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Micro Irrigation and NPK Fertilization to Improve Nutrient Uptake and Flavonoid of Shallot in Karst Land

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ABSTRACT

Background: Water and nutrient limitations in karst soils hinder the optimal growth of shallots, so water and nutrient management is carried out using variations in micro-irrigation and NPK fertilization. Variations in micro-irrigation and NPK fertilization can support the growth and flavonoid content of shallots.
Aims: This study aims to analyze nutrient uptake and total flavonoid production of shallots in karst soils with variations in micro-irrigation and NPK fertilization.
Methods: The research used a Randomized Block Design (RBD) containing two main factors. The first factor was the irrigation technique, consisting drip irrigation (I1) and mist irrigation (I2). The second factor was the NPK fertilizer dosage, consisting three levels: 0 kg/ha (N1), 500 kg/ha (N2), and 1000 kg/ha (N3). The parameters observed included soil moisture, soil NPK availability, plant NPK uptake, total flavonoids, growth, and shallot yield.
Results: The results showed that mist irrigation with an NPK dose of 1000 kg/ha yielded higher results compared to drip irrigation in terms of soil moisture, NPK availability and uptake, growth, and yield. The highest availability of nitrogen, phosphorus, and potassium in mist irrigation with a dose of 1000 kg/ha was 0.36%, 89.20 ppm, and 0.66 me%, respectively. Phosphorus uptake in mist irrigation was higher than in drip irrigation, at 0.81% and 0.89%, respectively. Growth and yield under mist irrigation with an NPK dose of 1000 kg/ha also yielded the best results compared to drip irrigation with an NPK dose of 1000 kg/ha, namely plant height (30.69 and 29.74 cm), number of leaves (27.65 and 25.77 leaves), and bulb diameter (30.07 and 27.02 mm). The highest total flavonoid content was observed in drip irrigation with a 500 kg/ha dose compared to mist irrigation with a 500 kg/ha dose, namely (78.83 and 50.96 mg/kg). Overall, irrigation techniques with varying NPK doses were able to increase nutrient and flavonoid uptake in shallot on karst land.

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1. Introduction

Shallot (*Allium ascalonicum*) is an important horticultural commodity in Indonesia as a cooking spice, but it can also be processed into food products such as flour, crackers, and pasta. This commodity contains carbohydrates, vitamins A, B, and C, as well as minerals such as calcium, phosphorus, and iron (Shahrajabian *et al.,* 2019). Additionally, shallot contain secondary metabolites in the form of flavonoids, which act as antioxidants, antimicrobials, and anti-inflammatories (Kothari *et al.,* 2020). Flavonoids play a crucial role in maintaining crop quality by protecting against oxidative stress, extending shelf life, and preserving organoleptic characteristics such as color and flavor (Lopresti *et al.,* 2024). Flavonoid synthesis is influenced by environmental conditions, particularly abiotic stresses such as drought and nutrient deficiency (Kumar *et al.,* 2023; Sansan *et al.,* 2024). Moderate water deficit has been reported to increase flavonoid accumulation, but severe drought has a negative impact on plant growth and physiology (Ren *et al.,* 2017).

Marginal lands such as karst lands have major constraints, namely low water reserves and nutrient availability due to the dominance of limestone, high porosity, and low water storage capacity (Lv *et al.,* 2020). These conditions hinder nutrient uptake efficiency, plant physiology, and crop yields (Salem *et al.,* 2022; El-Metwally & Saudy, 2021). Water management strategies through micro-irrigation are one approach that can be applied to improve water use efficiency in karst areas. Micro-irrigation includes drip irrigation and mist irrigation, which can efficiently deliver water directly to the root zone (Deshpande *et al.,* 2024). Drip irrigation works by slowly dripping water onto plant roots, minimizing evaporation and percolation, while mist irrigation sprays water particles evenly over the planting area, increasing air humidity and lowering microclimate temperature (Bansal *et al.,* 2021; Li & Su, 2017).

The water distribution patterns of each of these techniques affect soil moisture and plant physiological responses, including nutrient uptake and flavonoid biosynthesis (Naveena & Babu, 2021). In addition to water management, the availability of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) also plays a crucial role in supporting plant growth and the formation of functional compounds. NPK fertilization is necessary to enhance soil fertility and plant physiological performance. Nitrogen is involved in protein and chlorophyll synthesis, phosphorus is important for energy production and root development, while potassium supports photosynthesis, osmotic regulation, and the biosynthesis of secondary metabolites (Wang *et al.,* 2024).

Low water availability in karst soils will inhibit nutrient dissolution and plant metabolism, thereby affecting the growth and secondary metabolic synthesis of shallot (Sansan *et al.,* 2024). Optimal absorption of nitrogen, phosphorus, and potassium can support the enzymatic activity required for flavonoid biosynthesis. Previous studies have shown that plant nutrient content can influence secondary metabolic pathways. Research by Liu *et al.* (2021) shows that NPK fertilization not only affects tuber yield, but also the content of bioactive compounds, including flavonoids. Therefore, proper irrigation and fertilization management can support optimal nutrient availability and uptake for growth, yield, and flavonoid synthesis. Research on the interaction between micro-irrigation techniques and NPK fertilization rates on horticultural crop physiology has been extensively conducted, but it remains limited to specific crops and has not extensively addressed its impact on flavonoid content in karst soils. This study aims to analyze growth, yield, nutrient availability, nutrient uptake, and total flavonoid production in shallot on karst land with variations in micro-irrigation (drip and mist) and NPK fertilization (0, 500, and 1000 kg/ha). The use of NPK Phonska doses of 500 and 1000 kg/ha was chosen to represent different fertilization levels, where 500 kg/ha is the general recommended dose for shallot cultivation (Atman, 2021; Kementan, 2017), while 1000 kg/ha represents a high dose to evaluate plant response to greater nutrient availability. Comparing these two doses is important to determine the extent to which increased N, P, and K supply can affect growth, nutrient uptake, and the formation of secondary metabolites such as flavonoids under different soil moisture conditions. The results of this study are expected to provide a scientific basis for designing adaptive and sustainable cultivation strategies that can improve the physiological quality and functional value of shallot yields. These findings can also provide dosage recommendations for NPK fertilization on karst soil in shallot cultivation.

2. Methods

This research will be conducted on agricultural land located in Wareng Village, Wonosari District, Gunung Kidul, Yogyakarta from August 2024 to October 2024. Geographically, the research location is at coordinates 7° 59′ 07″ S and 110° 33′ 45″ E and an elevation of 167 meters above sea level.

2.1 Materials

The materials used in this study were shallot seeds (*Allium ascalonicum*) of the Tajuk variety, Phonska NPK fertilizer, manure, pesticides for pest control, PVC pipes, drip sticks, emitters, drip irrigation hoses, and mist irrigation hoses. The tools used in this study were an AWS (Automatic Weather System), MS10 soil moisture sensor (INFWIN, China), shovel, ruler for measuring plant height, pump, manometer, flow meter, digital scale, writing instruments, and camera.

2.2 Experimental Design

This study used a split plot design with a randomized block design (RAK) in an area of 256 m^2 . This study involved two independent variables, namely two types of irrigation and three doses of Phonska NPK fertilizer. The irrigation type variable consists of drip irrigation (I1) and mist irrigation (I2). The NPK Phonska fertilizer dose variable includes 0 kg/ha (N1); 500 kg/ha (N2) and 1000 kg/ha (N3). Each treatment will be applied to separate plots with three replications, resulting in 18 experimental units on the research plot. Samples will be randomly collected from each plot to measure dependent variables such as onion growth, yield, soil chemical analysis samples, and plant samples. The experimental layout is divided into two blocks for mist irrigation and drip irrigation. Each block has 9 experimental plots measuring 1.5 m x 3 m. The two experimental blocks are separated by a distance of 10 m to minimize bias during cultivation and data collection.

2.3 Soil Moisture Content

Data was collected using a special data cable and stored in .csv format. Soil moisture measurements were taken during the shallot growing season using an MS10 sensor installed 5 cm below the center of each experimental plot. Data can be accessed online and offline via the data log. The sensor automatically records data every 30 minutes to align with actual moisture content (% volumetric). Calibration was performed on the soil sensor using the same soil from the research field. Data collection involved weighing the soil from saturated to oven-dry conditions. The results were then converted into moisture content data based on % volumetric. The calibration results obtained were plotted in graph form, yielding the equation $y = 0.0093x + 3 \times 10^{-5}$. The regression equation derived from calibration was subsequently used to represent soil moisture values obtained from sensor data.

2.4 Plant Physiology and Biomass

Plant physiology measurements were performed by measuring plant height and number of leaves, while plant biomass was measured by weighing the wet weight of tubers, dry weight of plants, number and diameter of tubers in each experimental plot. Plant samples were oven-dried at 60°C for 3 days until constant weight was achieved. The oven-dried samples are then weighed using a digital scale with a precision of 0.01 grams to obtain the dry weight. The diameter of the tubers is measured at the widest part of the tuber using a caliper on tubers representing each experimental block.

2.5 Nutrient Availability and Nutrient Uptake

Soil nutrient testing and nutrient uptake were conducted for each treatment with three replicates. Soil sampling was performed continuously and randomly. The testing was conducted at the Chemistry and Soil Fertility Laboratory of UNS Surakarta. Samples were collected after harvesting. Nitrogen was analyzed using the Kjeldahl method, which consists of three main stages: destruction, distillation, and titration. A total of 0.5 grams of soil was converted with concentrated sulfuric acid and a catalyst, then heated until the solution was clear. The digestion product was distilled with the addition of NaOH solution, and the ammonia formed was captured in boric acid solution. Next, titration was performed with 0.01 N HCl. The end point of titration was marked by a stable pink color change for ± 30 seconds, and the nitrogen content could be calculated from the titration volume.

Plant tissue phosphorus was analyzed using wet destruction, while soil phosphorus was analyzed using dry destruction and the Olsen method, which involves extraction with 0.5 M NaHCO3 solution (pH 8.5). A total of 2.5 grams of soil was extracted with 50 mL of the solution and shaken for 30 minutes, then filtered. The extraction filtrate was reacted with molybdate-ascorbate reagent, producing a blue color. The intensity of the blue color was then measured using a spectrophotometer at a wavelength of 880 nm. Potassium was analyzed using the extraction method with 1N acetic acid solution at pH 7.00. Five grams of soil were extracted with 50 mL of the solution, shaken for 30 minutes, and filtered. The extraction filtrate was then analyzed using an atomic absorption spectrophotometer (AAS).

2.6 Total Flavonoid Content

Measurement of total flavonoid content using the UV-Vis spectrophotometer method. Shallot bulb samples were extracted with 70% ethanol solvent through a soxhlet extraction process for several hours. The extract obtained was then filtered and taken for analysis. The extract solution was mixed with a 10% aluminum chloride ($AlCl_3$) solution, a 1 M sodium acetate solution, and the mixture was incubated for 30–60 minutes at room temperature. Subsequently, the absorbance of the mixture was measured using a UV-Vis spectrophotometer at a maximum wavelength of 415 nm. The absorbance values were then compared with the standard curve of quercetin as the reference compound, enabling the total flavonoid concentration in the sample to be calculated and expressed in units of mg/kg. The total flavonoid content testing was conducted at the Integrated Research and Testing Laboratory, Gadjah Mada University, Yogyakarta.

2.7 Growth Rate Modeling

The mathematical model used to describe the growth rate of plants, including plant height and number of leaves in this study, is the quadratic exponential equation (France & Thornley, 2007). The quadratic exponential equation prediction model is shown in equation:

$$Wt = W_0 \cdot \exp \left[\mu_0 \left(t - \frac{Dt^2}{2}\right)\right]$$

Wt represents the plant height or number of leaves at time t. W0 indicates the initial plant height taken from the average measurement results in the early growth phase, μ_0 is the initial specific growth rate from the curve fitting that describes the plant's ability to grow rapidly in the early vegetative phase, and D is the growth rate decline coefficient estimated from the model to show the rate of growth deceleration over time.

2.8 Statistical Analysis

Data analysis was performed using several tests, namely ANOVA, Duncan's test, and T-test. ANOVA was performed on moisture content, NPK availability, NPK uptake, plant growth, and crop yield. Subsequently, a post-hoc test was performed using Duncan's test. The T-test was applied to both observational data and predictive data for model validation. Total flavonoid content was presented through descriptive analysis since it was only tested on a single sample representing each treatment without replicates.

3. Results and Discussions

3.1 Soil Moisture Content

The soil moisture content values for each irrigation technique and fertilizer dose treatment are shown in Table 1. Irrigation techniques had a very significant effect on soil moisture content, while NPK fertilizer doses and the interaction between the two treatments had no significant effect. Fog irrigation consistently produced higher soil moisture content than drip irrigation.

Table 1. Results of ANOVA test on average moisture content

Irrigation Techniques	NPK Dosage	Moisture Content (%)
Drip Irrigation	0 kg/ha	24,08 ± 6,48b
	500 kg/ha	18,67 ± 1,66b
	1000 kg/ha	19,81 ± 2,55b
Mist Irrigation	0 kg/ha	35,56 ± 2,25a
	500 kg/ha	34,22 ± 0,52a
	1000 kg/ha	34,20 ± 0,46a

a, b, c, d, e = letter notation is not similar, meaning that there is no real effect on the level Duncan test has a value of 5%.

The significant difference in soil moisture content between drip irrigation and mist irrigation is related to the water distribution mechanisms of each irrigation technique. The difference in soil moisture content between drip irrigation and mist irrigation is mainly due to differences in water distribution patterns. Drip irrigation delivers water slowly and directly to the root zone, thereby reducing losses due to evaporation, but its distribution is limited and uneven on clay-textured soils (Bansal *et al.,* 2021). In contrast, mist irrigation sprays water in the form of micro-particles that are more easily absorbed by the soil surface and create more homogeneous moisture. This condition expands the moist zone around the roots, increases water absorption capacity, and has implications for improved nutrient availability and plant growth (Li *et al.,* 2023; Liu *et al.,* 2021).

3.2 Nutrient Availability and Nutrient Uptake Dynamics

The NPK availability values for each irrigation technique and fertilizer dose treatment are shown in Table 2, indicating that irrigation techniques and NPK fertilizer doses affect phosphorus and potassium availability, while nitrogen availability does not differ significantly. In general, mist irrigation produces higher P and K availability compared to drip irrigation. This is related to more even soil moisture distribution, which accelerates the dissolution and diffusion of nutrients in the soil solution (Li *et al.,* 2023). Increasing the NPK fertilizer rate also enhances P and K availability, with the highest values recorded in mist irrigation at a rate of 1000 kg/ha (P = 89.20 ppm; K = 0.66 me%), indicating that this combination is most effective in providing essential nutrients for plants.

Table 2. Results of ANOVA test on average NPK availability

Irrigation Techniques	NPK Dosage	Nitrogen (%)	Phosphorus (ppm)	Potassium (me %)
Drip Irrigation	0 kg/ha	0.22± 0.02a	30.92± 4.74c	0.29± 0.10c
	500 kg/ha	0.20± 0.01a	36.48± 2.98c	0.37± 0.05bc
	1000 kg/ha	0.22± 0.02a	40.52± 1.80c	0.43± 0.06b
Mist Irrigation	0 kg/ha	0.23± 0.01a	62.07± 8.47b	0.40± 0.05bc
	500 kg/ha	0.22± 0.02a	57.60± 12.14b	0.60± 0.04a
	1000 kg/ha	0.36± 0.16a	89.20± 1.02a	0.66± 0.03a

a, b, c, d, e = letter notation is not similar, meaning that there is no real effect on the level Duncan test has a value of 5%.

Conversely, soil nitrogen content (0.20%–0.36%) did not show a consistent pattern between treatments. The nature of nitrogen, which is easily lost through leaching, denitrification, and volatilization, means that irrigation and fertilizer effectiveness have little effect on its availability (Shafreen *et al.,* 2021; Papadimitriou *et al.,* 2024). Overall, the results of this study confirm that mist irrigation, especially with high fertilizer doses, is more optimal in maintaining phosphorus and potassium availability compared to drip irrigation, thereby potentially increasing nutrient uptake and onion yields in karst soils. Significant differences in phosphorus and potassium content between mist irrigation and drip irrigation are due to the characteristics of mist irrigation, which distributes water evenly on the soil surface and maintains more stable moisture levels that can support the activity of phosphate-solubilizing microbes and reduce the level of P fixation by $Al3+$ and $Fe3+$, leading to the release of phosphorus from bound forms into available forms (Li *et al.,* 2023). Phosphorus is difficult to mobilize in dry soil, so it is more optimally available in soil with optimal water conditions because water dissolves phosphate compounds bound to soil particles, making them easily accessible to plants. Potassium is more mobile than phosphorus but still requires water to support transportation, diffusion, and movement in the soil (Liu *et al.,* 2018). Stable soil moisture in mist irrigation can reduce K binding by clay particles, thereby increasing its availability in the soil solution, whereas in drip irrigation with low doses shows low potassium content, indicating inefficient fertilizer distribution due to the narrower scope of nutrient movement and water pathways (Bansal *et al.,* 2021; Mouhamad *et al.,* 2016). The NPK uptake values for each irrigation technique and fertilizer dosage treatment are shown in Table 3.

Table 3. Results of ANOVA test on average NPK uptake

Irrigation techniques	NPK Dosage	Nitrogen (%)	Phosphorus (%)	Potassium (%)
Drip Irrigation	0 kg/ha	2.03± 0.26a	0.97± 0.08a	0.82± 0.03b
	500 kg/ha	1.47± 0.17a	0.85± 0.09a	1.46± 0.18a
	1000 kg/ha	1.95± 0.08a	0.85± 0.08a	1.02± 0.08ab
Mist Irrigation	0 kg/ha	1.68± 0.06a	0.88± 0.14a	0.88± 0.01b
	500 kg/ha	2.00± 0.59a	0.76± 0.07a	1.37± 0.28a
	1000 kg/ha	1.44± 0.19a	0.79± 0.09a	1.45± 0.32a

a, b, c, d, e = letter notation is not similar, meaning that there is no real effect on the level Duncan test has a value of 5%.

Nutrient uptake is influenced by the availability of nutrients in the soil, mobility, the chemical properties of each element, and the irrigation techniques used. The results indicate that K uptake increases with increased fertilizer application rates, particularly in mist irrigation systems, which maintain more uniform soil moisture levels, thereby supporting nutrient dissolution and diffusion (Li & Su, 2017; Bhattacharyya *et al.,* 2018). Conversely, N uptake remains relatively stable across treatments due to its high leaching and volatilization rates, meaning its availability in the soil does not always align with the applied fertilizer (Pal *et al.,* 2020;Xiang *et al.,* 2024). Phosphorus uptake did not show significant differences because it has low mobility and limited movement around the roots. Potassium has higher mobility and is distributed more evenly with the help of irrigation. Potassium ions (K+) can maintain relatively stable mobility, resulting in a more uniform distribution of K+ ions with mist irrigation compared to drip irrigation. Increased P and K uptake plays a crucial role in shallot bulb growth due to their roles in root formation, cell division, and bulb development (Wang *et al.,* 2021).

3.3 Shallot Growth

Table 4 show that irrigation techniques have a significant effect on shallot growth, both in terms of plant height and number of leaves. Conversely, NPK dosage only affects plant height, but does not affect the number of leaves. The interaction between the two factors does not show a significant effect on the observed growth parameters. In general, mist irrigation resulted in higher average plant height and number of leaves compared to drip irrigation.

Table 4. Results of ANOVA test on the average growth of shallots

Irrigation techniques	NPK Dosage	Plant Height (cm)	Number of Leaves (sheet)
Drip Irrigation	0 kg/ha	24,74 ± 2,30b	18,69 ± 2,72c
	500 kg/ha	26,27 ± 1,40b	19,86 ± 2,66bc
	1000 kg/ha	29,74 ± 0,69a	25,77 ± 3,88ab
Mist Irrigation	0 kg/ha	29,37 ± 1,68a	25,57 ± 4,42ab
	500 kg/ha	31,28 ± 0,57a	25,80 ± 2,58ab
	1000 kg/ha	30,69 ± 1,80a	27,65 ± 3,77a

a, b, c, d, e = letter notation is not similar, meaning that there is no real effect on the level Duncan test has a value of 5%.

The best treatment was observed in mist irrigation with an NPK dose of 1000 kg/ha, which produced the highest plant height (30.69 cm) and the greatest number of leaves (27.65 leaves). Conversely, the lowest growth was observed in drip irrigation without fertilization (24.74 cm; 18.69 leaves). The more stable humidity conditions in mist irrigation promote the development of meristematic tissue, thereby enhancing plant height growth and leaf formation (G.Li *et al.,* 2023). Increasing NPK doses also tended to increase plant height, indicating that the availability of macronutrients (N, P, K) supports cell division and elongation (Amare, 2020;Bekele, 2018). These findings align with Wang *et al.* (2019), who found that regulating soil moisture through irrigation plays a crucial role in supporting the vegetative growth of shallots.

3.4 Shallot Growth Rate

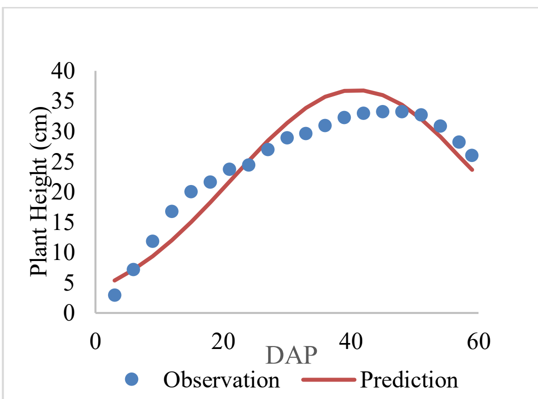
Modeling plant height growth with a quadratic-exponential function produces the equation $W(t) = W_0 \cdot \exp[\mu_0 (t - 0.5Dt^2)]$. The parameters obtained through non-linear regression reflect the initial growth conditions (W_0), relative growth rate (μ_0), and inflection point (D) that determine when the growth rate reaches its peak.

Table 6. Quadratic Exponential Growth Model Function

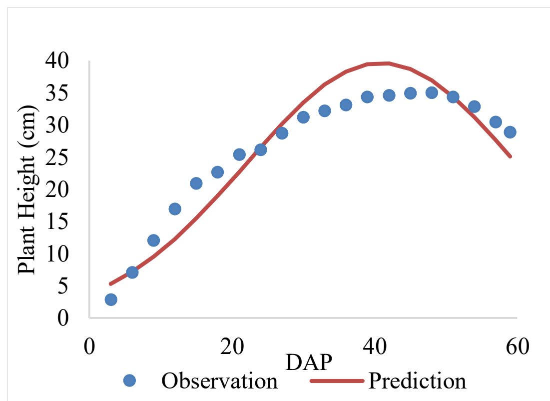
Irrigation techniques	NPK Dosage	Model function
Drip Irrigation	0 kg/ha	W(t) = 3.902 * exp (0.110 * (t - 0.5*0.024*t^2))
	500 kg/ha	W(t) = 3.805 * exp (0.114 * (t - 0.5*0.024*t^2))

	1000 kg/ha	W(t) = 3.629 * exp (0.121 * (t - 0.5*0.024*t^2))
Mist Irrigation	0 kg/ha	W(t) = 3.993 * exp (0.114 * (t - 0.5*0.024*t^2))
	500 kg/ha	W(t) = 3.989 * exp (0.115 * (t - 0.5*0.023*t^2))
	1000 kg/ha	W(t) = 4.088 * exp (0.111 * (t - 0.5*0.023*t^2))

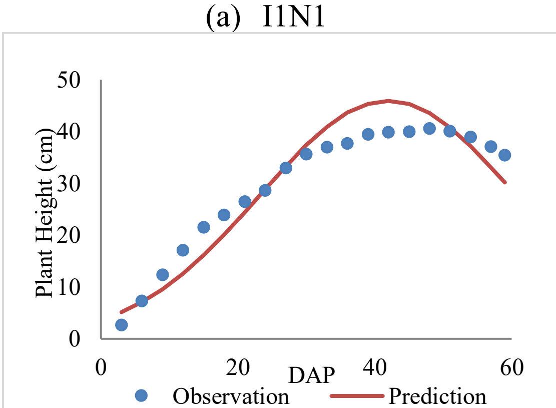
The prediction function in Table 6 was used to calculate daily plant height, and the prediction results were compared with field observation data to determine the accuracy of the model. The irrigation type variable consists of drip irrigation (I1) and mist irrigation (I2). The NPK Phonska fertilizer dose variable includes 0 kg/ha (N1); 500 kg/ha (N2) and 1000 kg/ha (N3). The prediction results and observations of plant height growth are presented in Figure 1.



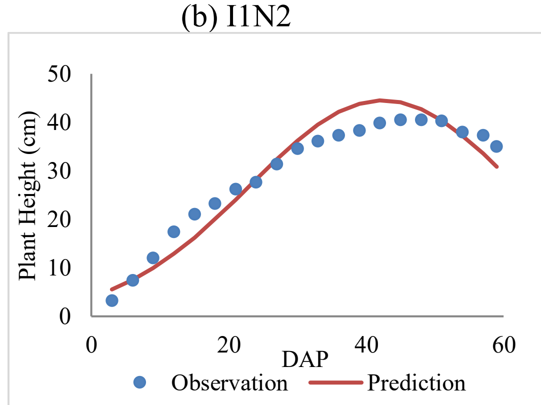
(a) I1N1



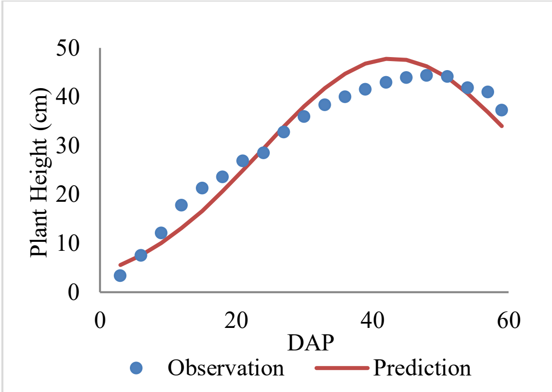
(b) I1N2



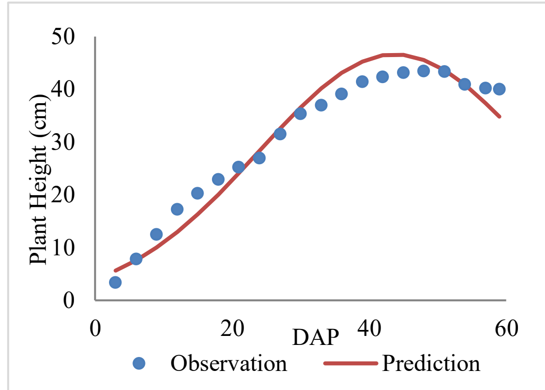
(c) I1N3



(d) I2N1



(e) I2N2



(f) I2N3

Figure 1. Graph of predicted and observed plant height growth

The highest growth was obtained in treatment I2N3, namely mist irrigation with 1000 kg/ha of NPK. Biologically, the growth pattern follows a quadratic exponential curve with three main phases, namely the slow initial phase (lag), the rapid growth phase (exponential), and the flat phase towards the end of the vegetative period (stationary) (Liu *et al.,* 2018). A higher μ_0 value indicates accelerated growth, while the D parameter relates to the plant's age when maximum growth is achieved. These findings are consistent with Sibly & Brown (2020), who stated that plant growth follows a sigmoidal pattern due to physiological and resource limitations. Thus, this model can be used as a basis for evaluating the effectiveness of treatments in accelerating the vegetative growth of shallots.

Table 7. Results of t-tests for predicted and observed plant height values

Irrigation techniques	NPK Dosage	p-*value*
Drip Irrigation	0 kg/ha	0,961
	500 kg/ha	0,953
	1000 kg/ha	0,944
Mist Irrigation	0 kg/ha	0,955
	500 kg/ha	0,955
	1000 kg/ha	0,960

A comparison graph between observed and predicted values shows the similarity of growth patterns (Figure 1), and a t-test reveals no significant difference ($p>0.05$) between the two (Table 7). This confirms that the model is sufficiently representative to describe the growth dynamics of shallot plants. The highest leaf growth rate was observed in treatment I2N3, which involved mist irrigation with 1000 kg/ha of NPK, and was comparable to the plant height growth rate. This further reinforces that this combination of treatments is capable of supporting plant growth through optimal leaf formation. Stable availability of water and dissolved nutrients can support plant tissue formation (Kudoyarova *et al.,* 2015) (Kareem *et al.,* 2024). Modeling of shallot plant height growth produced specific growth prediction functions for each treatment combination in Table 8.

Table 8. Average growth rate of leaf number

Irrigation techniques	NPK Dosage	Leaf Rate
Drip Irrigation	0 kg/ha	0.223
	500 kg/ha	0.257

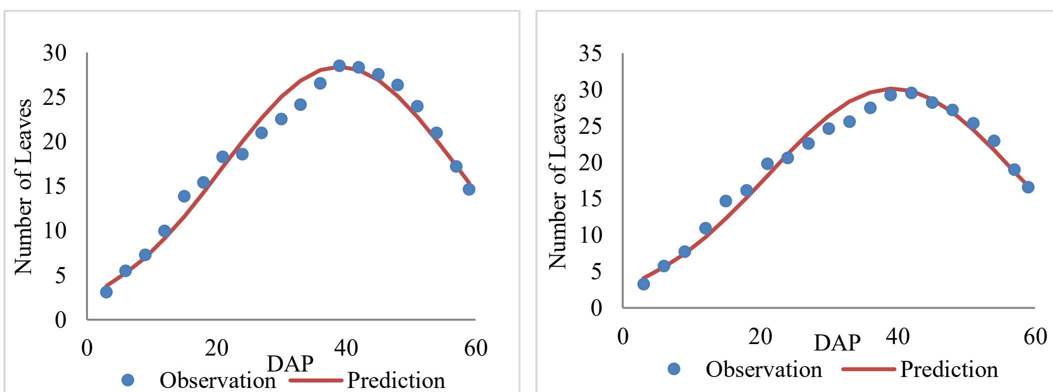
	1000 kg/ha	0.385
Mist Irrigation	0 kg/ha	0.420
	500 kg/ha	0.513
	1000 kg/ha	0.545

Modeling leaf number growth using a quadratic exponential function (Table 9) produced specific predictive equations for each treatment combination.

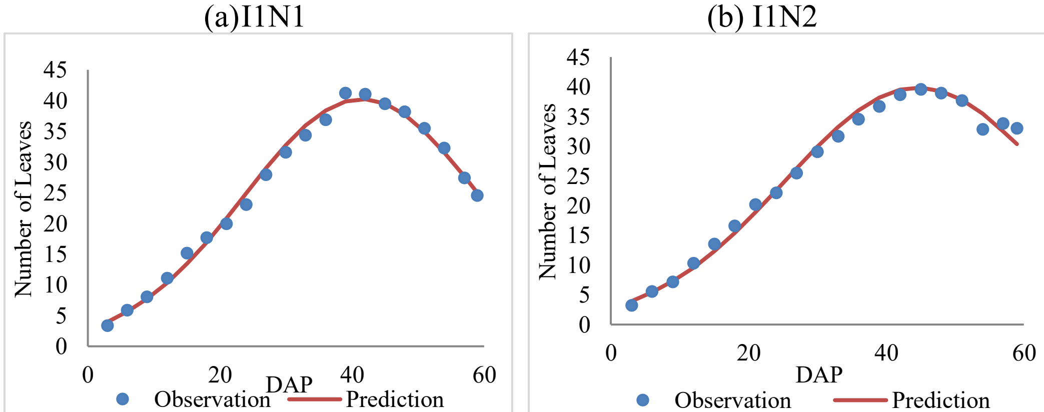
Table 9. Exponential Quadratic Leaf Number Growth Model Function

Irrigation techniques	NPK Dosage	Model Function
Drip Irrigation	0 kg/ha	W(t) = 2.672 * exp (0.121 * (t - 0.5*0.026*t^2))
	500 kg/ha	W(t) = 2.882 * exp (0.119 * (t - 0.5*0.025*t^2))
	1000 kg/ha	W(t) = 2.734 * exp (0.130 * (t - 0.5*0.024*t^2))
Mist Irrigation	0 kg/ha	W(t) = 2.772 * exp (0.119 * (t - 0.5*0.022*t^2))
	500 kg/ha	W(t) = 2.648 * exp (0.124 * (t - 0.5*0.023*t^2))
	1000 kg/ha	W(t) = 2.824 * exp (0.125 * (t - 0.5*0.023*t^2))

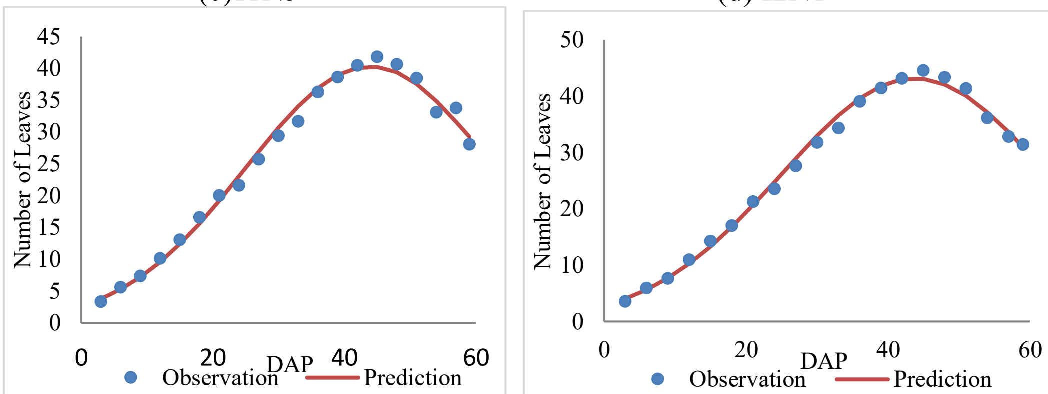
The irrigation type variable consists of drip irrigation (I1) and mist irrigation (I2). The NPK Phonska fertilizer dose variable includes 0 kg/ha (N1); 500 kg/ha (N2) and 1000 kg/ha (N3). The application of this model shows a high degree of agreement between predicted and observed values, as shown in Figure 2.



(a)I1N1 (b) I1N2



(c)I1N3 (d) I2N1



(e) I2N2 (f) I2N3

Figure 2. Graph of predicted and observed leaf growth

The results of the t-test (Table 10) indicate that all treatments have p-values > 0.05, meaning there are no significant differences between observed data and predicted results. Therefore, the model can be accepted as a representation of actual leaf number growth.

Table 10. Results of t-tests for predicted and observed number of leaf

Irrigation techniques	NPK Dosage	p-*value*
Drip Irrigation	0 kg/ha	0,985
	500 kg/ha	0,973
	1000 kg/ha	0,992
Mist Irrigation	0 kg/ha	0,979
	500 kg/ha	0,995
	1000 kg/ha	0,995

The consistent increase in the number of leaves reflects better plant biomass accumulation, as leaf area is directly related to light energy absorption capacity. According to Sibly & Brown (2020), the rate of leaf formation follows a logistic pattern determined by the interaction of genetic and environmental factors. The results of this study indicate that a micro-irrigation system supported by appropriately dosed NPK fertilization not only influences vegetative growth but also enhances plant photosynthetic capacity through increased leaf number (Zhao *et al.,* 2017). The highest leaf growth rate was observed in treatment I2N3, which consisted of mist irrigation with 1000 kg/ha of NPK, resulting in a plant height growth rate that was comparable to that of the control treatment. This further reinforces the fact that this combination of treatments is capable of supporting plant growth through optimal leaf formation.

3.5 Shallot Yield

Table 11 show that irrigation techniques have a very significant effect on the wet weight of tubers, total dry weight, and diameter of shallot tubers. Mist irrigation consistently yields higher values compared to drip irrigation, especially when combined with an NPK dose of 1000 kg/ha, which produces the highest fresh weight of bulbs (106.47 g), total dry weight (18.42 g), and largest bulb diameter (30.07 mm).

Table 11. Results of ANOVA tests on crop yields

Irrigation techniques	NPK Dosage	Wet Weight of Tubers (g)	Total Dry Weight (g)	bulb diameter (mm)
Drip Irrigation	0 kg/ha	49,34 ± 26,90 d	9,36 ± 2,15c	24,81 ± 1,70c
	500 kg/ha	62.40 ± 7,10 cd	10,47 ± 2,11c	25,18 ± 1,20c
	1000 kg/ha	79.61 ± 14,30 bc	11,48 ± 2,28bc	27,02 ± 1,12bc
Mist Irrigation	0 kg/ha	81.74 ± 6,87 bc	15,45 ± 2,61ab	28,13 ± 1,16ab
	500 kg/ha	98.39 ± 17,00 ab	16,65 ± 3,21a	29,04 ± 2,39ab
	1000 kg/ha	106.47 ± 18,8 a	18,42 ± 2,77a	30,07 ± 1,06a

a, b, c, d, e = letter notation is not similar, meaning that there is no real effect on the level Duncan test has a value of 5%.

This increase in yield is associated with more stable soil moisture under mist irrigation, which supports nutrient uptake, photosynthesis, and the translocation of assimilates to the bulbs (Terán-Chaves *et al.,* 2023; Li *et al.,* 2023). Increasing NPK doses tended to increase tuber fresh weight and tuber diameter but had no significant effect on total dry weight. This indicates that plant response is more pronounced in fresh biomass accumulation and tuber size enlargement compared to dry matter content. According to Singh *et al.* (2018), the role of NPK fertilizer is primarily in providing N, P, and K nutrients to support vegetative growth and tuber formation. The absence of interaction between irrigation and NPK dose indicates an additive response, but mist irrigation treatment with NPK at 1000 kg/ha proved most effective in increasing onion yield through enhanced bulb cell expansion and accumulation of reserve carbohydrates (Ombódi *et al.,* 2016).

3.6 Total Flavonoid Content of Shallot

The total flavonoid content in shallot bulbs showed differences in each treatment combination of irrigation system and NPK fertilizer dosage. In general, drip irrigation produced higher flavonoid levels than mist irrigation. Under drip irrigation, an NPK fertilizer dose of 500 kg/ha yielded the highest flavonoid content (78.83 mg/kg), higher than both the untreated control (63.96 mg/kg) and the 1000 kg/ha dose (59.89 mg/kg). This indicates that moderate doses can balance nitrogen and phosphorus supply to support phenolic compound biosynthesis without promoting excessive vegetative growth (Salama *et al.,* 2024).

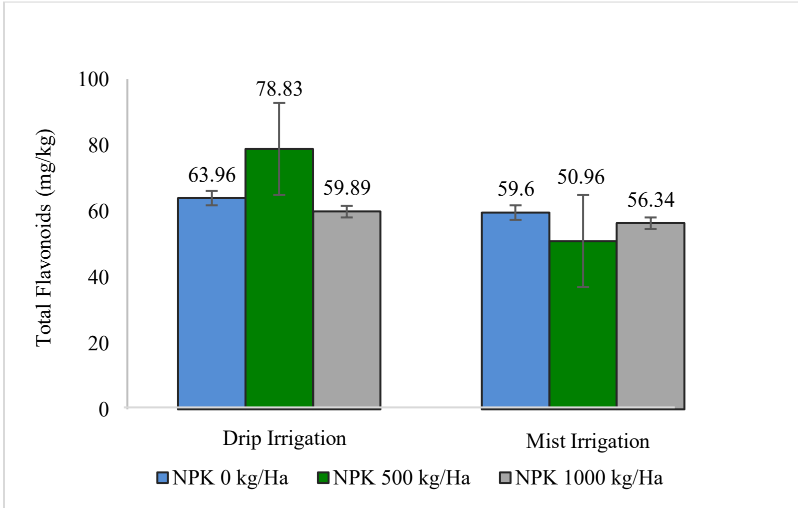


Figure 3. Total flavonoid content of shallot

In contrast, in mist irrigation, the flavonoid content was lower, ranging from 50.96 to 59.6 mg/kg. The high micro-humidity conditions in this system are thought to reduce the mild oxidative stress that is actually needed to induce the accumulation of secondary metabolites (Baskar *et al.,* 2018). Environmental factors such as water availability, nutrient status, and oxidative stress play a crucial role in regulating flavonoid biosynthesis (Patil *et al.,* 2024). Macronutrients such as NPK play a role in optimizing plant metabolism, including flavonoid biosynthesis. Nitrogen supports the synthesis of aromatic amino acids as precursors to flavonoids, phosphorus is involved in energy metabolism that supports biosynthetic pathways, while potassium can increase the activity of enzymes involved in phenylpropanoid pathways (Srivastava *et al.,* 2020). Therefore, the combination of drip irrigation and moderate NPK fertilization (500 kg/ha) is more recommended, as it not only enhances tuber growth but also enriches the bioactive flavonoid content, which is functionally valuable for both consumers and the food industry (Nugraha *et al.,* 2018).

4. Conclusions

This study shows that micro-irrigation techniques and NPK doses have a significant effect on the growth, yield, nutrient uptake, and flavonoid content of shallots. Fog irrigation with a dose of 1000 kg/ha resulted in the highest growth, nutrient uptake, and bulb yield, while drip irrigation with a dose of 500 kg/ha produced the highest flavonoid content (78.83 mg/kg). Therefore, the choice of cultivation technique should be tailored to production objectives: drip irrigation with 500 kg/ha NPK is more suitable for enhancing bioactive quality, while mist irrigation with 1000 kg/ha NPK is recommended for maximizing yield. Further research under various environmental conditions is needed to strengthen the sustainable application of these findings.

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6. Authors Note

The authors declare that there is no conflict of interest regarding to the publication of this article. Authors confirmed that the paper was free of plagiarism.

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