particle density reflects the incorporation of low-density organic materials into the solid phase of the soil. Organic constituents typically have densities below 2.0 g cm^{-3}, leading to a measurable decrease in average particle density when mixed with mineral soil (Rühlmann et al., 2006). The application of guano and rice husks increased soil organic matter content, thereby reducing soil bulk density (Robinson et al., 2025). A decrease in bulk density indicates improved soil aggregation and reduced compaction, both of which are beneficial for root penetration, water infiltration, and soil aeration (Czyz, 2004; Eng Giap & Ahmad, 2025; Lampurlanés & Cantero-Martínez, 2003). Lower bulk density in sandy loam soils is critical, as these soils are susceptible to structural degradation and compaction under intensive cultivation.

The application of guano and rice husks also improves soil structure through both biological and physical mechanisms. Guano provides organic carbon and nutrients that stimulate microbial activity, promoting the formation of stable soil aggregates (Singh et al., 2025). The fibrous and porous nature of rice husks enhances pore continuity and reduces bulk density (Varela et al., 2013). Similar results were reported by Tao et al. (2024), who found that organic amendments significantly decreased soil bulk density.

Although both particle and bulk densities decreased, the proportionally greater reduction in particle density resulted in a slight decrease in calculated total porosity. However, this minor change does not necessarily indicate a deterioration in soil structure. Porosity estimated from density values may not accurately represent the functional pore space, as organic amendments can increase macro-porosity and pore connectivity even when total porosity remains nearly constant (Rasa et al., 2024; X. Yu et al., 2025). Therefore, improvements in soil physical quality are more effectively assessed through indicators such as aggregate stability, infiltration rate, and bulk density, rather than relying solely on total porosity.

Under water deficit conditions up to the AD limit during the vegetative phase, shallot yield increased significantly, and irrigation water productivity (IWP) was higher than in treatments without any deficit. Maintaining field capacity moisture conditions during the generative phase resulted in high yields (2.50 ± 1.65 kg per plot) while further improving IWP. Reducing water application to the AD limit during the vegetative phase enabled water savings of up to 13%. Therefore, this watering strategy is effective for enhancing shallot yield and IWP, particularly in regions that experience periodic water shortages.

The addition of guano and rice husks to NPK fertilizer increased IWP from 3.48 kg m^{-3} with NPK alone to 4.04 kg m^{-3}, representing an improvement of approximately 16%. This result indicates that integrating organic materials with mineral fertilizers can enhance crop water use efficiency. The improvement is attributed to the complementary effects of guano and rice husks on soil nutrient availability and physical properties. Guano, rich in nitrogen and phosphorus, provides a gradual release of nutrients that supports plant growth and enhances nutrient uptake efficiency (Marwa et al., 2021). Rice husks, which contain silica and organic carbon, enhance soil structure, porosity, and moisture retention, thereby facilitating improved root development and water absorption (Karam et al., 2022; Li et al., 2025). These findings are consistent with previous reports, which show that integrating organic and inorganic inputs enhances soil–water relationships and nutrient use efficiency (Bo et al., 2025). Such combined applications improve soil fertility and support higher biomass production and yield per unit of water used.

Long-term application of guano can lead to the accumulation of nitrogen and phosphorus, potentially increasing soil electrical conductivity and creating nutrient imbalances (Singh et al., 2025). Its ammonium content may also contribute to a slight decline in soil pH (Wait et al., 2005). In contrast, raw rice husk decomposes slowly, gradually increasing soil organic matter and silicon availability, with a slight tendency to raise soil pH due to its neutral to slightly alkaline nature (Table 1). Regular soil monitoring is recommended to maintain balanced fertility and pH levels.

In this study, a watering strategy was developed based on the AD threshold for shallots. AD represents the lower limit of soil moisture deficit that can be tolerated while maintaining high yields. In regions with supplemental irrigation or relatively high rainfall, watering up to the AD limit can be an effective approach to reduce water use. However, its application requires real-time monitoring of soil moisture conditions. Compared with the traditional practice of full watering throughout the growing season, applying water up to the AD limit only during the vegetative phase, combined with organic fertilization, is more suitable for efficient shallot production.

CONCLUSIONS

The integration of guano and rice husks with NPK fertilizer, along with a watering regime based on allowable depletion, significantly improved shallot growth, yield, and soil physical quality. The combined fertilizer treatment enhanced plant height and leaf number by improving nutrient availability and root development, while also reducing particle and bulk densities and improving soil structure. Watering up to the allowable depletion limit during the vegetative phase, followed by field capacity watering in the generative phase, increased yield and irrigation water productivity (IWP) while reducing water use by about 13%. Although total porosity slightly declined, overall soil conditions remained favorable for plant growth. Future research should investigate the long-term effects of organic–inorganic integration and regulated watering on soil carbon dynamics, nutrient cycling, and yield stability across different soil types and climatic conditions.

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