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Research Paper

Evaluation of water use efficiency and yield on shallot (*Allium cepa* L.) cultivation under conventional irrigation and sensor-based drip irrigation

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ABSTRACT

Water shortage is a critical problem in unirrigated agricultural land in hilly regions, especially during the dry season. Inefficient irrigation practices and a lack of attention to crop water needs exacerbate the water shortage. A pot experiment aimed to evaluate conventional irrigation (CI) and sensor-based drip irrigation (SDI) approach on shallot cultivation in terms of total irrigation, water percolation, yield, and water use efficiency. Results revealed that the total amount of irrigation water in the CI was significantly higher than in the SDI at each growth phase, resulting in higher water percolation throughout the shallot's growth phases in the CI. The irrigation water use efficiency (IWUE) value increased significantly by 87.7% in the SDI compared to the CI, but resulted in a 26.7% yield reduction. This study provides information indicating that CI tends to use excessive amounts of irrigation water, so that it requires innovative water management to be more efficient, leading to an increased yield by using the SDI approach. Irrigation practices considering optimal soil water content at each plant growth phase are essential to improve water use efficiency and prevent excessive water percolation.

Keywords: Shallot, Drip irrigation, Water use efficiency, Pot experiment, Irrigation water requirement, Percolation

Water shortage poses a critical challenge to agricultural sustainability in hilly regions, where high elevations and steep slopes exacerbate the limited availability of water irrigation resources. Due to topographical constraints, most available water flows downstream, leaving upland areas with severe irrigation shortages. This issue is further intensified by climate change, as global warming increases the frequency and severity of droughts, threatening crop productivity and food security in vulnerable ecosystems (Ji *et al.,* 2023). Climate change-induced variability in precipitation patterns, allied with prolonged dry seasons, adversely affects agricultural productivity. Wing *et al.,* (2021) stated that climate change has a significant impact on the decline of farm yields worldwide, including those of horticultural crops. Overall, agricultural productivity has decreased by 21% since 1961 due to the effects of climate change (Ortiz-Bobea *et al.,* 2021). Innovative water management is urgently required to ensure water is utilized effectively to support sustainable agriculture, particularly in hilly regions with limited water sources (Sharma and Changade, 2025).

In Indonesia, shallot (*Allium cepa* L.) cultivation is also concentrated in hilly regions, where agricultural systems predominantly depend on inadequate water storage infrastructure. This topographic dependence renders shallot crops particularly susceptible to drought stress, especially during extended dry periods that are becoming increasingly frequent and intense due to climate change. Conventional irrigation (CI) as practiced by farmers in the field is characterized by rigid scheduling and unregulated water application, not only exhibiting water inefficiency but also

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Table 1: Initial soil properties

Properties	Value	Classification
Soil Texture (%)		Clay
Sandy	13.0	
Silt	20.3	
Clay	66.8	
Particle density (g cm^{-3})	1.9	
pH H_2O	7.3	Neutral
Cation exchange capacity (CEC) (cmol (+) kg^{-1})	53.5	Very High
Organic carbon (%)	1.8	High

exacerbating water loss through the percolation process (Hussain *et al.,* 2023). An alternative way to supply irrigation water is to extract groundwater by drilling wells. However, this activity may lead to land subsidence, which impacts agricultural sustainability in hilly regions (Galloway and Burbey, 2011). Therefore, applying sensor-based drip irrigation (SDI) by maintaining water at available water capacity is a promising strategy to overcome the problem of water overuse. Drip irrigation systems have shown promising performance for optimizing water use efficiency in areas with water-limited conditions (Sharma *et al.,* 2023; Oktavia *et al.,* 2025).

Drip irrigation approaches have been widely studied in water-limited areas. Still, the evaluation of conventional irrigation (CI) compared to sensor-based drip irrigation (SDI) practices in terms of water use efficiency in shallot cultivation is limited. This study aims to evaluate irrigation strategies between CI vs SDI in shallot cultivation in terms of total irrigation, water percolation, yield, and water use efficiency. The results of this study contribute to the development of more appropriate and efficient irrigation practices compared to existing practices or CI, supporting sustainable agricultural practices in water-limited areas.

MATERIAL AND METHODS

Study location

This research was conducted on a greenhouse scale at Universitas Gadjah Mada, Yogyakarta (Latitude: 7°46’32.205”, Longitude: 110°22’53.689”) during summer season of 2024. Soil samples for the experiment were obtained compositely from hilly agricultural land in Nawungan Village, Selopamioro, Bantul, Yogyakarta (Latitude: 7°57’45.508”, Longitude: 110°24’41.475”), which is one of the centers of shallot production in the Special Region of Yogyakarta Province. Initial soil characteristics were analyzed to determine the estimated water requirements of the plants presented in Table 1.

Pot experimental treatment

Pot experiment evaluated two different irrigation strategies as shown in Fig. 1, which are CI and SDI, on the shallot cultivation variety Bima Brebes from April 1 to June 15, 2024 (76 days). The pot volume used was 5 kg, with a depth of 25 cm, following the physiological conditions of thick roots. Fertilizer applications during the cultivation period included mature cow manure with an organic content of 2% at 3750 kg ha^{-1}, superphosphate fertilizer 36% (SP 36) at 400 kg ha^{-1}, NPK blue fertilizer 16-16-16 at 40 kg ha^{-1}, NPK Complex Fertilizer 15-15-15 at 120 kg ha^{-1}, and KCl at 120 kg ha^{-1}. Agronomic parameters of the plant, such as height, biomass, and yield of the shallot, were measured to assess the growth of the shallot. Temperature and humidity data in the greenhouse were recorded in real-time using a thermometer and hygrometer connected to the logger. The logger was used as a tool to automatically record and monitor data on the drip irrigation system, including data of microclimate, data of irrigation volume and duration, and data of water pressure and flow.

Drip irrigation system operation

Both of the irrigation practices, CI and SDI, utilize a drip irrigation system for shallot watering. In the CI system, watering is automatically scheduled based on farmers’ field practices with a frequency of once every 2 days in the morning. The determination of irrigation water volume given for each watering is based on the average irrigation water volume practiced by farmers in the field, with an average of 30 farmer samples. The SDI system supplies water until it returns to field capacity (FC), and the system automatically activates the valve when soil moisture passes the threshold approaching the permanent wilting point (PWP). Soil moisture levels were detected by putting a temperature sensor into the soil in each pot for each CI and SDI treatment, and were automatically recorded by the logger. Water percolation measurements are collected in a measuring cup located under the pot as shown in Fig. 1.

The determination of FC and PWP was carried out by analyzing soil samples in the laboratory using the pressure plate apparatus method (Balittan, 2006). Following standard protocols, FC and PWP were measured at a pressure of 1/3 bar (pF 2.54) and 15 bar (pF 4.2), resulting in water contents of 48.40% and 38.21%, respectively. These pF values represent the soil water potential, quantifying the energy state of water in the soil matrix and its availability to plants. For SDI treatment, irrigation volumes were set at 1.5 times the available water to account for elevated evapotranspiration rates in the greenhouse environment (Priatri, 2023). This adjustment compensated for the higher temperature-induced water losses while maintaining optimal soil moisture levels for plant growth.

The drip irrigation system was calibrated to determine the uniformity of discharge across all installed emitters. The uniformity of the irrigation discharge on the full-open valve resulted in an Emission Uniformity (EU) coefficient value of 78.64% with a water discharge of 11.04 L h^{-1}, which is higher than that of the half-open valve (Merriam and Keller, 1978). Referring to the calibration results, the full-open valve was chosen for use in this study.

Calculation of evapotranspiration, irrigation water requirement, and water use efficiency

Actual evapotranspiration within the greenhouse environment was calculated using the standardized Penman-Monteith equation (Allen *et al.,* 1998), with the input parameters derived from microclimate data recorded by an automated weather sensor inside the greenhouse. The actual evapotranspiration was

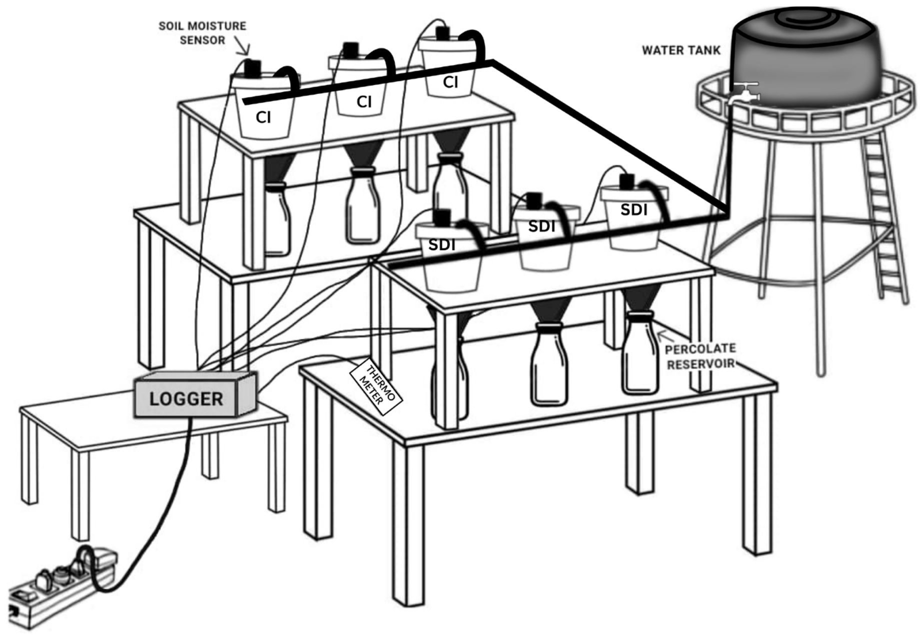

Fig. 1: Research experimental design

adjusted to crop-specific conditions using the equation:

$$ETc = ETo \times Kc$$

where: *ETc* – actual evapotranspiration (mm day^{-1}), *ETo* – constant evaporation (mm day^{-1}), *Kc* – crop coefficient.

$$ET_o = \frac{\left[0.408\,\Delta\,(Rn - G) + \left\{\frac{\gamma 900}{T + 273}\right\} U_2 (ea - ed)\right]}{[\Delta + \gamma(1 + 0.34U_2)]}$$

where: *Rn* – net radiation equivalent to evaporation (mm day^{-1}), *G* – soil heat flux (MJ/m^{-2}day^{-1}), *γ* – psychometric constant (kPa ^{o}C^{-1}), *T* – average temperature (^{o}C), U_2 – wind speed (m s^{-1}), (*ea-ed*) – difference between saturated and actual vapor pressure (kPa).

Irrigation water requirement (IWR) for shallot crops is calculated to ensure sufficient water for the plants. To determine the water requirement of shallot plants in pot scale, the following formula is required:

$$ETc\ (pot) = ETo \times Kc \times 0.1 \times A$$

where: *ETc (pot)* – water requirements for plants in pot (ml day^{-1}), *ETo* – potential evapotranspiration (mm day^{-1}), *Kc* – plant coefficient, *A* – pot area (cm^2).

Irrigation water use efficiency (IWUE) and crop water use efficiency (CWUE) were calculated using the following formula:

$$IWUE = \frac{Y}{I}$$

where: *Y* – crop yield (kg m^{-2}), *I* – amount of water irrigation (L m^{-2})

$$CWUE = \frac{Y}{ET}$$

where: *Y* – crop yield (kg m^{-2}), *ET* – evapotranspiration (Ghanem *et al.,* 2022)

Statistical analysis

The independent t-test was used to compare the significance of the differences between irrigation treatments of CI vs SDI. This study used a completely randomized design (CRD) with six replicate plots per treatment. Statistical analysis was performed using IBM SPSS Statistics 27 software at a significance level of $p<0.05$.

RESULTS AND DISCUSSION

Weather conditions in the greenhouse

Table 2 presents weather conditions in the greenhouse during the shallot cultivation period during April 1 to June 15, 2024. The average temperature in the greenhouse was 33.34°C, 31.37°C, 31.74°C, and 30.61°C in the initial, development, mid-season, and end-season phases, respectively. Additionally, the measured air humidity levels were 81.98%, 95.00%, 94.28%, and 95.00% in the initial, development, mid-season, and end-season phases, respectively.

Drip irrigation system observation

Drip irrigation system worked effectively in the CI and SDI treatments, as indicated by the stability of the soil moisture percentage range in Fig. 2. This system responded to predetermined triggers, particularly in the CI treatment, where the range of soil moisture percentages exhibited fluctuations that closely mirrored actual field conditions. The system provided feedback by activating the valve (valve on) when soil moisture decreased below the threshold and deactivating it (valve off) when moisture increased to a predetermined value. In the CI, watering occurred automatically every two days in the morning, with an average water volume of 448 mL per watering. In the SDI treatment, the system automatically regulated the watering within the field capacity range, with nine

Table 2: Weather conditions in the greenhouse during shallot cultivation

Variables	Growth phase			
	Initial	Development	Mid-Season	End-Season
Age (days)	28	22	14	12
ETo (mm day^{-1})	2.7	2.3	2.0	2.0
Kc	0.7	1.0	1.0	0.7
ETc (mm day^{-1})	1.9	2.4	2.1	1.5
IWR (L m^{-2} plant^{-1})	52.8	52.0	27.2	17.7
Tmean (°C)	33.4	31.4	31.7	30.6
Tmin (°C)	29.7	29.3	29.7	25.5
Tmax (°C)	38.5	32.4	33.4	32.1
RH mean (%)	82.0	95.0	94.3	95.0
RHmin (%)	57.4	95.0	85.0	95.0
RHmax (%)	95.0	95.0	95.0	95.0

Table 3: Total amount of irrigation and percolation water at each growth phase of the shallot

Growth phase	Total irrigation (L m^{-2})		Water percolation (L m^{-2})	
	SDI	CI	SDI	CI
Initial	44.6	199.8	-	117.0
Development	77.5	157.0	21.4	96.8
Mid-season	36.5	99.9	-	74.9
End-season	33.4	71.4	-	56.2
Total	192.0	528.1	21.4	345.0

waterings and an average water volume of 280 mL per watering.

Total volume of irrigation water and total percolation water

Total irrigation water and total water percolation for the CI and SDI treatments in different shallot growth phases are presented in Table 3. In general, the total irrigation water in the CI treatment was 175% higher than that in the SDI treatment. In addition, watering in the CI treatment resulted in total water percolation of 1512%, occurring in every growth phase of the shallot. Based on the measurement results, irrigation water in the initial phase of the SDI was 15.53% less than the IWR for shallots. This matter occurs due to the soil condition having high porosity and an initial compaction process, which may result in less accurate sensor readings. Therefore, soil pre-treatment and optimization of sensor readings are needed to ensure that the IWR is fulfilled in the early phase for optimal plant growth (Kumar *et al.,* 2024).

The percolation rate of water in SDI was lower than in the CI, indicating that the SDI approach was more efficient, while the CI tended to be excessive in irrigation water. The amount of percolation water affects fertilization because it may inhibit the absorption of nutrients by plants, especially those containing nitrates, which are highly susceptible to leaching (Hatiye *et al.,* 2016). Saccon (2017) emphasized that the time and appropriate amount of water irrigation application, integrated with an efficient irrigation system, are essential to ensure sufficient water for optimal yields.

The influence of irrigation treatment on shallot growth and yield

The trend of shallot plant height growth presented in

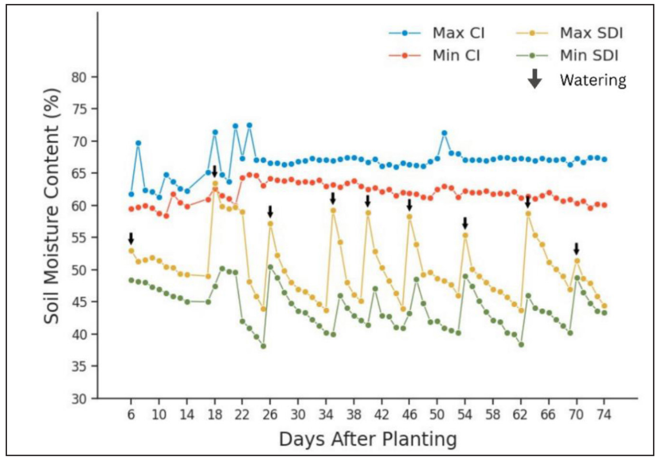

Fig. 2: Minimum and maximum soil water content in CI and SDI during shallot cultivation

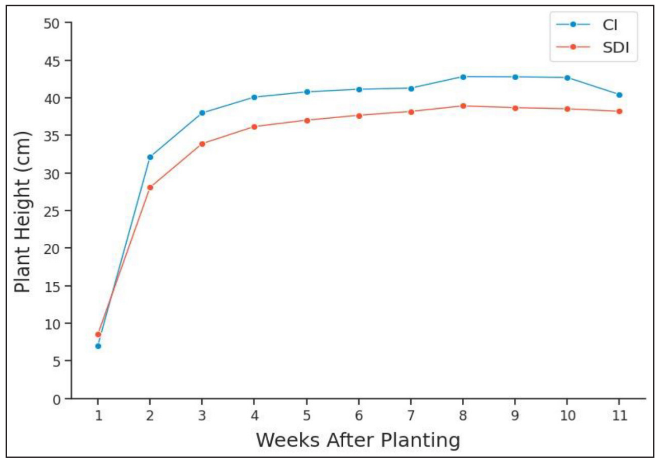

Fig. 3: Graph of shallot height in the CI and SDI treatments during shallot cultivation

Fig. 3 indicates that the CI treatment results in faster height growth compared to the SDI treatment. In the 10th week after planting, a decrease in plant height was observed in the CI and SDI treatments due to plant wilting. Wilting of shallot leaves is generally caused by the inhibition of cell development, indicating that the bulbs have reached maturity and are ready for harvest (Ansar *et al.,* 2022).

The yield calculated from biomass in SDI was reduced by 26.7% less than CI, as presented in Table 4. Reducing the irrigation water saves water, but it may result in suboptimal yields (Wei and Bailey, 2019). Previous research conducted by Woldetsadik *et al.,* (2004) recommends that soil water content for shallot plants be monitored at around 40% in the initial and development stages. Results of the SDI treatment confirm previous research that maintaining soil moisture within a wide range, approaching the permanent wilting point, was not suitable for supporting optimal yields. In contrast, the CI practice allows for continuous water availability to support plant growth through watering frequency of once every two days. Christmann *et al.,* (2013) reported that continuous water supply maintains leaf moisture, which is important in supporting the process of photosynthesis, especially in the absorption of CO_2.

Table 4: Biomass, yield, IWUE, and CWUE of shallot in the CI and SDI treatments

Treatment	Total biomass (g)	Yield (kg m^{-2})	IWUE (kg m^{-3})	CWUE (kg m^{-3})
CI	37.4*	1.2*	22.0	7.9*
SDI	27.6	0.9	41.3*	5.8

Note: Asterisks indicate significant differences ($p<0.05$) between CI and SDI treatments

The effect of irrigation treatment on IWUE and CWUE values

In general, the IWUE values in the SDI treatment showed higher efficiency compared to the CI (Table 4). IWUE value in the SDI was recorded as significantly increased, reaching 87.7% higher than in the CI. IWUE was used to assess the efficiency of water use in producing crop yields (Kumar *et al.,* 2007). Based on the results of the CI treatment, the volume of water used tends to be excessive. In contrast, the SDI approach was more efficient in managing water irrigation. This finding aligns with the research results by Ibragimov *et al.,* (2007), which reported that drip irrigation based on FC increased IWUE by 35–103% compared to the furrow irrigation system. While the IWUE value in SDI was efficient, irrigation efficiency was uncorrelated with optimal yields. Therefore, applying the SDI approach with watering frequency from the CI practices (once every 2 days) may be an alternative way to increase IWUE and yields without excessive water irrigation and water loss through percolation processes.

The CWUE value in the CI treatment was higher than that in the SDI treatment. Under SDI treatment, substantial fluctuations in soil moisture led to discontinuous water availability, reducing plant water uptake efficiency. Soil properties, including fine texture, high dry bulk density, and high temperature, may decrease the accuracy of soil moisture sensors in detecting water content (Payero *et al.,* 2017; Xiao *et al.,* 2021; Kelley *et al.,* 2024). It is essential to note that maintaining the proper range of soil moisture and considering soil characteristics is important for achieving optimum yields in shallot cultivation.

CONCLUSION

This greenhouse pot experiment showed that sensor-based drip irrigation (SDI) improved Irrigation water use efficiency (IWUE) by 87.7% compared to conventional irrigation (CI), though it resulted in a 26.7% yield reduction, likely due to moisture stress approaching the PWP threshold. While the CI produced higher yields, it was inefficient with excessive water use and significant percolation losses. The findings suggest that adjusting SDI to match CI watering intervals (e.g., every two days) could strike a better balance between water use efficiency and yield. This modified approach may optimize water use while minimizing yield loss and reducing water loss. Given the controlled greenhouse setting, field-scale studies are needed to validate these results. Future research should also examine socio-economic factors influencing SDI adoption, including labor savings, cost-effectiveness, and long-term viability. A holistic understanding is essential to guide practical recommendations for adopting the CDI approach to farmers in terms of improving water use efficiency and yield, particularly for water-scarce hilly regions.

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Data Availability: The author does not have permission to share the data used in this study.

Conflict of Interest: The author declares no conflicts of interest regarding this study.

Authors contribution: **A. Turrodiyah:** Conceptualization, Methodology, Visualization, Writing-Original draft, Editing; **BW. Santoso:** Investigation, Data Analysis; **N.I. Priatri:** Investigation, Methodology; **F.A. Rizqi:** Reviewing; **C.I. Hsieh:** Resources; **Subejo:** Supervision; **J. Widada:** Supervision; **J. Sartohadi:** Conceptualization, Supervision.

Authors certificate: The manuscript or any part thereof is not under consideration for publication elsewhere and has been approved by all co-authors.

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