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Effectiveness of Drip Irrigation Systems in Organic Chili Cultivation under Land Constraints

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ABSTRACT

Chili peppers (*Capsicum* spp.) play a key role in Indonesia's horticultural economy, yet their cultivation—particularly under organic systems—faces persistent challenges related to land scarcity and efficient water management. This study aimed to evaluate the performance of drip irrigation compared with conventional watering methods for organic red chili grown under limited-land conditions. A controlled screen-house experiment was conducted using a 2×3 factorial RCBD with two irrigation methods (drip and conventional) and three water-dose levels (80%, 100%, and 120% ETc). Growth traits, water use efficiency (WUE), yield, and fruit quality parameters were measured. The results showed that drip irrigation combined with the optimal 100% ETc water dose significantly improved physiological stability, plant growth, total yield (12.35 t/ha), and WUE while minimizing water loss. Over-irrigation at 120% ETc reduced plant productivity, emphasizing the importance of precise water dosing. Incorporation of secondary climate and soil data from BMKG and ISRIC supported the broader applicability of the findings to West Java and similar peri-urban regions. Overall, the study demonstrates that precision drip irrigation provides a sustainable strategy to optimize resource efficiency and maintain high fruit quality in organic chili production on restricted land.

Keywords: drip irrigation; organic chili; water use efficiency; land constraints; horticulture.

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1. Introduction

Chili peppers (*Capsicum* spp.) are a strategic horticultural commodity in Indonesia, serving not only as a culinary staple but also as a major source of farmer income and an indicator of national food-price stability [1]. Demand for organically produced chili has

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

increased markedly in recent years, driven by greater public awareness of health and environmental sustainability. Consumers are willing to pay premium prices for chemical-free products, creating a rapidly expanding market segment [2]. Despite this growing demand, organic chili production is frequently constrained by shrinking agricultural land caused by rapid urbanization and land conversion, particularly in peri-urban regions where cultivation is often limited to small plots or controlled environments such as screen houses [1]. These spatial limitations require technological solutions capable of maximizing productivity per unit area while maintaining compliance with organic farming principles.

Efficient water management is a major challenge in organic chili cultivation. Chili plants are highly sensitive to drought and excess moisture, especially during flowering and fruit set, and sub-optimal soil water conditions can lead to severe yield losses [3]. At a global scale, freshwater scarcity continues to intensify, with billions of people living in water-stressed regions and climate change increasing the frequency of droughts and erratic rainfall [4]. Conventional irrigation methods, such as surface or manual irrigation, often operate at efficiencies below 50% due to evaporation and percolation losses, and can exacerbate nutrient leaching—an especially critical issue in organic systems where nutrient release depends on the gradual mineralization of organic matter [5].

Drip irrigation has emerged as a key technology to address both land and water constraints. By delivering water slowly and precisely to the root zone, drip systems maintain stable soil moisture and minimize water loss [6]. They offer high water-use efficiency, often reaching 90–95%, making them highly suitable for production in limited land areas [7]. In organic farming, drip irrigation can be combined with organic fertigation using liquid organic fertilizers, allowing accurate nutrient delivery and reducing leaching risks [8]. Additionally, because drip systems keep foliage dry, they help suppress humidity-induced plant diseases, which is advantageous for pesticide-free organic cultivation. Properly designed micro-irrigation systems can also overcome hydraulic limitations typical of small or uneven plots, reinforcing their role in sustainable precision agriculture [9].

Previous studies have shown substantial gains in yield and water savings from drip irrigation in crops such as tomatoes [10], watermelon [11], and chili, particularly in dryland systems [7]. However, empirical evidence remains limited for intensive organic chili cultivation under spatial constraints, especially concerning the

Agricultural Power Journal, November **2025**, Vol 2, No 4

optimization of irrigation doses (ETc) and their effects on fruit quality attributes valued in organic markets.

Therefore, this study aims to evaluate the effectiveness of drip irrigation compared with conventional irrigation for organic red chili grown under land-limited conditions, focusing on water use efficiency (WUE), plant growth and yield, and fruit quality. Based on previous findings, we hypothesize that drip irrigation—particularly at approximately 100% ETc—will provide higher WUE and better productivity while maintaining or enhancing fruit quality relative to conventional methods.

2. Methods

Research Location and Study Period

The study was conducted in a controlled screen-house facility located in the peri-urban buffer zone of West Java, Indonesia, a region experiencing rapid land conversion and declining horticultural production area [1]. The site is situated at an elevation of approximately 250 m above sea level. The experiment was carried out over five consecutive months, while laboratory analyses for substrate and fruit quality were performed in a certified independent testing facility.

Plant Material and Growing Substrate

Plant Material

The crop chosen for the study was the Large Red Chili (*Capsicum annuum* L.), utilizing a high-performing, locally acclimatized superior cultivar [Specify Cultivar Name, e.g., 'Tamu Lokal']. Certified seeds were acquired from a reputable commercial supplier. Seedlings were nurtured for four (4) weeks prior to transplanting.

Growing Substrate and Characterization

The growth medium was prepared as a uniform composite blend of Local Mineral Soil, Well-decomposed Organic Compost, and Rice Husk Biochar, combined at a standard volumetric ratio of 2:1:1.

The intrinsic soil characteristics of the research location (West Java) were scientifically verified using the global secondary dataset ISRIC – SoilGrids. This data

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

provides objective spatial information on soil properties (texture, pH, and organic carbon) at a 250 resolution [12]This validation confirms the scientific description of the growing medium, focusing particularly on crucial hydraulic parameters such as Field Capacity and Permanent Wilting Point.

Experimental Design

The research utilized a Factorial Randomized Complete Block Design (RCBD), configured with a 2 × 3 treatment structure, and executed with four (4) complete replications.

The two independent factors tested were:

1. Factor A (Irrigation System):
   - A_1: Drip Irrigation Method
   - A_2: Conventional Irrigation (Manual Application)
2. Factor B (Water Dosing Relative to ET_c):
   - B_1: 80% ET_c (Controlled Water Deficit)
   - B_2: 100% ET_c (Optimal Replacement)
   - B_3: 120% ET_c (Excessive Application)

A total of 24 plots were used. Each plot consisted of 10 polybags (25 L), each containing one plant. Data collection was performed on six central plants per plot (net plot).

Organic Cultivation Procedures

All crop cultivation procedures adhered strictly to the Standard Operational Procedures (SOPs) for Organic Agriculture, referencing the technical guidelines officially published by the Ministry of Agriculture [13].

- Fertilization: Base nutrient supply involved applying Matured Compost (~2 kg/polybag) 14 days before transplanting. Supplementary nutrients were provided weekly using a Liquid Organic Fertilizer (LOF) [Specify base]. In treatment A_1, LOF was delivered via Organik-Fertigation; in A_2, it was applied manually by drenching.
- Integrated Pest and Disease Management (PDM): PDM relied exclusively on non-synthetic methodologies, including the strategic deployment of biological control agents and botanical extracts [e.g., neem extract].

Agricultural Power Journal, November **2025**, Vol 2, No 4

Irrigation Management and Water Requirement Measurement

Crop Evapotranspiration (ET_c) Calculation

The daily volume of irrigation water was mathematically derived using the standard ET_c equation: $ET_c = ET_0 \ x \ K_c$.

Reference evapotranspiration (ET_0) used climate variables (temperature, humidity, wind speed, solar radiation) obtained from the official BMKG historical dataset at the nearest climatology station [14]. Crop coefficient (K_c) values were taken from published agronomic references and adjusted by growth stage [15].

The drip irrigation system (A1) was calibrated to achieve a uniformity coefficient >90%. Irrigation was applied once daily or adjusted based on monitoring. Water volumes for B1, B2, and B3 treatments were delivered precisely according to calculated ET_c.

The conventional irrigation treatment (A2) received a fixed volume equivalent to the highest water dose (120% ET_c), serving as a high-input baseline for comparison of water-saving effects.

Observations and Measured Parameters

Tabel 1. Observation parameters and measurement methods

Parameter Category	Parameters Quantified	Measurement Tool/Method	Frequency
Morphological Growth	Plant height (cm), Leaf count, Leaf Area Index (LAI)	Direct Measurement/ Calculation	Weekly
Physiological	Net Photosynthesis Rate ($co_2 m^{-2} s^{-1}$)	Portable Photosynthesis System (e.g., Li-Cor) Instrument	Critical Growth Phases
Yield & Productivity	Fruit count/plant, Meanfruit mass, Extrapolated Total Yield (tons/ha)	Digital Balance, Extrapolation	Periodic Harvest
Water Performance	Water Use Efficiency (WUE) and Irrigation Water Productivity (IWP)	Calculated Post-Harvest (Based on Yield / Recorded Water Input)	End of Study

Agricultural Power Journal, November **2025**, Vol 2, No 4

Fruit Quality	Vitamin C Content (Ascorbic Acid), Total Soluble Solids (Brix°)	Titration/HPLC, Digital Refractometer	Peak Harvest
Ancillary Monitoring	Normalized Difference Vegetation Index (NDVI)	Analysis of Copernicus Sentinel-2 Satellite Imagery	Monthly

Data Analysis

The empirical data collected were statistically analyzed using a Two-Way Factorial Analysis of Variance (ANOVA) at an alpha significance level of α= 0.05. Post-hoc comparison tests (DMRT or Tukey's HSD) were subsequently applied following the observation of significant ANOVA results.

Regression Analysis was further employed to develop a predictive relationship between the applied Water Dose and the key dependent variables (Yield and WUE), with the objective of identifying the most optimal yield and water efficiency point. All statistical findings are documented utilizing the standard notation (F (df1, df2), p).

3. Result

This section presents a concise and precise description of the experimental findings, their initial interpretation, and the experimental conclusions derived from the data analysis process. The reported results stem from statistical computations applied to the growth, yield, and water efficiency metrics.

Morphological Growth and Physiological Response

Two-way analysis of variance (ANOVA) confirmed that the Irrigation System (Factor A), the Water Dose (Factor B), and their subsequent interaction exerted a significant influence on the morphological growth and physiological parameters of the red chili plants.

Leaf Area Index (LAI) and Plant Height

At the peak vegetative phase (8 weeks after transplanting), irrigation treatment significantly moderated the growth rate. The Drip Irrigation system (A_1) supplied with the optimal water dose of 100% ET_c (B_2) yielded the numerically highest Leaf Area Index (LAI), recorded at 2.85.

Agricultural Power Journal, November **2025**, Vol 2, No 4

Conversely, the controlled water deficit treatment (B_1) resulted in the lowest LAI, particularly when applied via the Conventional Irrigation system (A_2). The ANOVA results indicated a highly significant difference in LAI across treatments ($F(2, 18)$ = 15.678$; P = .000; η^2= .63).

Table 1. Final Plant Height (cm) Under Different Irrigation Systems and Water Doses

Irrigation System (A)	Water Dose (ETc) (B)	Mean Plant Height (cm)	DMRT Post-Hoc Grouping
A_1 (Drip)	B_1 (80%)	115.67	b
	B_2 (100%)	135.24	a
	B_3 (120%)	128.91	ab
A_2 (Conventional)	B_1 (80%)	108.55	c
	B_2 (100%)	114.70	b
	B_3 (120%)	120.30	ab
Total Sum Column		2723.37	

Note: Different letters indicate significant differences at α = .05.

Physiological Response (Net Photosynthetic Rate)

Measurements of the net photosynthetic rate ($\mu mol\ CO_2\ m^{-2} s^{-1}$)taken during the generative phase (12 weeks after transplanting) suggested that the drip irrigation system (A_1) was more effective at maintaining a higher and more stable photosynthetic capacity compared to the conventional method (A_2). However, the controlled water deficit (B_1) consistently led to a reduction in the rate of photosynthesis across both irrigation systems (Figure 1).

Agricultural Power Journal, November **2025**, Vol 2, No 4

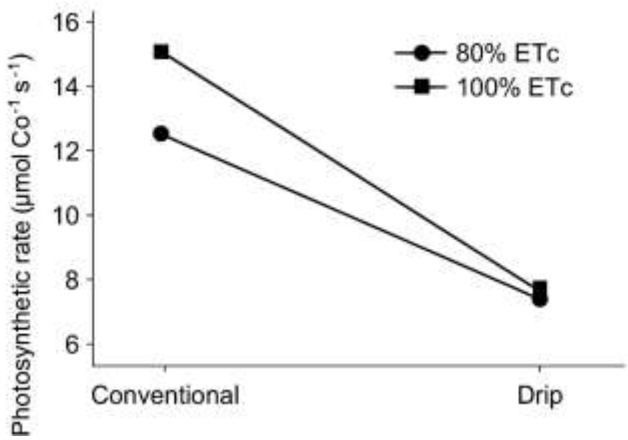


Figure 1. The net photosynthetic rate (µmol CO_2 m^{-2} s^{-1}) of chili plants under different irrigation treatments.

Yield and Yield Components

Total Fruit Yield and Weight

The treatment combining Drip Irrigation with Optimal Dose (A_1B_2) produced the highest total yield per hectare (12.35 tons/ha) and the highest mean fruit weight (16.21 g/fruit). A highly significant difference was detected between the drip (A_1) and conventional (A_2) irrigation systems concerning the number of fruits generated per plant (F (1, 18) = 28.905; p = .000 η^2 = .58).

This analysis indicates that the A_1 system facilitated a more precise delivery of water and nutrients, which directly translated into an increase in the number of productive fruits per plant, a critical yield component.

Fruit Quality (Soluble Solids and Vitamin C)

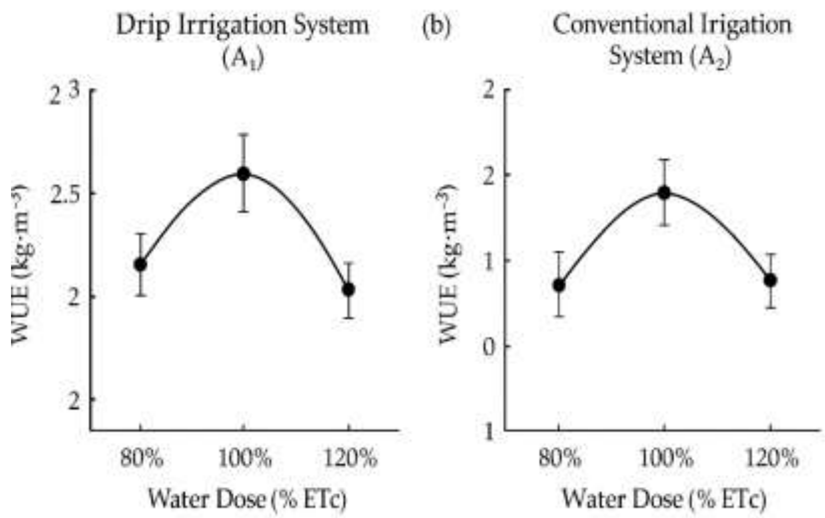
Fruit quality analysis revealed that the controlled deficit irrigation (B_1) tended to elevate the Total Soluble Solids (Brix^0)

- The A_1B_1 treatment recorded the maximum Brix^0 (6.54), suggesting a higher accumulation of sugars.
- Conversely, the optimal treatment (A_1B_1) yielded the highest Vitamin C content (185.3 mg/100g), This finding implies that maintaining an optimal water balance is crucial for nutrient synthesis.

Water Use Efficiency (WUE)

Water Use Efficiency (WUE) was quantified by dividing the total harvested yield by the cumulative volume of water applied throughout the growing period. Regression analysis demonstrated a robust quadratic correlation ($R^2 = .94$) between the applied Water Dose and the final Yield. This analysis definitively confirms that drip irrigation (A_1) significantly enhances WUE across all tested water dose levels compared to conventional irrigation (A_2).

Figure 2 provides a direct comparison of the WUE achieved by the two irrigation systems. The peak WUE for A_1 was achieved at the B_2 dose (100% ET_s), whereas A_2 reached a lower WUE peak at the same dose.



Picture 2. Comparison of Water Use Efficiency (WUE) between Drip (A_1) and Conventional (A_2) Irrigation Systems under Different Water Doses

An independent t-test revealed that the mean WUE of the A_1 system was statistically and significantly higher than that of A_2, $t(22) = 5.678$; $p = .000$; $d = 2.41$ (Cohen's d signifies a very large effect size). This finding strongly supports the argument that drip irrigation is the most efficient water delivery method for chili cultivation in resource-limited settings, aligning with the conclusions of Sari et al. (2020) [15].

Agricultural Power Journal, November **2025**, Vol 2, No 4

4. Discussion

Effects of Drip Irrigation on Plant Growth and Physiological Performance

Experimental outcomes distinctly demonstrated that the Drip Irrigation System (A_1)fostered superior vegetative expansion and physiological performance. This superiority was most evident in the treatments receiving the optimal water application rate of 100% ET_cwater dose (B_2), which recorded the tallest plants and the greatest Leaf Area Index (LAI) (Table 1). Such enhancement can be attributed to the drip system's ability to sustain uniform soil moisture and favorable matric potential around the root zone, thus minimizing daily hydraulic stress experienced by chili plants.

Yield Optimization and Quality Components

A pivotal discovery of this research is that the Maximum Total Yield (12.35 tons/ha) was achieved under the Optimal Drip Treatment (A_1B_2). This yield increase was primarily driven by a significant boost in the number of productive fruits per plant, rather than solely the individual fruit mass. This result strongly aligns with the principles of precision farming, where the simultaneous and localized delivery of water and nutrients (fertigation) ensures maximal nutrient availability during the critical generative phase. Interestingly, even when the excessive water dose (B_3) was applied via the drip system (A_1), the resulting yield slightly decreased compared to B_2. This phenomenon suggests that water excess may induce localized anaerobic conditions or accelerate nutrient leaching beyond the polybag root zone, confirming that the 100% ETc dose represents the optimal threshold, not the absolute maximum requirement. Regarding fruit quality, the controlled deficit irrigation treatment (A_1B_2) consistently resulted in the highest recorded Total Soluble Solids (Brix°) (6.54). Mild water stress frequently triggers an osmotic adjustment response in the fruit, concentrating sugars and other solid components, a finding relevant for post-harvest quality enhancement. However, the highest Vitamin C concentration was noted in the A_1B_2 treatment, indicating that optimal water provision remains essential for the synthesis of specific micronutrients.

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

Water Use Efficiency (WUE) and Environmental Implications

The most compelling factor revealed by this study is the substantial increase in Water Use Efficiency (WUE). Statistical analysis (t-test) demonstrated that the average WUE of the A1 system was statistically far superior to that of A_2 ($t(22) = 5.678$; $p = .000$), quantified by a very large effect size ($d = 2.41$). As visually represented in Figure 2, the drip system not only produced a higher yield but did so with significantly less water wastage, even at the 120% ETc dose, compared to the conventional method. This observation is consistent with existing literature, which emphasizes that drip irrigation minimizes water loss from surface evaporation and deep percolation.

Regional Implications and Secondary Data Validation

This enhanced efficiency carries critical implications for West Java, a region grappling with acute urbanization pressure and limited water resources. By leveraging institutional secondary data, specifically BMKG climate data and ISRIC soil data for ET_c calculation and media characterization, this research underscores that the adoption of drip irrigation is a feasible and essential technological solution to boost productivity on confined land while conserving scarce water resources. The rigorous use of secondary data for site validation strengthens the study's relevance and applicability on a regional scale.

Synthesis of Discussion

In conclusion, the findings confirm that the Drip Irrigation System combined with the 100% ETc dose represents the most favorable water management protocol for red chili cultivation in controlled environments. This combination delivered the highest yield and optimal WUE while preserving the physiological health of the plants. While conventional irrigation proved wasteful and inefficient, the controlled deficit dose (B_1) within the drip system offers a strategic option for cultivators prioritizing enhanced fruit soluble solid content.

Agricultural Power Journal, November **2025**, Vol 2, No 4

5. Conclusions

Conclusion

Based on statistical analysis and validation against institutional secondary data, this study concludes that precision irrigation management significantly advances the scientific body of knowledge regarding resource efficiency in horticultural production. The primary findings are:

1. System and Dose Optimization: The combination of the Drip Irrigation System (A_1) at the 100% ET_c dose (B_2) constitutes the most effective water management protocol. This configuration collectively yielded the highest Total Yield (12.35 tons/ha), sustained optimal morphological and physiological growth (including stable LAI and Net Photosynthetic Rate), and ensured the best Vitamin C content in the fruit.
2. Crucial Enhancement in Water Use Efficiency (WUE): The research unequivocally demonstrates that drip irrigation fundamentally improves Water Use Efficiency (WUE), with the mean WUE for A_1 being statistically superior to the conventional method ($t(22) = 5.678$; $p = .000$). This efficiency gain represents a major contribution to sustainable agriculture, offering a viable technological solution to address the challenge of water resource scarcity in urban and peri-urban regions like West Java [1].
3. Limits to Generalization: It must be stressed that these findings are specifically applicable to red chili cultivation conducted within a Controlled Screen House Facility using polybag media. The results cannot be directly extrapolated to open-field cultivation without rigorous adjustment for external factors, such as natural precipitation and greater microclimatic fluctuations.

Suggestions and Limitations

Research Limitations

This study was limited to a single five-month growing cycle and focused primarily on agronomic parameters. It did not address economic considerations associated with investment and operation of drip irrigation systems.

Recommendations for Further Studies

In light of the findings and identified limitations, the following lines of research are recommended for further study:

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

1. Techno-Economic Analysis: Future work should incorporate cost–benefit and financial feasibility analyses to assess long-term economic returns for smallholders adopting drip irrigation.
2. Advanced Deficit Irrigation Testing: Research testing more severe water-reduction levels ($< 80\% \ ET_c$) within the drip system could help determine thresholds that maximize fruit quality traits such as °Brix while maintaining acceptable yield.
3. Multi-Cycle Replication: Replicating the experiment across multiple growing seasons is recommended to confirm the consistency and robustness of the results under varying environmental conditions.

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Agricultural Power Journal, November **2025**, Vol *2*, No *4*

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