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# Integrating Automated Drip Irrigation and Organic Matter to Improve Enzymatic Performance and Yield of Water Efficient Chilli in Karst Region

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## ABSTRACT

Karst landscape, characterised by drought-prone areas, limited water retention and nutrient-poor soils, pose significant challenges for the sustainability of small-scale agricultural systems. This study investigated the impact of smart precision irrigation (SPI) technology, which integrates drip irrigation (DI) and organic fertilisation, on the growth, physiological performance and water use efficiency of chilli plants cultivated in a karst landscape in Gunungkidul District, Yogyakarta, Indonesia. This experiment involved a combination of drip irrigation (D), non-drip irrigation (ND), organic fertiliser (F), and no fertiliser (NF), with a semi-automatically installed SPI system to monitor and adjust soil moisture and watering requirements. The results showed that the combination of drip irrigation and organic fertiliser (D + F) significantly increased plant growth parameters, including plant height, leaf area, and chlorophyll content, and improved physiological traits such as photosynthetic rate, stomatal conductance, and leaf water use efficiency (LWUE). These improvements were attributed to the optimised water distribution and nutrient availability provided by the DI system, which minimised water loss and reduced drought stress, as evidenced by lower proline accumulation and reduced antioxidant enzyme activity in plants. In addition, the D+F treatment resulted in the highest biomass production, fruit yield and water use efficiency, underlining its potential as a sustainable agricultural practice in water-scarce karst environments. The study concludes that adopting organic matter irrigation and fertilisation strategies can improve the productivity and resilience of horticultural crops in areas facing similar environmental constraints.

**Keywords:** agronomy, irrigation, precision, soil, water efficiency.

## INTRODUCTION

The threat of drought is often a serious problem in agricultural development systems carried out on karst landscapes. Agricultural commodities of food crops such as horticulture become difficult to develop because the availability of water does not meet the water needs during the plant growth period. Water deficiencies that occur in karst landscapes can come from low rainfall or the inherent geological characteristics of these areas that are relatively difficult to store water (Wang et al., 2019). The unique geological characteristics are shown in the many fissures and pores in the limestone rock that allow rainwater to be quickly absorbed into the soil and reduce the availability of water on the land surface. Meanwhile, groundwater is often trapped in deep aquifer systems that are relatively difficult to access. This high reliance on subsurface water often leads to over-extraction which can lead to declining water tables and further environmental degradation in karst landscapes.

This problem is exacerbated by water-intensive agricultural practices, especially in the cultivation of crops such as chilli (*Capsicum annum*) that require consistent and optimal water supply. Traditional irrigation methods are often inefficient. Water is wasted due to evaporation, runoff and uneven watering. These inefficiencies not only deplete water resources but also reduce crop productivity, given that chillies are very sensitive to water shortages at certain growth phases. In addition, the economic potential of chilli is not only in food sources, but also has a market in the pharmaceutical and cosmetic industries (Idrees et al., 2020).

A major challenge in chilli cultivation in karst landscapes is ensuring adequate water and nutrient availability throughout the vegetative to generative growth cycle. The low water storage capacity of karst land surfaces often leads to shortages of water and nutrients essential for horticultural crop production (Li et al., 2020). The erratic dynamics of water and nutrient availability can disrupt the enzymatic performance of plants, resulting in suboptimal vegetative and generative phases (Rouphael et al., 2012). Therefore, the variability of soil conditions and water availability in karst landscapes requires a more adaptive approach to ensure the sustainability of optimal chilli productivity.

In an effort to overcome the main problem of developing agricultural systems in drought-prone karst landscapes, this research will explore automatic drip irrigation technology in chilli cultivation. Drip irrigation technology allows more precise water management by adjusting the volume and frequency of irrigation according to the specific needs of plants and soil conditions, and allows more accurate water distribution into the rhizosphere region of plants so as to reduce water loss due to evaporation and surface flow (Ma et al., 2020). In addition, soil moisture sensors integrated with IoT enable real-time monitoring of soil conditions, so that watering can be optimised according to crop needs. This approach not only significantly increases water use efficiency, but also improves soil physicochemical conditions with the addition of organic matter, which has proven effective in a variety of water-deficient marginal soil conditions (Touil et al., 2022).

In addition, the addition of soil organic matter also plays an important role in increasing the soil's capacity to store water, reducing runoff and improving soil structure. This combination of automated drip irrigation and soil quality improvement is expected to not only increase water use efficiency, but also improve surface and subsurface water management by reducing the need for excessive irrigation and minimising the negative environmental impacts of conventional agricultural practices. Several previous studies have developed the utilisation of such technology such as (Bhattarai et al., 2008; Tl et al., 2009; Reyes-Cabrera et al., 2016; Parthasarathi et al., 2018; Slamini et al., 2022), but its effect on chilli growth as reflected in enzymatic activity still needs to be investigated further.

Enzymatic activity in plants is an important indicator of plant health and growth, especially under environmental stress conditions such as relatively extreme water and nutrient deficiencies (Seleiman et al., 2021). Enzymes such as catalase, peroxidase, and superoxide dismutase play a role in plant defence mechanisms against oxidative stress (Siddiqi and Husen, 2016; Jomova et al., 2024). This study will evaluate the changes in enzymatic activities in *Capsicum annum* grown in karst landscapes. With increasing climate change and future pressures on global water resources, efficient agricultural solutions such as these are increasingly important to adopt in different regions with similar soil or landscape characteristics.

## MATERIAL AND METHODS

### Study area

This study was conducted in Gunungkidul, Yogyakarta Special Region Province, Indonesia with geographical coordinates of 110°44‘4.7” E and 7°58‘5.9” S. Rainfall in the karst ecosystem of Gunungkidul averaged from 2009 to 2022 around 2126 mm/year (Figure 1) with Schmidt-Ferguson classification for dry months lasting 4 months (rainfall < 60 mm/month), humid months lasting 2 months (rainfall between 60–100 mm/month), and wet months lasting 6 months (rainfall > 100 mm/month). The large rainfall potential is the basis for the utilisation of water resources using smart precision irrigation (SPI) technology implemented with the drip irrigation method. The location of the study is presented in Figure 2, where the experimental plots were placed in a

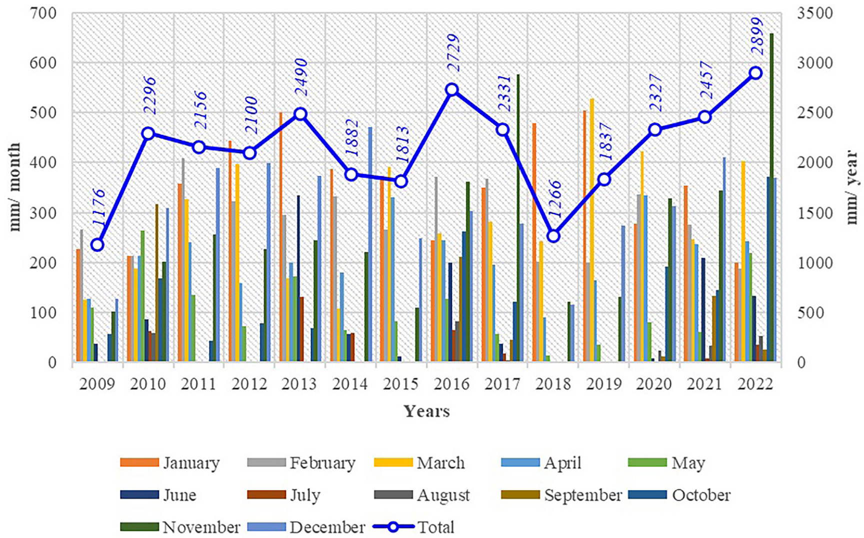


**Figure 1.** Rainfall in Gunungkidul, Yogyakarta from 2009 to 2022

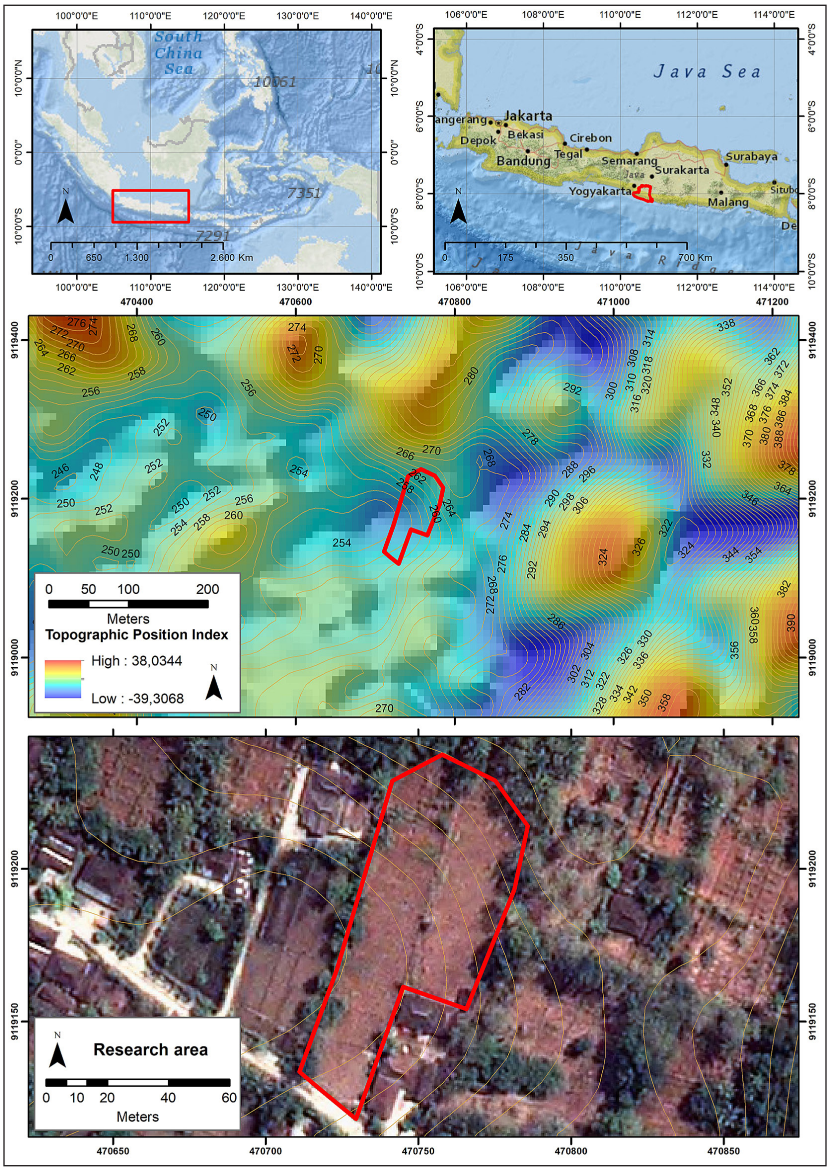


**Figure 2.** Study area

karst valley. The morphology of the land surface was identified through the process of analysing topographic position index (TPI) data, which showed that pixels with low TPI values indicated lower relative heights (Noviyanto, 2024). These low relative heights are also synonymous with valley locations. One of the morphological characteristics of valleys is water concentration. The potential water flow occurring in the karst hills surrounding the valley can be utilised as a source of water storage in drip irrigation ponds.

## Experimental treatments

The SPI is installed with a soil moisture sensor and is operated semi-automatically. The treatments involved combinations of drip irrigation (D), non-drip irrigation (ND), organic fertilizer (F), and no fertilizer (NF). Watering is adjusted to meet the daily water needs of the plants and adapted to soil moisture conditions. Data monitoring is conducted at 10-minute intervals to ensure that soil moisture and water availability are always met. The drip irrigation system was automated to activate when soil moisture content fell below 17%. The system would continue to operate until the soil moisture reached 35%, at which point it would automatically deactivate. The rhizosphere typically required approximately 15 minutes to attain a soil moisture content of 35%. The volume of water discharged during this interval was measured and recorded to be 625 mL. This data will be utilized in the subsequent calculation of the irrigation system's water use efficiency (WUE) as followed by formula by Abdelkhalik et al. (2019):

$$Irrigation\ WUE = \frac{Fresh\ mass\ (kg\ m^{-2})}{Irrigation\ water\ applied\ (m^{-3}\ m^{-2})} \quad (1)$$

The use of DI ensures that water management is more precise in providing water availability to plant roots. An illustration of the SPI experimental plot is presented in Figure 3.

Irrigation was activated once soil water tension reached predetermined levels, specifically -40 kPa for field capacity and -70 kPa for 50% field capacity, indicating deficit irrigation. These tension thresholds corresponded to soil water content levels of 35% for field capacity irrigation and 18% for deficit irrigation. The selection of these criteria was informed by the research conducted by Zamljen et al. (2020). The organic fertilizer in form of cattle manure was applied at a rate of 20 tons per hectare, in accordance with the recommended dosage from the Indonesian Agricultural Instrument Standardization Agency.

Synthetic fertilization was carried out for all treatments following the recommendations from the Indonesian Agricultural Instrument Standardization Agency. The type of synthetic fertilizer applied was NPK, with a dosage of 2 grams per plant during weeks 0–3 after transplanting, 3 grams per plant during weeks 4–7, and 5 grams per plant from week 8 until the end of the harvest. Additionally, all treatments received a foliar

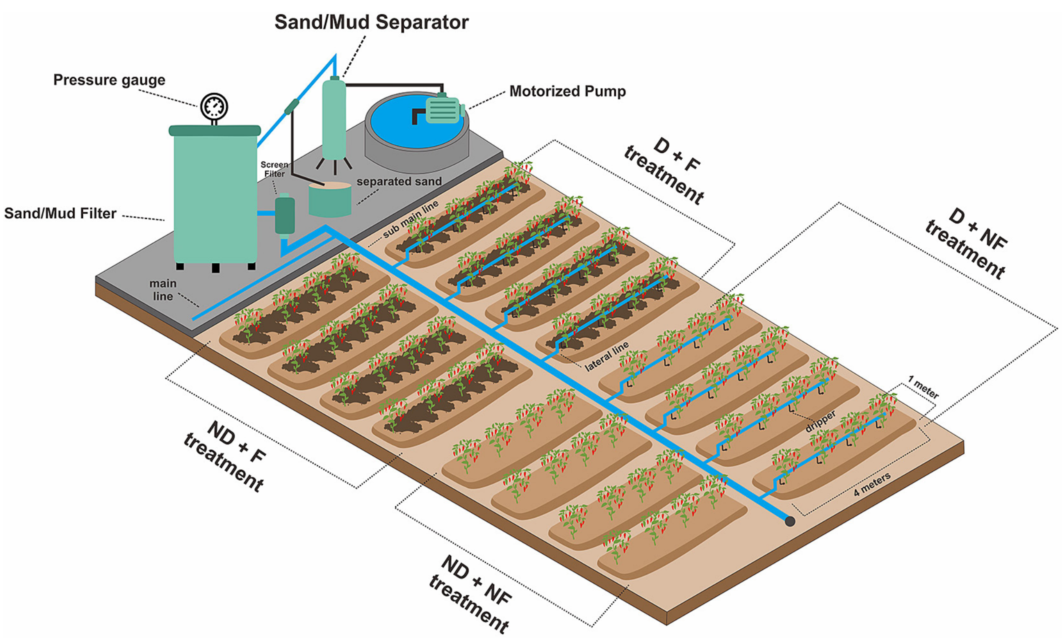


**Figure 3.** Illustration of smart precision irrigation with multiple treatments

fertilizer containing micronutrients at a dosage of 1 gram per liter, which was applied starting when the chili plants entered the generative phase.

Soil volumetric water content was measured using an FST100-2006 soil moisture probe (Hunan Firstrate, CHN), positioned at the center of the root zone. Soil moisture was continuously monitored using an automated system, with measurements taken at intervals of every 10 minutes throughout the study period. The probe has a reported accuracy of 3%, as stated in the manufacturer's catalog. Additionally, we performed calibration using the gravimetric method, which confirmed the sensor's accuracy to be 96.76%. Figure 4 presents the soil moisture sensor recording during chilli production.

## Collecting data

### *Determination of growth parameters*

Plant samples were taken randomly to observe non-destructive parameters (n = 20 for each treatment). The plant performance parameters observed include plant height (H), stem diameter (SD), plant width (PW), dichotomous height (DH), plant branch (PB), leaf number (LN), leaf area (LA), leaf area index (LAI) and relative water content (RWC).

$$RWC\ (\%) = \frac{FW-DW}{SW-DW} \times 100 \quad (2)$$

### *Determination of physiological traits*

Proline analysis uses the method presented by Bates (1973). Chlorophyll analysis using the Arnon (1949) method with ethanol extraction method and determined at 645 and 663 nm wavelength. Physiological observations of plants such as net photosynthesis (Pn), transpiration (E), Stomatal conductance (gsw), intercellular $CO_2$ concentration (Ci), leaf water use efficiency (LWUE) involve direct measurements of the rate of gas exchange on the leaf surface using portable gas exchange systems the Li-COR 6800.

$$LWUE = \frac{Pn}{E} \quad (3)$$

### *Plant biomass, yield, and water use efficiency parameter*

Sample plants were randomly taken from the plot for destructive observation Root dry weight (RDW) and shoot dry weight (SDW) separated between roots and shoots were weighed to obtain their fresh weight and then dried in an oven (80 °C) for 72 hours to obtain their dry weight. Other observations were fruit number (FN), fruit length (FL), flower diameter (FD), fresh fruit weight (FFW), plant production (PP) and water use efficiency (WUE)

### *Root ABA and enzymatic assay*

Root ABA method was determined using method developed and modified by Bączek-Kwinta et al. (2023). Chilli plant roots (n = 3) were freeze-dried and ground into powder (30–150 mg DW). ABA extraction was performed by adding 1.5 mL of cold, redistilled water to the powder, followed by heating at 90 °C for 3 minutes and overnight shaking at 4 °C and 560 cycles per minute (Yellow Line OS 5 Basic, CH500 Angelantoni chamber). The resulting aqueous extract was

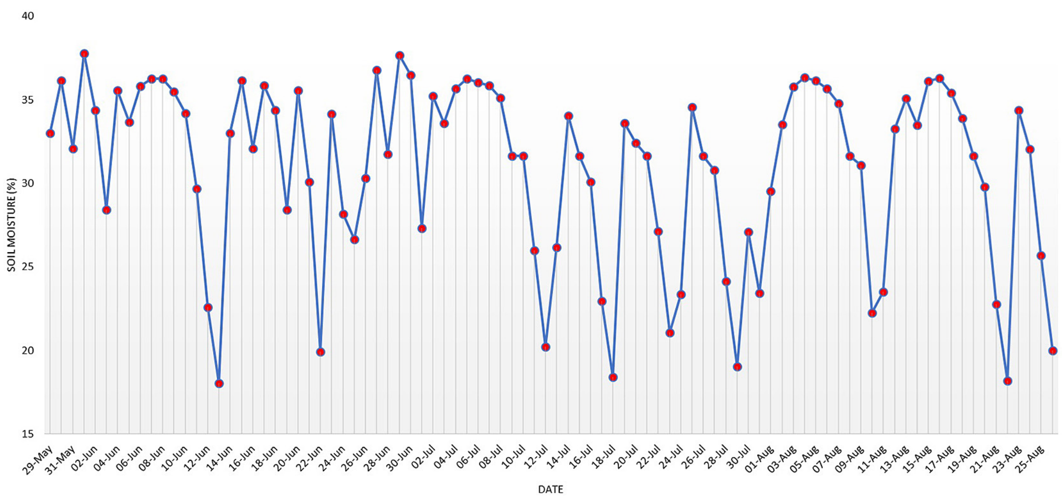


**Figure 4.** Soil moisture sensor recording

centrifuged at 18,000 x g for 20 minutes to obtain the supernatant. ABA concentration in the supernatant was determined using an indirect ELISA method with a MAC 252 antibody (Babraham Technix, Cambridge, UK). Absorbance was measured at 405 nm using a microplate reader (Model 680, Bio-Rad Laboratories, Hercules, CA, USA).

Catalase activity was determined by measuring the reduction in absorbance at 240 nm, indicating hydrogen peroxide (30 mM) decomposition, using a spectrophotometer. One unit of catalase activity corresponds to a 0.001 absorbance decrease per minute. A reaction mixture containing sodium phosphate buffer (100 mM, pH 7.0), hydrogen peroxide (30 mM), and a crude extract (100 μL) in a total volume of 3.0 mL was used for the assay (Aebi, 1974).

Peroxidase (POD) activity was measured spectrophotometrically at 420 nm using method developed by Onsa et al. (2004). The substrate used was 4-methylcatechol, whose oxidation by hydrogen peroxide (5 mM) resulted in increased absorbance. The reaction mixture contained sodium phosphate buffer (100 mM, pH 7.0), 4-methylcatechol (5 mM), hydrogen peroxide (5 mM), and a crude extract (500 μL) in a total volume of 3.0 mL. One unit of enzyme activity was defined as a 0.001 absorbance increase per minute under assay conditions.

Superoxide dismutase (SOD) activity was determined by measuring its inhibitory effect on nitroblue tetrazolium (NBT) photoreduction according to Kumar et al. (2012). The reaction mixture consisted of sodium phosphate buffer (50 mM, pH 7.6), EDTA (0.1 mM), sodium carbonate (50 mM), L-methionine (12 mM), NBT (50 μM), riboflavin (10 μM), and a crude extract (100 μL) in a final volume of 3.0 mL. A control reaction without the crude extract was also performed. The reaction mixture was exposed to white light for 15 minutes at room temperature. Absorbance was then measured at 560 nm. One unit (U) of SOD activity inhibited NBT photochemical reduction by 50%.

### Statistical analysis

Data was collected and subsequently analyzed using ANOVA through R software version 4.4.0, setting the significance level at 5%. In the event of detecting significant differences, a post-hoc analysis employing fisher's least significant difference (LSD) test was conducted.

## RESULTS AND DISCUSSION

The study assessed the significant impact of various irrigation and fertilization strategies on the growth and physiological performance of *Capsicum annuum*. The treatments involved combinations of drip irrigation (D), non-drip irrigation (ND), organic fertilizer (F), and no fertilizer (NF). These approaches provided edaphological engineering to the rhizosphere area, influencing water supply frequency and altering chemical properties through the addition of soil organic matter. Drip irrigation, which directly applies water to the root zone, minimized water loss through evaporation and runoff, optimizing surface water use and highlighting its role in sustainable water management. Organic fertilization played a crucial role in improving soil water retention, facilitating nutrient dissolution, and enhancing the physiological performance of *Capsicum annuum*, underscoring the distinct benefits of these combined practices.

The measurement of soil chemical properties showed that the parameters of soil pH, organic matter, Total P, available P, Total Mg, and available Mg were not significant for all treatments. Soil pH values ranged from 6.15 to 6.46 which is included in the criteria of slightly acidic. Soil organic matter in all treatments was in the range of 14.98 to 16.41 $g \cdot kg^{-1}$ which can be classified as high organic matter content. The value of total P and available P in the soil in all treatments showed no significance, where total P was in the range of 0.57 to 0.68 $g \cdot kg^{-1}$ and P-available was in the range of 17.95 to 18.97 $mg \cdot kg^{-1}$. Meanwhile, the magnesium element which is usually found in karst landscapes showed insignificant performance for all treatments. Total Mg ranged from 8.26 to 8.41 $g \cdot kg^{-1}$ and Mg-exchange was in the range of 0.64 to 0.73 $g \cdot kg^{-1}$.

Soil chemical properties that showed significant influence were Ca-total and Ca-exchange with LSD values of 0.54 and 0.23. While highly significant results were shown in cation exchange capacity with LSD 0.35 and N-total with LSD 0.27. While the test results that showed very significant differences were K-Total and K-available in the soil with LSD values of 0.09 and 3.94, respectively. This significance variation is indicated to come from nutrient solubility and mineralization of soil organic matter.

Soils found in karst landscapes may contain higher Ca values compared to other soils. The

Ca-total and Ca-exchange values show significant differences. Where, Ca-total values ranged from 11.22 to 12.39 g·kg$^{-1}$ and Ca-exchange was in the range of 4.37 to 5.09 g·kg$^{-1}$, all of which were in the low category. However, Ca-total values increased gradually from the treatment without drip irrigation and organic fertilizer (ND+NF) to the complete treatment (D+F). However, Ca availability as indicated by the Ca-exchange value was relatively more variable.

The application of organic fertilizer (F) gave a positive impact on CEC, which was shown in CEC values between 18.01 to 18.55 cmol·kg$^{-1}$. While the treatment that did not use organic fertilizer (NF) gave lower values, namely 17.64 cmol.kg$^{-1}$ for D+NF and 13.45 cmol.kg$^{-1}$ for ND+NF. The combination of treatments also gave a very significant difference in the value of total N in the soil, where the range of values obtained was gradually increasing from 1.71 for ND+NF, 2.18 for ND+F, 2.33 for D+NF and 2.74 for D+F, all of which were also in the very high category. The increase in N-total may come from the addition of soil organic matter as a source of N which along with the use of drip irrigation will increase the N-total content in the soil.

The soil chemical properties that showed the highest significance were the K-total and K-available contents in the soil. K-total values ranged from 0.19 to 0.52 g·kg$^{-1}$ which is categorized as very low, while K-exchange values ranged from 60.98 to 73.36 mg·kg$^{-1}$ which is also categorized as very low. Although all of them are categorized as very low, the K-total and K-exchange contents in the soil have highly variable values. The variation in values may indicate that K is very competitively needed by *Capsum annuum* plants, especially with the conditions of drought-prone areas K is needed for the adaptation process of plants to open stomatal and adapt to drought.

This method ensures that a higher proportion of applied water is available for plant uptake, enhancing overall water use efficiency (WUE). The higher water availability and uniform distribution under drip irrigation likely contributed to enhanced cell turgidity and elongation, promoting greater plant height compared to non-drip irrigation (ND). Additionally, drip irrigation is known to improve soil moisture consistency, which can enhance root development and nutrient uptake, further supporting robust plant growth (Mačkić et al., 2023; Guo and Li, 2024; Zhang et al., 2024). Table 1 below presents the results of soil analysis.

For plant height, the D + F and D + NF treatments resulted in plants reaching an average height of 58.20 cm, which was comparable to the ND + NF treatment at 59.40 cm. However, the ND + F treatment produced shorter plants with an average height of 53.80 cm. This indicates that both drip irrigation treatments, regardless of fertilizer addition, supported greater plant height compared to the non-drip irrigation with fertilizer (Akkamiş and Caliskan, 2023).

Stem diameter, plant width, and dichotomous branch height did not show significant differences among the treatments. Specifically, the stem diameter ranged from 0.70 cm to 0.79 cm, plant width varied from 38.80 cm to 40.60 cm, and dichotomous branch height ranged from 36.80 cm to 38.00 cm across all treatments. This suggests that the irrigation and fertilization methods did not substantially impact these structural parameters

**Table 1.** Soil chemical properties under different water management and organic matter

| Properties | D + F | D + NF | ND + F | ND + NF | Sig | LSD |
|---|---|---|---|---|---|---|
| pH | 6.44 | 6.41 | 6.15 | 6.36 | ns | - |
| CEC (cmol·kg$^{-1}$) | 18.55 | 17.64 | 18.01 | 13.45 | ** | 0.35 |
| OM (g·kg$^{-1}$) | 16.09 | 15.81 | 14.98 | 16.41 | ns | - |
| TN (g·kg$^{-1}$) | 2.74 | 2.33 | 2.18 | 1.71 | ** | 0.27 |
| TP (g·kg$^{-1}$) | 0.64 | 0.57 | 0.68 | 0.66 | ns | - |
| TK (g·kg$^{-1}$) | 0.52 | 0.63 | 0.19 | 0.33 | *** | 0.09 |
| Av-P (mg kg-1) | 18.43 | 18.97 | 17.95 | 18.83 | ns | - |
| Av-K (mg kg-1) | 73.36 | 65.22 | 67.81 | 60.98 | *** | 3.94 |
| Tca (g·kg$^{-1}$) | 12.39 | 11.84 | 11.87 | 11.22 | * | 0.54 |
| TMg (g·kg$^{-1}$) | 8.27 | 8.41 | 8.32 | 8.26 | ns | - |
| Ex-Ca (g·kg$^{-1}$) | 5.09 | 4.37 | 4.67 | 4.59 | * | 0.23 |
| Ex-Mg (g·kg$^{-1}$) | 0.73 | 0.72 | 0.67 | 0.64 | ns | - |

(Cui et al., 2024). The number of plant secondary branches showed significant variation among the treatments. The D + F treatment resulted in the highest number of secondary branches, with an average of 20.00 branches, significantly higher than the ND + NF treatment, which had the lowest number at 14.00 branches. The D + NF and ND + F treatments had intermediate values of 16.20 and 18.40 branches, respectively.

In terms of leaf number, the D + F treatment had the highest number of leaves at 119.20, which was significantly higher than the ND + NF treatment at 98.40 leaves. The D + NF and ND + F treatments had leaf numbers of 115.60 and 111.40, respectively. Leaf area and LAI were significantly higher in the D + F treatment, with values of 3531.59 cm² and 1.41, respectively. The D + NF treatment had an LA of 2916.95 cm² and an LAI of 1.17. The ND + F treatment resulted in an LA of 1915.57 cm² and an LAI of 1.17, while the ND + NF treatment had an LA of 2776.11 cm² and an LAI of 1.11. These results highlight that drip irrigation combined with organic fertilizer significantly enhances leaf development and overall canopy structure. RWC in the leaves was highest in the D + F treatment at 86.24%, followed by D + NF at 83.57%, ND + F at 82.19%, and ND + NF at 70.30%. Table 2 presents the growth parameters of *Capsicum annuum*, while Figure 5 presents photos of *Capsicum annuum* in each treatment.

The results in physiological parameter revealed significant differences among the treatments. The total chlorophyll content in leaves demonstrated notable differences across treatments. The D + F treatment led to the highest chlorophyll content at 2.86 mg $g^{-1}$ FW, signifying enhanced chlorophyll synthesis under drip irrigation with organic fertilizer, crucial for photosynthesis. Conversely, the lowest chlorophyll content was observed in the ND + NF treatment at 2.01 mg $g^{-1}$ FW, reflecting the stress associated with non-drip irrigation without fertilizer. Proline content as indicator of plant stress, varied significantly with ND + F treatment showing a peak at 13.06 μmol $g^{-1}$ FW. This indicates that non-drip irrigation prompts higher proline accumulation, suggesting greater stress levels compared to drip irrigation treatments, which maintained lower proline levels (Mishra et al., 2016).

**Table 2**. Plant growth parameter of *Capsicum annuum* under different water management

| Properties | D + F | D + NF | ND + F | ND + NF | Sig | LSD |
|---|---|---|---|---|---|---|
| H (cm) | 58.20 | 58.20 | 53.80 | 59.40 | *** | 2.67 |
| SD (cm) | 0.79 | 0.72 | 0.76 | 0.70 | ns | - |
| PW (cm) | 38.80 | 40.60 | 40.20 | 39.40 | ns | - |
| DH (cm) | 38.00 | 37.20 | 36.80 | 37.80 | ns | - |
| PB | 20.00 | 16.20 | 18.40 | 14.00 | * | 4.29 |
| LN | 119.20 | 115.60 | 111.40 | 98.40 | * | 12.94 |
| LA (cm²) | 3531.59 | 2916.95 | 1915.57 | 2776.11 | *** | 109.39 |
| LAI | 1.41 | 1.17 | 1.17 | 1.11 | *** | 0.04 |
| RWC (%) | 86.24 | 83.57 | 82.19 | 70.30 | ** | 2.14 |


**Figure 5.** Performance of *Capsicum annuum* under different drip irrigation and organic fertilizer

For chlorophyll content (Chl), the highest value was observed in the D + F treatment (2.86 mg $g^{-1}$ FW), which was significantly different from the ND + NF treatment (2.01 mg $g^{-1}$ FW) based on an LSD of 0.31. Meanwhile, D + NF (2.62 mg $g^{-1}$ FW) and ND + F (2.71 mg $g^{-1}$ FW) were similar to each other but significantly higher than ND + NF. Proline (Pro) levels peaked in the ND + F treatment (13.06 μmol $g^{-1}$ FW), with values significantly greater than D + F (3.80 μmol $g^{-1}$ FW) and D + NF (4.11 μmol $g^{-1}$ FW), indicated by an LSD of 1.02. Additionally, the ND + NF treatment (12.80 μmol $g^{-1}$ FW) was also significantly higher than both D + F and D + NF, though not different from ND + F.

Photosynthetic rate (Pn) varied significantly among treatments. D + F exhibited the highest Pn (18.51 μmol $m^{-2}$ $s^{-1}$), surpassing ND + NF (15.86 μmol $m^{-2}$ $s^{-1}$) notably. Intermediate Pn values were observed for D + NF (17.7 μmol $m^{-2}$ $s^{-1}$) and ND + F (17.50 μmol $m^{-2}$ $s^{-1}$). Conversely, transpiration rate (E) showed no treatment-related differences. Stomatal conductance (gsw) mirrored the Pn trend, with D + F demonstrating the highest conductance (1.14 mol $m^{-2}$ $s^{-1}$), significantly exceeding ND + NF (0.82 mol $m^{-2}$ $s^{-1}$). Intermediate gsw values were found for D + NF (0.95 mol $m^{-2}$ $s^{-1}$) and ND + F (0.88 mol $m^{-2}$ $s^{-1}$). Internal $CO_2$ concentration (Ci) followed a similar pattern, peaking in D + F (321.89 ppm) and reaching its nadir in ND + NF (305.50 ppm). Leaf water use efficiency (LWUE), calculated as the ratio of Pn to E, was highest in D + F (4.47 μmol $mol^{-1}$), significantly surpassing ND + NF (3.05 μmol $mol^{-1}$). Intermediate LWUE values were observed for D + NF (3.70 μmol $mol^{-1}$) and ND + F (3.40 μmol $mol^{-1}$).

Organic fertilizer (F) significantly improved leaf number, leaf area, and chlorophyll content. Organic fertilizers release nutrients slowly, providing a steady nutrient supply that supports continuous plant growth and development. The increased chlorophyll content in treatments with organic fertilizer indicates enhanced photosynthetic capacity, as chlorophyll is critical for capturing light energy. The observed enhancement in photosynthetic rate (Pn) under the D + F treatment was primarily driven by an increase in stomatal conductance (gsw). This suggests that the improved water availability and nutrient supply in this treatment facilitated stomatal opening, leading to higher $CO_2$ uptake and consequently, elevated photosynthetic efficiency. The concomitant increase in internal $CO_2$ concentration (Ci) further supports this notion. While transpiration rate (E) did not vary significantly, the combined effects of increased gsw and Pn resulted in a notably higher leaf water use efficiency (LWUE) in D + F plants (Gao et al., 2022).

Conversely, the reduced Pn in ND + NF plants can be attributed to stomatal limitations. The lower gsw in this treatment restricted $CO_2$ diffusion into leaves, thereby limiting photosynthetic capacity. This condition likely exacerbated by suboptimal water and nutrient availability, as indicated by the lower LWUE. The intermediate performance of D + NF and ND + F treatments suggest a balance between the positive effects of nutrient application and the negative impacts of water deficit (Sakoda et al., 2021). The combination of drip irrigation and organic fertilizer (D + F) provided optimal conditions for nutrient and water availability, leading to the best growth outcomes. The significant increase in proline content in non-drip irrigation treatments, particularly ND + F, indicates higher stress levels. Proline accumulation is a common plant response to osmotic stress, suggesting that non-drip irrigation plants experienced greater water stress. Drip irrigation likely mitigated this stress by maintaining more consistent soil moisture levels. Furthermore, the higher relative water content (RWC) in the D + F treatment demonstrates better hydration status, reducing drought stress and enhancing water use efficiency (WUE) (Whitehead et al., 2011).

Root ABA content was highest in ND + NF (4.13 nmol $g^{-1}$ DW), significantly lower in D + NF (0.83 nmol $g^{-1}$ DW), with D + F (1.01 nmol $g^{-1}$ DW) and ND + F (1.04 nmol $g^{-1}$ DW) intermediate. SOD, POD, and CAT activities followed a similar trend, with highest values in ND + NF (334.47 U·$mg^{-1}$ protein, 8.67 U·$mg^{-1}$ protein, 316.89 U·$mg^{-1}$ protein), lowest in D+F (275.87 U·$mg^{-1}$ protein, 6.94 U·$mg^{-1}$ protein, 267.08 U·$mg^{-1}$ protein), and intermediate in D + NF (280.99 U·$mg^{-1}$ protein, 6.94 U·$mg^{-1}$ protein, 287.44 U. $mg^{-1}$ protein) and ND+F (325.23 U. $mg^{-1}$ protein, 7.06 U. $mg^{-1}$ protein, 298.85 U. $mg^{-1}$ protein). All differences were significant except between D+F and ND+F for each parameter. Physiological parameters of *Capsicum annuum* plants are presented in Table 3.

Root dry weight (RDW) was highest in the D + NF treatment (3.39 g), significantly different from ND + NF (2.12 g) with an LSD of 0.56. The D + F treatment (2.99 g) was also significantly higher than ND + F (2.46 g) and ND + NF but not significantly different from D + NF. Shoot

**Table 3.** Plant physiological parameter of *Capsicum annuum* under different water management

| Properties | D + F | D + NF | ND + F | ND + NF | Sig | LSD |
|---|---|---|---|---|---|---|
| Chl (mg $g^{-1}$ FW) | 2.86 | 2.62 | 2.71 | 2.01 | *** | 0.31 |
| Pro (μmol $g^{-1}$ FW) | 3.80 | 4.11 | 13.06 | 12.80 | *** | 1.02 |
| Pn (μmol $m^{-2}$ $s^{-1}$) | 18.51 | 17.7 | 17.50 | 15.86 | *** | 1.77 |
| E (mol $m^{-2}$ $s^{-1}$) | 4.14 | 4.05 | 4.18 | 4.21 | ns | - |
| gsw (mol $m^{-2}$ $s^{-1}$) | 1.14 | 0.95 | 0.68 | 0.82 | * | 0.13 |
| Ci (ppm) | 321.89 | 318.27 | 320.07 | 305.50 | ** | 10.52 |
| LWUE (μmol $mol^{-1}$) | 4.47 | 3.70 | 3.40 | 3.05 | ** | 0.27 |
| Root ABA (nmol $g^{-1}$ DW) | 1.01 | 0.83 | 1.04 | 4.13 | * | 0.46 |
| SOD (U. $mg^{-1}$ Protein) | 275.87 | 280.99 | 325.23 | 334.47 | * | 9.13 |
| POD (U. $mg^{-1}$ Protein) | 6.91 | 6.94 | 7.06 | 8.67 | * | 0.45 |
| CAT (U. $mg^{-1}$ Protein) | 267.08 | 287.44 | 298.85 | 316.89 | * | 12.01 |

dry weight (SDW) peaked in the D + F treatment (61.41 g), significantly different from ND + NF (37.94 g) as indicated by the LSD of 15.76. The D + NF treatment (43.38 g) and ND + F treatment (44.36 g) was not significantly different from each other but were both significantly lower than D + F and higher than ND + NF.

Fruit number (FN) varied significantly among treatments. ND + F produced the highest FN (168 fruits per plant), contrasting sharply with ND + NF (89 fruits per plant). Intermediate values were observed for D + F (158 fruits per plant) and D + NF (145 fruits per plant). Fruit length (FL) and flower diameter (FD) exhibited no significant differences across treatments. Fresh fruit weight (FFW) mirrored the FN pattern, with D + F producing the heaviest fruits (4.01 g), significantly exceeding ND + F (2.76 g) and ND + NF (3.17 g). D + NF displayed intermediate FFW (3.93 g), significantly greater than the control (ND + NF) but not different from D + F. Plant production (PP) and water use efficiency (WUE) were positively correlated with fruit yield. D + F excelled in both parameters, yielding 0.65 kg of fresh fruit per plant and converting water into biomass at a rate of 0.54 g $L^{-1}$. ND + NF exhibited the poorest performance in both metrics (0.37 kg PP and 0.33 g $L^{-1}$ WUE). Intermediate values were observed for D + NF (0.62 kg PP and 0.39 g $L^{-1}$ WUE) and ND + F (0.54 kg PP and 0.39 g $L^{-1}$ WUE). These findings collectively suggest that drip irrigation and organic fertilizer mitigate drought stress and enhance water use efficiency in *Capsicum annuum* (Handru et al., 2024).

The activities of antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) were higher in the ND + NF treatment. This suggests that plants under non-drip irrigation without fertilizer experienced oxidative stress, triggering an increased antioxidant response to combat reactive oxygen species (ROS) (Hasanuzzaman et al., 2021). In contrast, the D + F treatment likely maintained lower ROS levels due to better water and nutrient management, reducing the need for high antioxidant enzyme activities (Jomova et al., 2024). The D + NF treatment exhibited the highest root dry weight, likely due to the deeper and more extensive root systems developed under drip irrigation. This root development can be attributed to the consistent and localized water supply, encouraging roots to grow and explore a larger soil volume for nutrients (M'hamdi et al., 2023). Shoot dry weight was highest in the D + F treatment, reflecting the synergistic effect of optimal water and nutrient availability on above-ground biomass production. Fruit number and fresh fruit weight were significantly higher in the D + F treatment, suggesting that optimal water and nutrient conditions are crucial for reproductive success and fruit quality in *Capsicum annuum*. The increased water use efficiency observed in the D + F treatment underscores the effectiveness of this combination in maximizing yield while conserving water resources, which is particularly important in arid and semi-arid regions (Kano-Nakata et al., 2011; Kou et al., 2022). The results of measuring the parameters of plant biomass, yield, and water use efficiency (WUE) in *Capsicum annuum* are presented in Table 4.

The use of organic fertilizer (F) in combination with drip irrigation (D + F) not only improved plant growth metrics but also demonstrated superior water use efficiency (0.54 g $L^{-1}$) compared to other treatments. This suggests that organic fertilizer can enhance the soil's water-holding capacity,

**Table 4.** Plant biomass, yield, and water use efficiency parameter of *Capsicum annuum* under different water management

| Properties | D + F | D + NF | ND + F | ND + NF | Sig | LSD |
|---|---|---|---|---|---|---|
| RDW (g) | 2.99 | 3.39 | 2.46 | 2.12 | ** | 0.56 |
| SDW (g) | 61.41 | 43.38 | 44.36 | 37.94 | * | 15.76 |
| FN | 158 | 145 | 168 | 89 | ** | 23 |
| FL (cm) | 13.79 | 14.37 | 12.32 | 13.86 | ns | - |
| FD (cm) | 0.71 | 0.6 | 0.65 | 0.68 | ns | - |
| FFW (g) | 4.01 | 3.93 | 2.76 | 3.17 | *** | 0.48 |
| PP (kg) | 0.65 | 0.62 | 0.54 | 0.37 | ** | 0.13 |
| WUE (g $L^{-1}$) | 0.54 | 0.39 | 0.39 | 0.33 | * | 0.09 |

reducing the need for frequent irrigation and thus conserving both surface water and groundwater resources (Bhadha et al., 2017). The improved hydration status and reduced drought stress in the D + F treatment indicate that such an integrated approach can mitigate the impact of water scarcity, particularly in regions reliant on limited groundwater reserves (Dai et al., 2022; S. Ma et al., 2023).

## CONCLUSIONS

Cultivation of *Capsicum annuum* in karst landscapes presents significant challenges due to the inherent water scarcity and low nutrient retention capacity of this region. This study established that the integration of automatic drip irrigation with organic fertilisation can effectively address water scarcity issues. The study also revealed that the integrated irrigation and fertilisation strategy can alleviate water stress and reduce oxidative stress in plants, as evidenced by lower proline accumulation and decreased antioxidant enzyme activities. These findings suggest that D + F treatments not only support better vegetative growth and reproduction, but also contribute to more sustainable water and nutrient management in karst landscapes. Therefore, adopting modern agricultural practices can improve the resilience of horticultural crops such as chilli in drought-prone karst areas, which in turn can improve food security and economic outcomes in other areas with similar agroecological constraints.

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