

Assessing Two Optimized Smart Automated Irrigation Systems for Four Chili Cultivars

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ABSTRACT

Chili is one of the most important horticultural crops and a strategic national commodity. Efficient irrigation management is essential to sustain its productivity, particularly under increasing climate variability and water scarcity. This study evaluated the effects of two automated irrigation systems on the growth and yield of chili cultivars. The greenhouse experiment employed a split-plot design with two irrigation treatments—environmental sensor-based automatic irrigation (S1) and scheduled irrigation (S2)—on four chili cultivars (Arisa, Adelina, Genie, and Bara). Growth traits, including plant height, dichotomous height, number of leaves, number of branches, stem diameter, and SPAD, were observed weekly, while yield traits (fruit number, fresh weight, dry weight, average fruit weight, and fruit length) were measured at harvest. Results revealed no significant effect of interaction. Irrigation system affected number of branches, while varieties affected plant height, dichotomous height, SPAD and all yield traits except fruit number. The two irrigation systems did not statistically differ in yield, however, S1 consistently resulted in higher yield and save 61% water usage compared to S2. These findings indicate that S1 can enhance resource efficiency without compromising productivity, drought tolerant chili cultivars are recommended for supporting the sustainable cultivation of chili as a strategic commodity.

1. INTRODUCTION

Chili (*Capsicum annum* L.) is a strategic horticultural commodity with strong consumer demand. According to the Ministry of Agriculture, approximately 70.46% of chili consumption is attributed to household use, 17.62% to the HoReCa sector (hotels, restaurants, catering, and food services), and 7.53% to the food and beverage processing industry (Kementerian Pertanian, 2024). Tasmara *et al.* (2025) reported that chili consumption per capita reached 2.42 kg per year, representing a 7.11% increase compared to previous years, while national production reached 1.55 million tons. Data from Statistics of Indonesia (BPS, 2022) showed that large chili production in Indonesia amounted to 1.36 million tons in 2021, an increase of 96.83 thousand tons compared to 2020. The high level of consumption and demand necessitates balanced cultivation practices to meet consumer needs while maintaining national food security. Nevertheless, chili cultivation faces several challenges affecting plant growth, including climate change, global warming, and limitations in human resources and agricultural land availability.

Climate change affects all regions globally, with increasing severity driven by the frequency and intensity of natural disasters. Rising temperatures can accelerate plant growth and shorten growing seasons, potentially reducing crop productivity. Drought stress caused by water deficits can severely affect seedling establishment, early vegetative growth, photosynthesis, reproductive development, and final yield, highlighting the critical importance of appropriate water

management (Kim & Lee, 2023). Sato *et al.* (2024) reported that climate change significantly impacts agricultural crop yields, with heat and drought stress being the primary factors negatively affecting plant development and reproduction. These climate-related processes inevitably influence the productivity of large chili cultivation systems.

Large chili plants are classified as stress-sensitive crops, requiring adequate water supply and relatively moist soil conditions to maintain optimal growth. Efficient and effective irrigation methods play a crucial role in sustaining chili production (Nagaz *et al.*, 2012). However, water scarcity often constrains the normal operation of irrigation systems. One key aspect that can significantly improve irrigation management is the implementation of reliable data acquisition systems capable of providing real-time information on soil moisture, weather conditions, and plant status, thereby supporting timely and informed decision-making. Such capabilities can be achieved through the adoption of smart agriculture technologies based on the Internet of Things (IoT) (Abdelmoneim *et al.*, 2025). One of the technology applications is smart irrigation based on evapotranspiration.

The primary objective of automated irrigation is to optimize agricultural water management using real-time data, thereby maximizing water-use efficiency while minimizing environmental impacts (Ali *et al.*, 2025). These technologies also support more accurate and efficient decision-making processes (Obaideen *et al.*, 2022).

Irrigation scheduling and evapotranspiration (ET)-based irrigation differ fundamentally in their approach to water management. Scheduling methods rely on fixed intervals or soil moisture thresholds, providing more stable soil water conditions and simpler implementation, whereas ET-based irrigation dynamically adjusts water supply based on climatic demand, offering higher precision and improved water use efficiency. Previous studies have shown that ET-based irrigation enhances water application accuracy and efficiency while maintaining stable yields, while scheduling based on soil matric potential sustains plant performance by maintaining optimal soil moisture conditions defined by plant water status (Thompson *et al.*, 2007; Mačkić *et al.*, 2023). Maintaining moderate soil matric potential has also been reported to stabilize growth and yield in chili pepper (Jinzhao *et al.*, 2024). Both approaches have been tested in chili cultivation and demonstrate the ability to support crop growth and productivity; however, their relative performance remains inconsistent, as well-calibrated scheduling can achieve outcomes comparable to ET-based irrigation under certain conditions (Mačkić *et al.*, 2023).

Automated irrigation systems have been widely recognized as a key technological advancement in improving agricultural productivity, water-use efficiency, and resource management under water-limited conditions. These systems operate based on time scheduling or real-time environmental feedback, enabling precise and consistent water delivery aligned with crop water requirements. The integration of evapotranspiration-based irrigation scheduling has been shown to optimize irrigation performance and enhance crop water productivity in pepper cultivation by aligning water supply with plant demand (Adekaldy *et al.*, 2021). Recent advances in sensor-based irrigation systems have further improved precision water management in horticultural crops. In addition, automated irrigation systems improve the uniformity of water distribution while substantially reducing labor dependency through minimized manual intervention, leading to increased operational efficiency in modern agricultural systems (Pereira *et al.*, 2002; Evans & Sadler, 2008). Despite these advancements, limited studies have systematically evaluated genotype-specific responses under integrated automated irrigation strategies combining scheduling and evapotranspiration approaches, highlighting the importance of the present study.

This study aimed to evaluate the efficiency and effectiveness of two automated irrigation systems, namely real-time evapotranspiration sensor-based automatic irrigation and automated schedule-based irrigation, on vegetative growth and yield of four chili cultivars. Specifically, this research examined water-use efficiency under both irrigation systems and assessed whether differences in water input affected vegetative growth and yield performance among the cultivars. Four chili genotypes were employed in this study, consisting of two large-fruited varieties (Adelina and Arisa) and two bird eye types (Bara and Genie), to evaluate genotype-specific responses under distinct automated irrigation strategies. The selected genotypes represent contrasting drought tolerance characteristics, where Arisa and Genie are classified as relatively drought-tolerant, while Adelina and Bara are considered drought-sensitive. This distinction is critical, as chili genotypes exhibit substantial variability in physiological, morphological, and biochemical responses under water-deficit conditions, which directly influence plant adaptation, yield stability, and productivity. Previous studies have demonstrated that drought tolerance in chili is strongly associated with traits such as stomatal regulation, relative water content, and root system architecture, all of which vary significantly among genotypes (Malika *et al.*, 2019; Sahitya *et al.*

al., 2019). Moreover, the interaction between genotype and water regime plays a decisive role in determining crop performance, as genotype and irrigation interactions significantly affect growth, yield, and water-use efficiency in pepper cultivation (Ntanasi *et al.*, 2025).

The findings are expected to contribute to the optimization of agricultural resource use, enhance the sustainability of horticultural production systems, and provide practical insights for agricultural stakeholders regarding the effectiveness and efficiency of smart farming-based cultivation practices.

2. MATERIALS AND METHODS

The experiment was conducted in a greenhouse at the Laboratory for Agro-Industrial and Biomedical Engineering Development (LAPTIAB), KST BJ Habibie, South Tangerang, Indonesia, from July to November 2025. The study employed a split-plot experimental design with two factors. The subplot main factor was the automated irrigation system, comprising two treatments: irrigation control based on plant water requirements using evapotranspiration sensors (S1) (Figure 1) and irrigation control based on a fixed schedule (S2) (Figure 2). The main subplot factor consisted of chili genotypes with four levels, including two large chili cultivars (Adelina and Arisa) and two bird’s eye chili cultivars (Bara and Genie). Among these, Arisa (V3) and Genie (V2) were classified as drought-tolerant cultivars, while Adelina (V4) and Bara (V1) were considered drought-sensitive. The criteria of chili cultivar tolerance to drought were based on yield performance and the Drought Sensitivity Index (DSI) on morphological and anatomical traits from another previous research (Widuri *et al.*, 2020; Lestari *et al.*, 2024). The experiment was replicated six times, resulting in a total of 48 experimental units.

Figure 1 shows the evapotranspiration-based irrigation system operated using an automated irrigation pump that supplied water according to the actual water requirements of the plants. Water demand was calculated by sensors measuring four environmental parameters: air temperature, relative humidity, wind speed, and light intensity. These parameters were averaged over the previous measurement interval and subsequently used to calculate reference evapotranspiration (ET₀) using the FAO-recommended Penman–Monteith equation as follow:

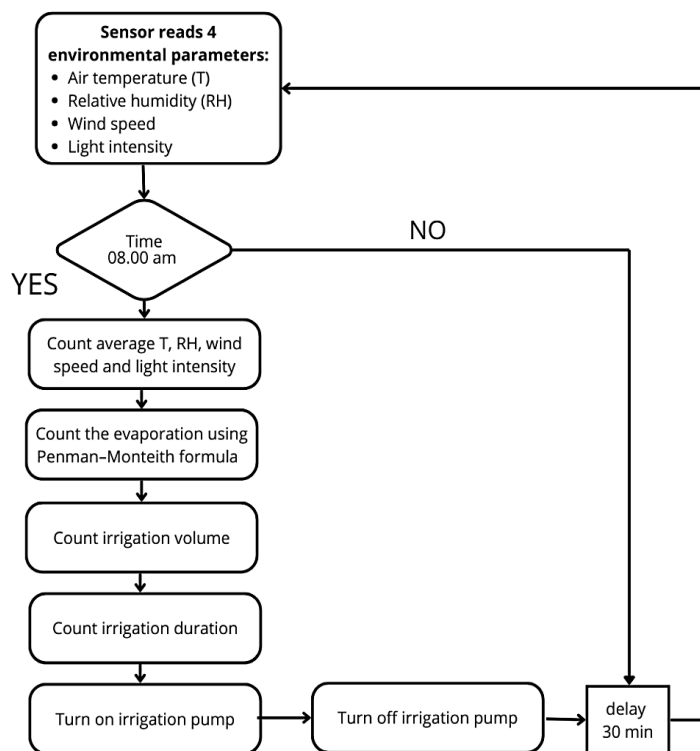


Figure 1. Flow chart of smart irrigation based on evapotranspiration environmental sensors (S1)

$$ET_0 = \frac{0,408 \Delta R_n + \gamma \frac{900}{(T+273)} U_2 (e_s - e_a)}{\Delta + \gamma(1+0,34 U_2)} \quad (1)$$

where ET_0 is reference evapotranspiration (mm/day), Δ is rate of change of saturation specific humidity with air temperature (kPa/°C), R_n is net irradiance (MJ·m⁻²·day⁻¹), T is average of air temperature at 2m (°C), u_2 is wind speed at 2m height (m/s), e_s is saturated vapor pressure (kPa), e_a is actual vapor pressure (kPa), and γ is psychrometric constant (kPa/°C).

The calculation was conducted as stated at [SNI 7745 \(2012\)](#). The calculated ET_0 value was then used to determine irrigation volume based on the cultivated area. The ET_0 value used is a predicted value obtained from the average ET_0 value over the last 10 days. The irrigation system operated daily at 08.00 WIB, delivering water volumes adjusted to sensor-derived plant water requirements. Pump activation duration was calculated based on the pump discharge capacity, and the system automatically terminated irrigation once the calculated duration was completed. Subsequent measurement cycles were initiated after a 30-minute delay.

Figure 2 shows the schedule-based irrigation system applied water according to predefined time settings (time-based control). Irrigation was initiated through setpoint inputs specifying irrigation time and pump activation duration. The irrigation pump automatically operated at 6 am and 5 pm. During each irrigation event, the pump and solenoid valve were activated for a fixed duration of 25 seconds, delivering 275 mL of water per plant. The water volume given was based on the result of [Prastono et al. \(2024\)](#). During operation, emitter flow rates were maintained at 11–12 mL/s to ensure uniform water distribution across all plants. After completion of the irrigation duration, the system automatically deactivated the pump and closed the solenoid valve. Outside the scheduled irrigation periods, the system remained in standby mode and did not supply water.

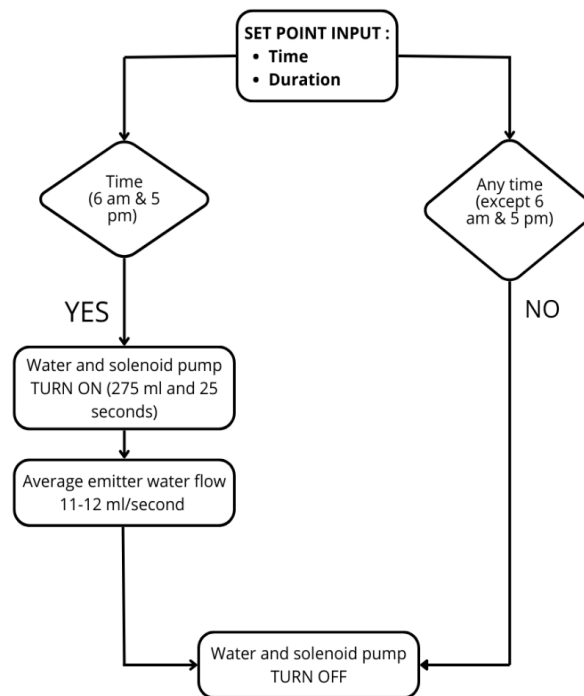


Figure 2. Flow chart of automated irrigation based on irrigation schedule twice a day (each 275 ml/plant)

2.1. Instruments and Materials

Figure 3 shows experimental condition involving greenhouse and irrigation installation, environmental sensors, monitoring and controlling system, and research lay out. The equipment used in this study included 35-cm diameter pots, plant stakes, nutrient solution tanks, irrigation pumps, irrigation pipelines, environmental sensors for evapotranspiration calculation (air temperature, relative humidity, wind speed, and light intensity), a SPAD chlorophyll

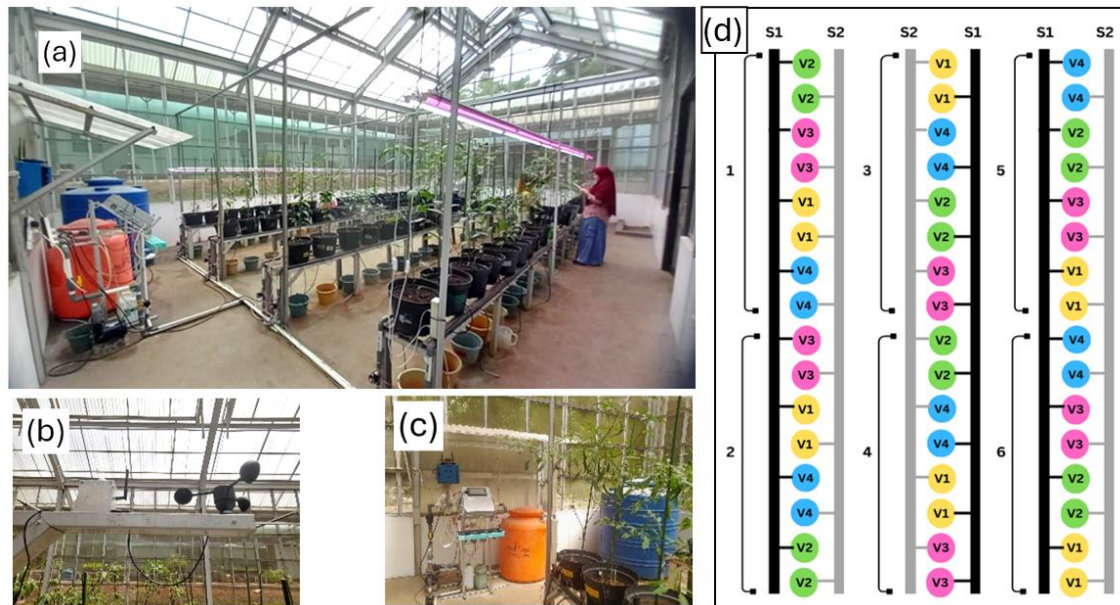


Figure 3. Experimental condition: (a) greenhouse and irrigation installation, (b) environmental sensors, (c) monitoring and controlling system, (d) research lay out

meter (Konica Minolta), rulers, digital calipers, and a digital balance (Sartorius). Cultivation tools included shovels, hoes, pruning shears, plant stack (*ajir*), and knapsack sprayers. The genetic materials consisted of chili seedlings of large chili cultivars (Adelina and Arisa) and bird’s eye chili cultivars (Bara and Genie). Growing media comprised soil, rice husk charcoal, and compost.

The control system consists of sensor modules and the main control module. The sensor module reads environmental parameters such as air temperature and humidity using the DHT22 sensor, light intensity using the BH1750FVI sensor, and wind speed using the anemometer sensor. All three sensors are connected to an ESP32 microcontroller, which reads the sensor values and then sends them to the main control module. The data transfer mechanism from the sensor module to the main control module uses the Hypertext Transfer Protocol (HTTP) with the POST method. This mechanism was chosen because it is simpler, easier to implement on a microcontroller, and compatible with standard web server technology. A 5-volt, 3-amp adapter is also used to power the ESP32 and several sensors.

The main control module serves as the irrigation control center. It consists of a Raspberry Pi 4 as the control center for calculating evapotranspiration and irrigation water requirements. Several solid-state relays are used as actuators to power the water pump and a 220-volt AC solenoid valve to provide water to the plants. In addition, a 5-volt 3-ampere adapter is also used as a power supply for the Raspberry Pi 4 to run the system as a whole.

2.2. Research Procedures

2.2.1. Growing Media Preparation and Seedling Establishment

Preparation involved setting up the automatic irrigation system, including sensors, solenoid pumps, and emitters, as well as pots and the greenhouse growing area. Seedlings were prepared by selecting high-quality seeds of each cultivar. Seed trays were filled with a growing medium composed of manure, rice husk charcoal, and soil in a 1:1:1 ratio and placed inside the greenhouse for 1 month.

2.2.2. Planting and Maintenance

Planting was conducted using healthy chili seedlings transplanted into the growing media in the greenhouse. Crop maintenance consisted of fertilization, pest, disease, and weed control. Fertilization was applied through smart fertigation using AB mix fertilizer at a concentration of 1,500 ppm. Nutrient solutions are added throughout the

cultivation process, along with irrigation. The nutrient solution is mixed with the raw water when the tank reaches its minimum level. Proper maintenance was essential to ensure optimal plant growth, as chili plants are sensitive to unsuitable environmental temperatures, which may reduce yield quantity and quality. Chili plants grow optimally at temperatures ranging from 21–27 °C during the vegetative stage, while ideal temperatures during the generative stage range from 16–23 °C (Widhiantari *et al.*, 2023).

2.2.3. Vegetative Growth Observation

Vegetative growth was evaluated weekly up to 12 weeks after planting (WAP). Observations were carried out on plant height, dichotomous height, number of leaves, leaf chlorophyll content (SPAD), number of branches, and stem diameter. Chlorophyll content (SPAD) was measured during the vegetative growth stage using a SPAD chlorophyll meter. Measurements were conducted once a week on fully expanded leaves located at the uppermost branching position. Each leaf was gently clamped between the sensor surfaces of the SPAD device to obtain relative chlorophyll content values in a non-destructive manner. This method ensures consistency in sampling by selecting physiologically mature leaves with a uniform developmental stage across all experimental units.

2.2.4. Yield Observation

Fruit harvesting was carried out 7 times from 9 to 16 weeks after planting (WAP) once a week. At each harvest, fruits were collected and analysis to determine yield components, including fruit length, number of fruits per plant, fresh weight, and dry weight. Fruit length was measured using a digital caliper and manual ruler, while fresh weight was recorded immediately after harvest. For dry weight determination, fruit samples were oven-dried at 40 °C until a constant weight was achieved.

2.2.5. Water Use Efficiency of Two Irrigation System

Water use efficiency (WUE) was determined to evaluate the effectiveness of irrigation water utilization in chili production. Total fresh fruit yield was recorded from each irrigation treatment across all chili cultivar (S1, S2) throughout the harvesting period. Irrigation water volume was measured daily, and the cumulative irrigation water applied during the entire growing season was calculated. Water use efficiency was then calculated as the ratio of total fresh yield (kg) to the total irrigation water applied (m³), using the following equation:

$$WUE = Y / I \quad (2)$$

where WUE represents water use efficiency (kg/m), Y is the total fresh fruit yield for all cultivar per irrigation system (kg), and I is the cumulative irrigation water applied (m³).

2.3. Data Analysis

Data analysis was performed using Analysis of Variance (ANOVA) or F-test at $\alpha = 5\%$. When significant differences were detected, mean separation was performed using Duncan's Multiple Range Test at $\alpha = 5\%$. All analyses were conducted using SAS®Studio v94.

3. RESULTS AND DISCUSSION

3.1. Water Use

Daily water-use measurements obtained using IoT-based sensors revealed substantial differences between the two irrigation systems. The evapotranspiration sensor-based system (S1) used an average of 217 mL/day per plant, whereas the scheduled irrigation system (S2) used 550 mL/day, resulting in water savings of 333 mL/day ($\approx 61\%$) under S1 (Figure 4). The average irrigation volume in S1 at vegetative stage was 199.49 and at generative stage was 224.61 ml/plant/day, which was 13% higher than vegetative stage (Table 1) while at S2 treatment the average on both stages was fixed at 550 ml.plant⁻¹.day⁻¹. Therefore, S1 showed a better water use efficiency compared to the S2 in general on 4 chili cultivars.

Table 1. Average of environmental condition values, ETo, and irrigation volume of sensor-based irrigation treatment (S1) during research for 146 days grouped into vegetative and generative phase.

Parameter	Mean \pm Standard Deviation (Range)			
	Vegetative (Day 1-45)		Generative (Day 46-146)	
Air temperature ($^{\circ}\text{C}$)	28.40 ± 0.14	(26.31-30.24)	29.02 ± 0.09	(27.22-30.89)
Relative humidity (%)	87.54 ± 0.89	(74.00-96.61)	87.29 ± 0.46	(73.00-96.70)
Wind speed (m/s)	0.01 ± 0.01	(0.00-0.21)	0 ± 0	(0.00-0.03)
Total radiation	7.40 ± 0.38	(0.80-11.53)	6.81 ± 0.21	(1.10-11.8)
ETo (mm day^{-1})	2.82 ± 0.15	(0.31-4.47)	3.18 ± 0.10	(1.20-6.50)
Irrigation volume (ml)	199.49 ± 10.51	(22.03-316.10)	224.61 ± 6.86	(84.98-459.38)

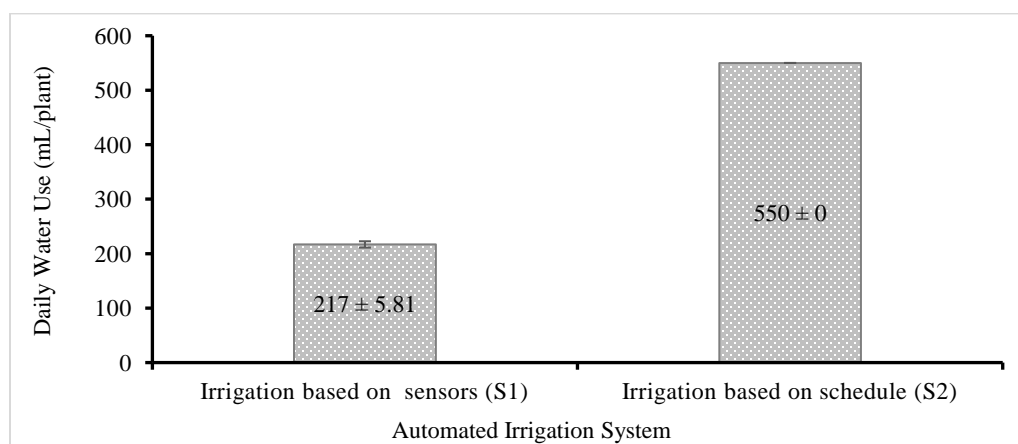


Figure 4. Water use comparison between two automated irrigation systems

The substantial reduction in irrigation volume between S1 and S2 indicates a significant improvement in water-use efficiency (WUE) in S1 where S1 was 190% more efficient than S2 (Table 2). Quantitatively, the 61% reduction in water input resulted more than a twofold increase in WUE compared to scheduled irrigation. These findings are consistent with [Abdelmoneim *et al.* \(2025\)](#), who reported that precision irrigation systems, although not always producing significant yield increase, are significantly able to improve water productivity, making them very valuable in water-scarce areas. They also explain that precision irrigation systems using IoT and wireless sensor networks (WSN) result in a 20–30% reduction in water use compared to conventional methods.

Table 2. Water use efficiency of the two irrigation systems across all tested chili cultivars

Irrigation	Total yield (kg)	Total water (m^3)	Water Use Efficiency (kg/m^3)
Irrigation based on sensors (S1)	0.04279	0.79157	0.054
Irrigation based on schedule (S2)	0.03146	1.68630	0.019

3.2. Automated Irrigation Response

Analysis of variance results showed no significant interaction effects between 2 automated irrigation systems and 4 chili varieties on all vegetative and harvest traits. The automated irrigation system significantly affected number of branches. Despite achieving water savings of approximately 61% under the evapotranspiration-based irrigation system compared to the schedule-based irrigation system, plant height, dichotomous height, and SPAD of chili plants were not adversely affected. However, number of branches on the S2 irrigation system were better than on S1 (Figure 5). The two irrigation systems did not produce statistically significant differences in yield. However, the sensor-based system (S1) consistently produced higher fresh fruit weight and dry fruit weight per plant, weight per fruit, and fruit length than the schedule-based system (S2) (Figure 6).

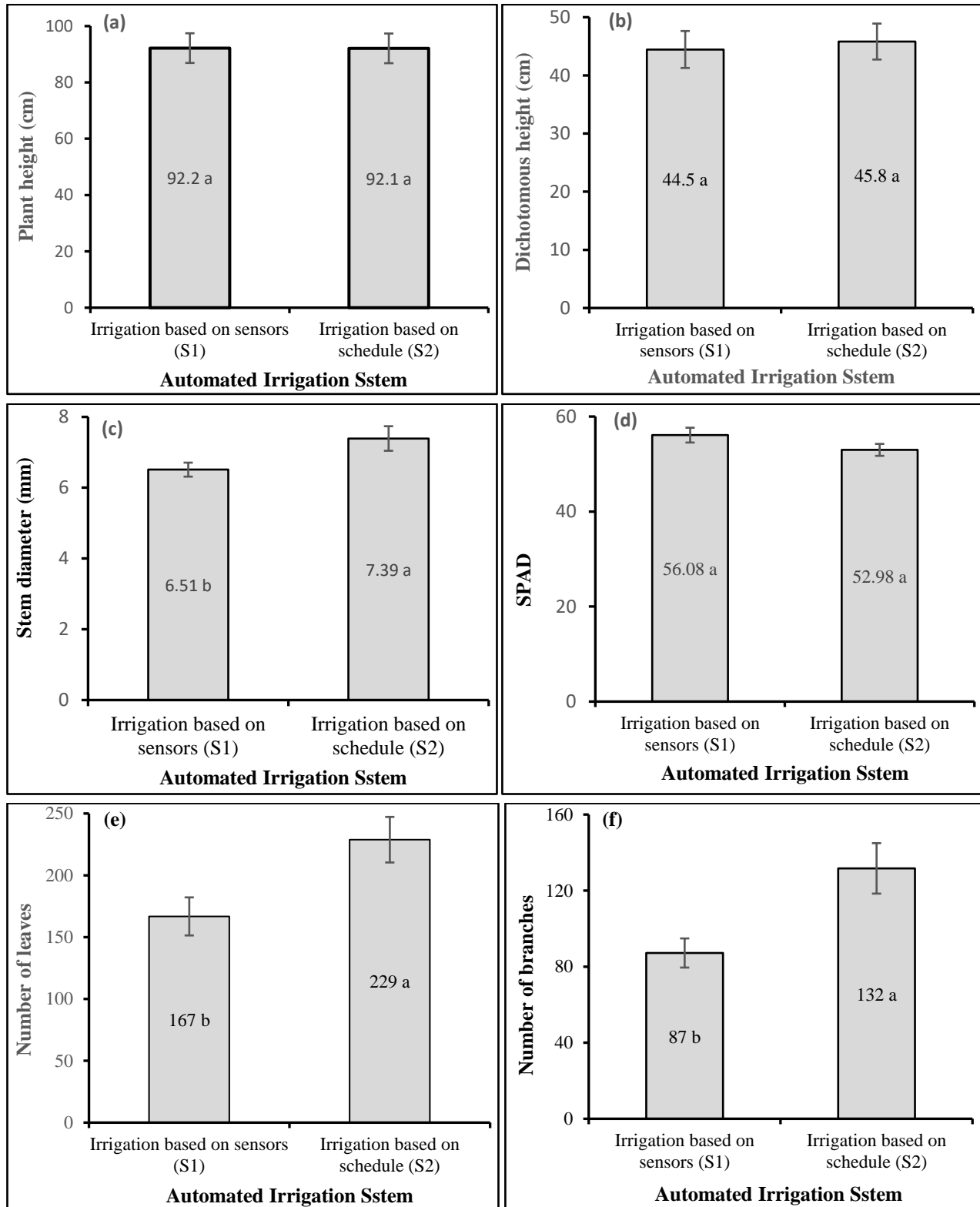


Figure 5. Effect of irrigation system on vegetative growth at the last observation: (a) Plant height, (b) Dichotomous height, (c) Stem diameter, (d) SPAD, (e) Number of leaves, and (f) Number of branches. [Means \pm standard error followed by the same letter at each graph were not statistically different based on Duncan's Multiple Range Test at $\alpha = 5\%$]

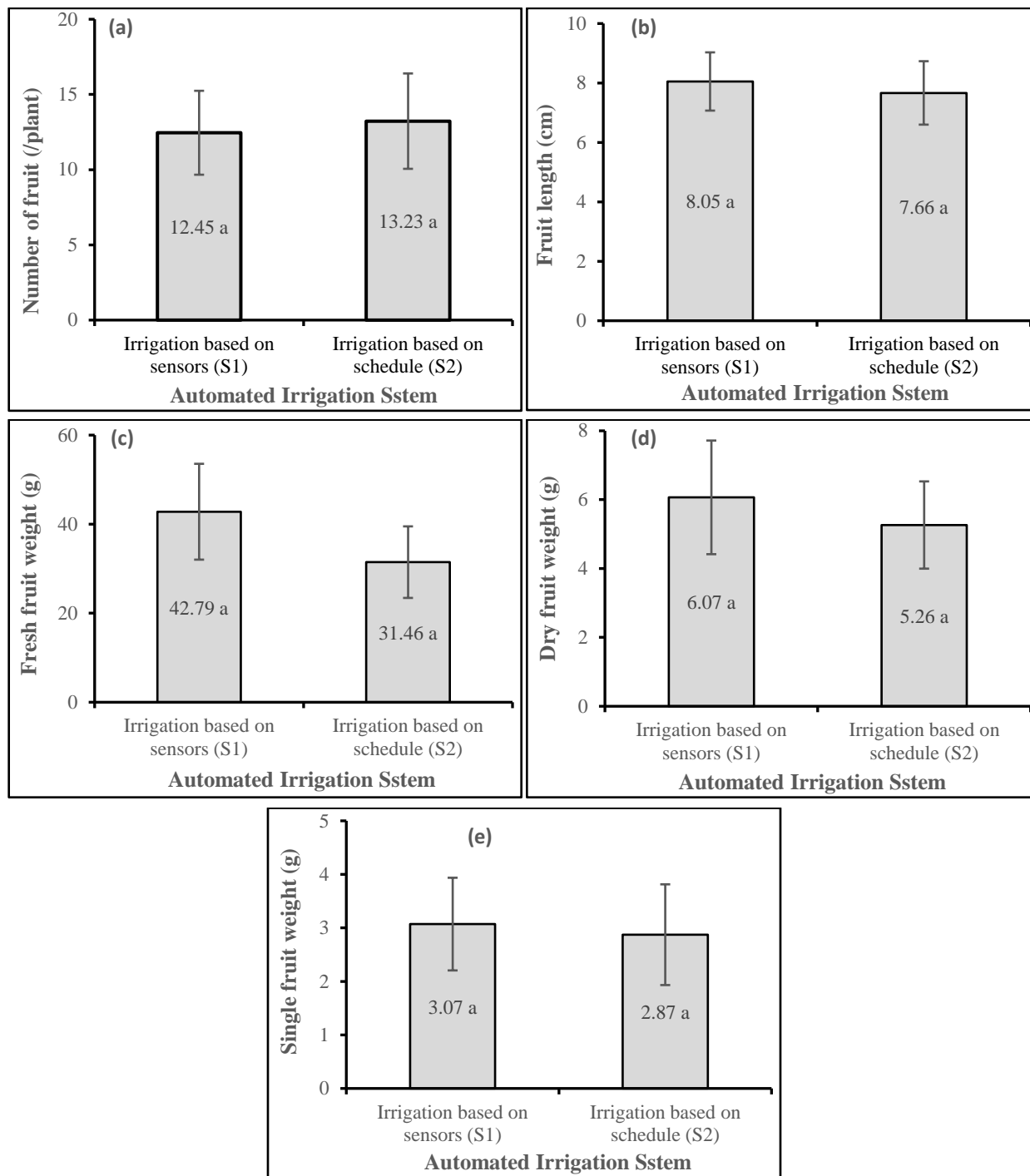


Figure 6. Effect of irrigation system on crop yields: (a) Number of fruit per plant, (b) Fruit length, (c) Fruit fresh weight, (d) Fruit dry weight, and (e) Single fruit weight [Means \pm standard error followed by the same letter at each graph were not statistically different based on Duncan's Multiple Range Test at $\alpha = 5\%$]

These findings are supported by [Osroosh *et al.* \(2016\)](#), who reported that real-time, data-driven automatic irrigation systems can enhance water-use efficiency by precisely supplying water according to plant requirements, thereby reducing water losses while maintaining adequate water availability for optimal vegetative growth. Furthermore, previous studies have demonstrated that sensor-based irrigation systems with optimized water-use efficiency can

significantly improve vegetative growth parameters, including stem diameter, leaf length, and crop yield, compared to conventional irrigation practices (Singha *et al.*, 2024).

The results of this study align with those of Li *et al.* (2024), who compared cucumber plants using sensor-based irrigation for humidity, radiation, and evapotranspiration (ETc). The evapotranspiration method reduced total irrigation volume by 25–34% without significantly reducing yields and even increased irrigation water productivity (IWP). The difference between the two irrigation systems lies in the dynamic response of the water. The scheduled irrigation system is static, not fully adapting to microclimate fluctuations and plant physiological needs, while the sensor-based evapotranspiration irrigation system works adaptively, triggering irrigation based on actual root zone conditions or transpiration needs, significantly reducing water loss due to percolation or evaporation.

The irrigation systems used in this study demonstrate that more precise water management can maintain plant water status, increase cell turgor pressure, and support optimal vegetative tissue expansion. The positive response of stem diameter and branch number in the S2 system indicates that water availability tailored to actual plant needs is more effective in supporting structural plant growth. The results showed that, although the S2 irrigation uses more water than the S1, both irrigation systems share the same goal of maintaining more stable soil moisture. This stability ensures continuous air availability, supporting cell expansion, meristematic activity, and nutrient uptake, ultimately promoting consistent vegetative growth, including stem elongation and branching. In contrast, the S1 (evapotranspiration-based irrigation) system supplied water according to climatic factors, resulting in temporal variability in soil moisture. While this approach improved water use efficiency by synchronizing irrigation with plant evapotranspiration, it could lead to short-term fluctuations in plant water status that could limit sustained vegetative development. Therefore, S2 is more effective in maintaining stable vegetative growth through consistent soil moisture conditions, while S1 is more efficient in optimizing water use through demand-based irrigation (Jinzhao *et al.*, 2024; Mačkić *et al.*, 2023).

Table 3. Effect of different irrigation system to yield trait

Yield trait	Irrigation based on environmental sensors (S1)	Irrigation based on schedule (S2)	Percentage different of S1-S2 (%)
Fruit number/plant	12.45	13.23	-6.20
Fruit fresh weight/plant (g)	42.79	31.46	26.47
Fruit dry weight/plant (g)	6.07	5.26	13.24
Average weight/fruit (g)	3.07	2.87	6.45
Fruit length (cm)	8.05	7.66	4.79

Different responses of the two automated irrigation system which showed S2 better than S1 in several traits (Figure 5), did not produce better yield of S2 compared to S1 (Figure 6). Chili yields varied, but these variations did not show statistically significant changes. These results demonstrate that the use of an evapotranspiration-based irrigation system (S1), which significantly reduces irrigation water volume compared to schedule-based irrigation, does not reduce the potential yield of chili peppers. Yield traits such as fresh weight per plant, dry weight per plant, average weight per fruit and fruit length showed relatively comparable or even higher values in the S1 treatment compared to the S2 treatment, namely 26.47%, 13.24%, 6.45% and 4.79%, respectively (Table 3). These results indicate that even with drastic reductions in water input, plants are still able to utilize water efficiently to support physiological processes, vegetative growth, and fruit development without experiencing detrimental water stress. This interpretation aligns with research demonstrating that the use of efficient irrigation systems, such as drip and shallow subsurface drip irrigation, can maintain high yields and irrigation efficiency without causing significant differences in yield compared to conventional irrigation. Effective and efficient irrigation can produce yields that are not significantly different from conventional irrigation (Mačkić, 2023).

Furthermore, Berholtz (2023) explained that SW-based irrigation can reduce irrigation volume by 35-42% compared to commercial irrigation without significantly reducing yields. Test results showed no significant difference in yield between different irrigation treatments, even though the irrigation volume used was more efficient. Furthermore, mild irrigation deficits or proper water management can maintain yields while increasing water use efficiency (Kabir *et al.*, 2021).

Li *et al.* (2024) explained that although vegetative parameters differed between irrigation treatments, crop yields did not show significant differences. However, the IWP significantly increased in the evapotranspiration-based irrigation system. Agronomically, this condition indicates that plants possess physiological plasticity, namely the ability to maintain yields even when water supply is reduced, as long as minimum physiological needs are met.

Based on this research, it can be seen that the sensor-based irrigation system (S1) demonstrates effectiveness and efficiency in chili cultivation. This is consistent with research by Roy *et al.* (2021), who explained that automatic irrigation helps increase crop productivity compared to traditional manual irrigation methods, extends network life compared to existing systems, while still achieving reliability over a relatively long period of use. This automatic evapotranspiration irrigation method can replace traditional agricultural methods in saving water use. Zia *et al.* (2021), who compared and optimized water use at a plantation trial site for 9 months by implementing IoT devices, stated that significant water savings were followed by increased crop yields compared to water use and yields using traditional irrigation.

Evapotranspiration (ET) based irrigation systems have the potential to significantly improve irrigation efficiency and save water. ET controllers can generate significant annual water savings compared to time-based irrigation schedules that don't take real-time rainfall into account, while still maintaining crop quality. This is because ET controllers can more accurately adjust water needs based on soil and climate conditions, thereby reducing over-irrigation and water waste (Davis & Dukes, 2010). Experiments with evapotranspiration irrigation systems were also conducted by Adekaldu (2021), where an irrigation system based on crop evapotranspiration combined with rice straw mulch significantly increased water use efficiency and crop yields. This irrigation system was able to save up to 44.5% of water (compared to daily irrigation) while creating ideal soil moisture and temperature conditions.

While scheduled irrigation systems are not as efficient as evapotranspiration-based irrigation, precision irrigation can be implemented by consistently delivering water to crops using Deficit Irrigation. This strategy is designed to provide water in amounts lower than the plant's full needs, but adjusted to minimize negative impacts on crop yields or even produce other benefits (Fernandez, 2017). Based on research by Zhang *et al.* (2022), which compared automatic irrigation systems with manual ones based on sensorless evapotranspiration, the results showed that the automatic irrigation system resulted in a 22.1% higher marketable fruit yield and increased water use efficiency by up to 27.7%.

The irrigation system also plays a significant role in influencing vegetative growth, particularly in stem diameter and the number of branches. This sensor-based irrigation system is capable of supplying water in accordance with the actual requirements of the plant, thereby maintaining cellular turgor stability and optimally supporting cambial activity, which in turn promotes stem thickening, increased branching, and other aspects of vegetative development. This finding is consistent with Lestari *et al.* (2024), who reported that water availability exerts a stronger influence on cell division and cell enlargement in vascular tissues than on stem elongation, especially under conditions of controlled soil moisture fluctuations. Therefore, precision irrigation contributes more substantially to the formation of an efficient plant architecture than merely to increasing plant height.

3.3. Variety Response

Vegetative traits, such as plant height and dichotomous height, and the entire yield traits were primarily influenced by cultivar differences (Figures 7, 8). However, other traits showed similar responses between the two systems used, but not statistically different. Based on the statistical analysis result under two smart irrigation systems, red chilli consistently showed better yield (fresh and dry weight) in Arisa variety (drought tolerant) than in Adelina (drought susceptible) and bird's eye chili showed the same trend where Genie (drought tolerant) performed higher yield than Bara (drought susceptible). While bird's-eye chili showed inconsistent response between varieties Bara and Genie. The four varieties tested showed that they were affected by water intensity and drought stress, with the Arisa variety showing better yields than Adelina in large chili and Bara was better than Genie in bird's eye chili. This is due to morphological and physiological characteristics that are susceptible to water-deficient conditions. The tolerant variety has more efficient physiological mechanisms for maintaining relative water content, photosynthesis, and resource allocation to the fruit than the susceptible to drought.

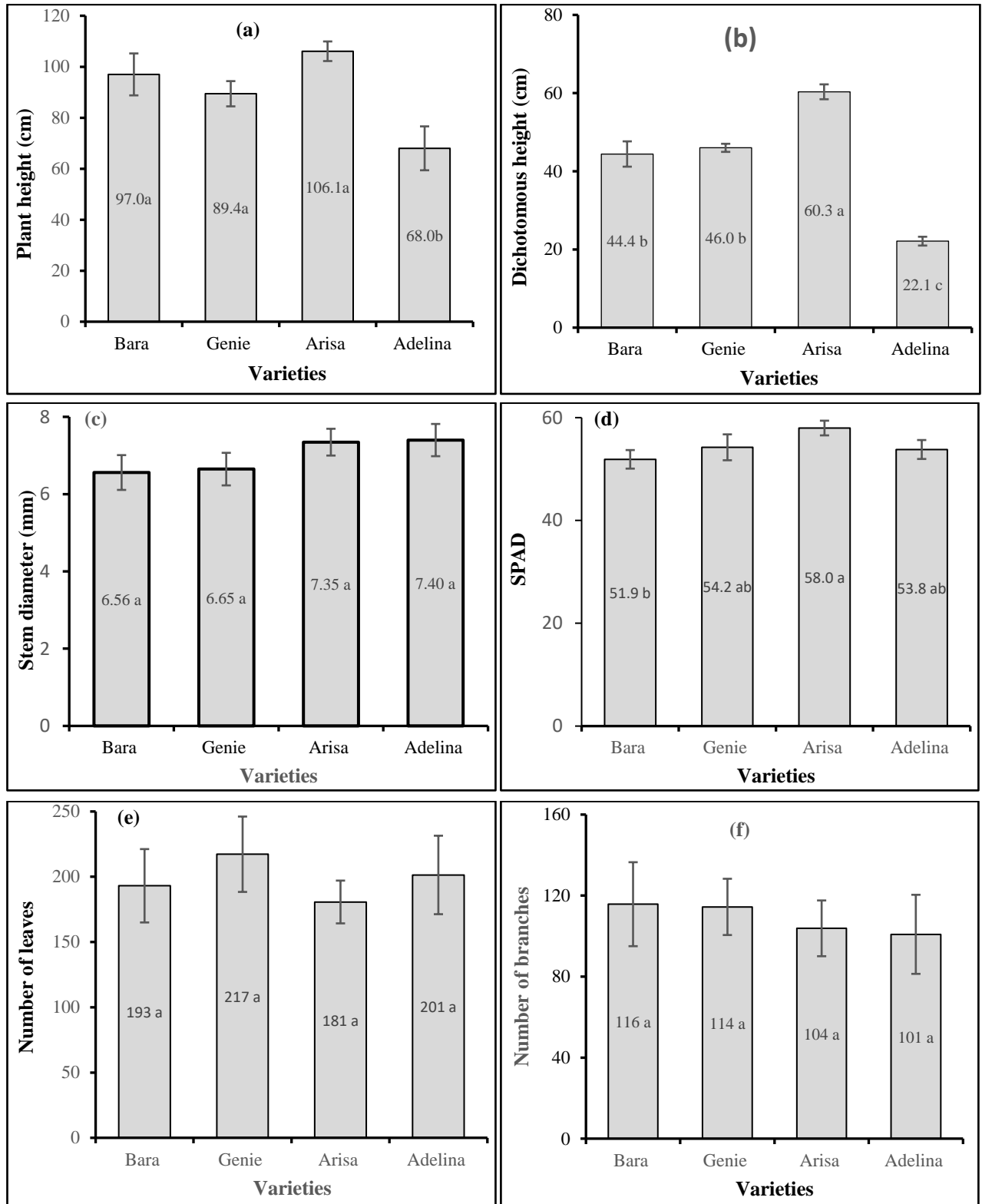


Figure 7. Effect of varieties on vegetative growth at the last observation: (a) Plant height, (b) Dichotomous height, (c) Stem diameter, (d) SPAD, (e) Number of leaves, and (f) Number of branches. [Means \pm standard error followed by the same letter at each graph were not statistically different based on Duncan's Multiple Range Test at $\alpha = 5\%$]

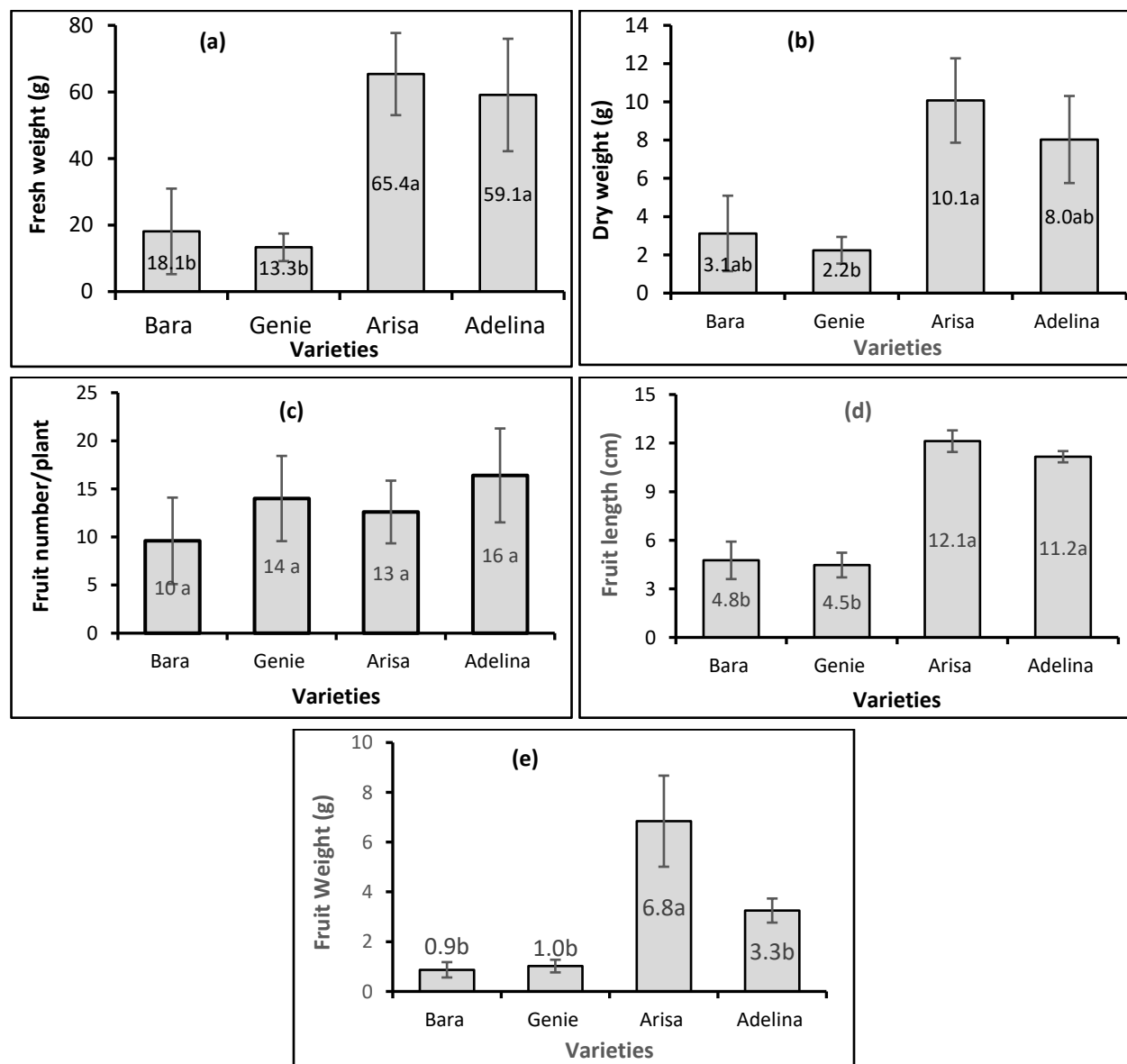


Figure 8. Effect of varieties on crop yields: (a) Fresh fruit weight, (b) Dry fruit weight, (c) Number of fruit per plant, (d) Fruit length, and (e) Single fruit weight. [Means \pm standard error followed by the same letter at each graph were not statistically different based on Duncan's Multiple Range Test at $\alpha = 5\%$]

Differences in vegetative growth indicate that the Arisa, Bara, Genie, and Adelina varieties have distinct physiological characteristics that regulate vegetative growth even under the same irrigation conditions. [Lestari \(2023\)](#) stated that in a drought stress experiment on chili, during dry periods, the tolerant genotypes developed more fibrous roots, enabling them to absorb more water, transport water to plant tissues by lowering the relative leaf water content, increasing the leaf water potential from the root and media water potential, and maintaining open stomata. These genotypes exhibited growth plasticity (escape) by slowing vegetative growth during drought and flowering immediately after the drought has passed. The mechanism of drought tolerance was found to be associated with higher levels of leaf antioxidants (anthocyanins, phenolics, and flavonoids). The differences in vegetative responses between varieties are explained by [Kabir *et al.* \(2021\)](#) as indicating that increasing water availability in accordance with plant needs positively affects leaf water potential, photosynthetic rate, and stomatal conductance, which in turn encourages increased vegetative growth such as stem diameter and branch formation.

The yields in this study, measured by the number of fruits, fresh weight per plant, dry weight per plant, average fruit weight per plant, and fruit length, showed variations between the varieties used. These differences indicate that genetic factors between each variety are different, indicating differences in the efficiency of assimilate allocation to generative organs between each variety. Kabir *et al.* (2021) explained that although vegetative growth can decrease under certain conditions, fruit yield can still be maintained if the plant has efficient sink-source capabilities during the generative phase. These varietal differences indicate differences in harvest yield between varieties. The differences yield response between these varieties are more determined by the physiological and morphological characteristics of the fruit types between varieties. Overall, the results of this study indicate that differences in the varieties Arisa, Bara, Genie, and Adelina affect the height, SPAD and yield of chili peppers, while the sensor-based irrigation system plays a role in optimizing plant structural growth and water use efficiency.

4. CONCLUSIONS

The evapotranspiration sensor-based automated irrigation system (S1) showed a better water use efficiency of about 61% water compared to the schedule-based automated irrigation system (S2) in general on 4 chili cultivars. Analysis of variance results showed no significant interaction effects on all vegetative and harvest traits. Different irrigation systems affected number of branches, while varieties affected plant height, dichotomous height, SPAD and all harvest variables except fruit number. The two irrigation systems did not produce statistically significant differences in yield, but the sensor-based system (S1) consistently produced higher fresh fruit weight and dry fruit weight per plant, average weight per fruit, and fruit length than the schedule-based system (S2). The absence of significant interaction indicates that cultivar responses were generally consistent across irrigation systems. Therefore, a significant decrease in water use by using an evapotranspiration sensor-based automated irrigation system did not affect chili yield, which resulted better water use efficiency. These findings highlight the potential of integrating smart irrigation technology with drought-tolerant chili cultivars to enhance resource efficiency and support sustainable intensification of chili production under increasing water scarcity and climate variability. Practical implication of this research is the adoption of smart irrigation systems can help farmers to optimize irrigation scheduling based on real-time crop water demand, thereby reducing unnecessary water application, lowering pumping energy costs, and minimizing nutrient leaching risks. The limitations of this research were conducted under controlled greenhouse conditions and on a single growing season, and therefore field condition, seasonal variability and long-term system performance were not assessed yet. Future work suggested to evaluate smart irrigation performance under multi-season and open-field conditions, to improve the generalizability of the findings and expanding the range of irrigation technologies, such as machine learning, or integrated fertigation systems, for a more comprehensive understanding of precision water management in chili cultivation.

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AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
ZR	✓	✓		✓	✓	✓		✓	✓	✓	✓			
LD	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓
MHF	✓	✓		✓						✓		✓		
HP	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓		
RA	✓	✗		✓		✓		✓	✗	✗		✗	✓	

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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