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Solar-Powered Automated Drip Irrigation System Scheduling

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ABSTRACT

The necessity of irrigation management has become increasingly important in many regions due to water scarcity. With agriculture consuming 72% of the world's freshwater, it is crucial to use water efficiently in all areas of life, particularly in agriculture. Pressurized irrigation systems, when combined with automation, have significantly improved irrigation practices. Currently, there is a growing shift from manual systems to automated operations in pressurized systems, as automation and electronics in agriculture are becoming more widespread globally.

In the study, an automatic irrigation system powered by solar energy was used to calculate plant water consumption based on solar radiation throughout the entire growing season. This study aimed to evaluate the performance of a solar-powered automatic drip irrigation system compared to manual irrigation, focusing on crop yield outcomes, improving water use efficiency, and reducing labor and energy costs. The developed system utilized solar radiation data to estimate plant water consumption and automatically applied irrigation water equivalent to the crop's evapotranspiration throughout the entire growing season. The system was programmed to activate and deactivate at predetermined times based on calculated water requirements. The study's results showed no statistically significant difference in yield between the manually controlled drip irrigation system (6.72 t/ha) and the automated drip irrigation system (6.80 t/ha); however, the use of solar energy to power the automatic drip irrigation system eliminated irrigation energy costs by 100% during daylight hours, and the integration of automation reduced labor costs. The study indicates a potential 50-60% reduction in labor efforts, as the automated system independently scheduled and executed irrigation without the need for human intervention. Despite an observed over-irrigation in June, the system effectively maintained soil moisture at field capacity throughout the plant's growth stages. This approach prevented excessive water use and nutrient leaching beyond the root zone, thereby making significant contributions to environmental sustainability.

Keywords: Drip irrigation, Irrigation automation, Solar panels, Solar radiation, Microcontroller

1. Introduction

The scarcity of water makes it essential to use water economically in all areas of life, especially agriculture since it uses 72% of the world's freshwater (Cai & Rosegrant 2003). Therefore, efficient water use in agriculture is extremely important for our environment and future generations. Today, the economical use of water in agriculture will be possible through the widespread adoption of modern irrigation systems. Nowadays, irrigation systems are shifting from manually controlled systems to automated systems. On the other hand, just like in all other sectors, agriculture also requires energy to carry out its activities. Diesel or hydroelectric energy is widely used at many stages of agricultural activities; however, the rising costs of these energy sources are reducing the profit margins of agricultural products. This situation is driving producers to use towards both cheaper and renewable energy sources. Today, many studies are being conducted to utilize solar energy in agricultural practices (Armaroli & Balzani 2011), as these systems reduce costs for producers. Furthermore, renewable energy sources are cleaner and have less harmful effects on both nature and human beings (Rages et al. 2016). The adoption of solar energy in irrigation has gained significant momentum, driven by the growing demand for sustainable and renewable energy solutions in agriculture. A study by Fidelis & Idim (2020) underscores the potential of solar-powered drip irrigation systems in arid regions, showing that these systems can substantially reduce water consumption while offering a cost-effective and efficient irrigation solution. They present a practical option for both small- and large-scale farmers, helping them maintain and enhance their agricultural productivity sustainably. Ahmmed et al. (2021) also reported similar findings in their study, highlighting the effectiveness of automation in ensuring optimal moisture conditions for plant growth. By automating the irrigation process, it not only ensures optimal moisture conditions for plant growth but also helps save time and reduce human errors associated with manual adjustments. Furthermore, the system contributes to maximizing crop yield by providing consistent and efficient water distribution, ultimately enhancing overall farm productivity and sustainability.

There are many systems in irrigation automation that provide water to plants, ranging from simple to more complex systems. For example, Wang et al. (2010) observed plant water content using thermal imaging and applied water based on plant surface temperature. Yuan et al. (2004) attempted to optimize plant water usage by programming irrigation according to the Crop Water Stress Index (CWSI). Nemali et al. (2006) implemented irrigation automation based on the volumetric water content of the soil, using data obtained from dielectric moisture sensors to control the devices used in irrigation automation. Gutiérrez et al. (2014) developed a solar-powered system that automatically irrigated plants using data from soil moisture and temperature sensors placed in the root zone, with wireless communication and the system was tested for 136 days, and compared to traditional methods, it was found to save 90% of water.

Dong et al. (2013) developed a center-pivot system where soil moisture sensors placed in the soil communicated wirelessly through a network system. Irrigation management in this system was based on real-time data received from the soil moisture sensors. Boobalan et al. (2018) and Pernapati (2018) developed automatic IoT-based irrigation systems that automatically carried out irrigation by monitoring soil and atmospheric conditions. Casadesus et al. (2011) developed an automated irrigation system running by the amount of radiation intercepted by the canopy of apple trees.

In irrigation automation, automatic irrigation algorithms are successfully used at the industrial level. Nowadays, the use of optimal control techniques and advanced algorithms in the management of irrigation systems are current research topics in irrigation automation. Some researchers, such as Tunez et al. (1992), Nixon et al. (2001) and Schütze et al. (2012) have developed algorithms specific to the regions where irrigation is applied. Irrigation water should meet the water needs of plants and prevent water accumulation in the growing environment (Sonneveld 2000). Excessive water application can lead to the loss of both irrigation water and nutrients applied with the water through drainage, increasing irrigation costs and causing negative effects on environment by polluting groundwater (Gallardo & Tase 2007).

Irrigation management has become essential in many regions, particularly in the Mediterranean areas (Abrishambaf et al. 2020). The primary goal in irrigation is to maintain soil moisture in the plant root zone at an appropriate level between field capacity and the wilting point. New technologies applied in irrigation are meeting plant water needs while minimizing losses by using less water compared to traditional methods. Among modern irrigation systems, it is known that water use efficiency is high in drip irrigation when the necessary rules are followed during the design stage. A characteristic feature of drip irrigation is the ability to frequently irrigate, delivering water directly to the plant root zone. Rivera et al. (2020) developed a microprocessor-controlled drip irrigation system and fertilization system in sugarcane, which automatically determines the plant's nutrient requirements based on different growth stages. This system optimizes both irrigation water and fertilizer amounts. Caya et al. (2018) measured temperature and humidity values using a DHT22 sensor and rainfall amounts with a rain gauge in an agricultural area. They determined the reference crop water consumption using the Hargraves-Samani method and, based on the obtained values, carried out the irrigation of the Brassica Rapa plant, known as Chinese cabbage, using software defined on a microprocessor. This distinguishes drip irrigation from other known irrigation methods (Vermeiren & Jobling 1980). The most widely used and straightforward method for scheduling irrigation up to now involves estimating crop transpiration using the radiation-based method (Stanhill & Scholte 1974). The success of the irrigation automation system depends on providing the plant with the required water at the right time and in the right amount. Therefore, an alternative parameter for determining plant water needs is the estimation of evapotranspiration (ET). ET is influenced by climatic parameters such as solar radiation, temperature, relative humidity, wind speed, and plant factors (Allen et al. 1998).

Katsoulas et al. (2006) stated that systems that automatically trigger irrigation based on radiation have been used for a long time, especially in soilless agriculture. Research indicates a growing trend toward automation systems to use solar radiation as an indicator for evapotranspiration. One of the main objectives of this study was to develop an automatic irrigation system powered by solar energy, which calculates the plant's water consumption based on solar radiation and applies the amount of irrigation water equal to the amount of crop evapotranspiration to the root zone, and automatically to activate the system at a specific time of day for irrigation. The solar radiation data were obtained from a pyranometer sensor and convert this data into plant water consumption values using equations determined for each month. This information was used by software stored in the microprocessor, by processing the data and equations the system automatically applied irrigation water to the plant root zone using the system's self-generated energy. Using self-generated solar energy eliminates dependency on the power grid or fossil fuels, significantly reducing operational costs. It also ensures system autonomy during daylight, especially critical in remote or off-grid locations. Additionally, it supports sustainability by lowering greenhouse gas emissions and promoting the use of renewable resources.

This approach presents a promising solution for improving irrigation efficiency by integrating solar energy and automation. By utilizing solar radiation data to precisely calculate plant water consumption and adjusting irrigation accordingly, the system not only optimizes water usage but also reduces reliance on external energy sources. The automatic activation based on predetermined times enhances convenience and minimizes human intervention, while the significant savings in labor and energy highlight the potential for large-scale application in water-scarce regions. This system aligns well with the increasing need for sustainable agricultural practices.

2. Material and Methods

2.1. Experimental design and system components

The experiment was carried out at the Dardanos Agricultural Research Station of Canakkale Onsekiz Mart University in Canakkale (Dardanelles), Turkiye in summer between May and September of 2023. The experiment site is located at 40.08°N latitude, 28.20°E longitude at an altitude of 3 meters. The kapia pepper seedlings (*Capsicum annuum* L.) were transplanted on May 17, 2023, to the field. Soil analysis revealed that the field capacity of the soil at a root depth of 0-90 cm is 34.4%, the wilting point is 19.1%, and the soil texture class is clay loam at the site in two different treatment plots. Each plot was 10 m long and the kapia pepper seedlings were planted 0.7 m between rows and 0.33 m within rows. Each plot was established in 2.8 m wide and 3.3 m long, each containing 4 rows, and each row having 10 plants. Hence, a total of 40 plants in each plot had been grown in an area of 9.5 m^2. The experiment was laid out using a randomized complete block design with 3 replications. Climate parameters solar radiation (W m^{-2}), temperature (°C), relative humidity (%) at the site were measured 1.5 m above the canopy of the plants using a HOBO U12 data logger (Figure 1d). Solar radiation measurements were conducted in an open and shadow-free environment at a height of 1.5 m using an Apogee pyranometer sensor (sensitivity: ± 5%, measurement range: 0-1750 W/m²) connected to a HOBO U12 data logger. Simultaneously, at the same location, we obtained solar radiation readings using another Apogee pyranometer sensor with identical specifications connected to a microcontroller in our own circuit. A calibration curve with 99% accuracy was obtained and defined in the memory of the microcontroller. Subsequently, solar radiation measurements were initiated through the automation system.

The essential components of solar-powered drip irrigation system are a well (Figure 2); having a depth of 7 m and supplied a constant water source. Solar photovoltaic panels (PV); used an array of PV to produce electricity and in the automation system, four solar panels were used (Figure 1c), each capable of producing 285W of energy. Main board (Figure 1b); used to receive data from the pyranometer sensor, send it to the microcontroller (ATmega328), save it on an SD card, process the obtained data to decide how long the submersible pump should run, and after running the pump for the required duration and then turn off the pump via relays. A submersible pump, having a discharge of 2 m³/h and pressure head of 45 m, has a 32 mm outlet and pumped water from a 7-meter deep well to the soil surface using a 32 mm pipe, and then conveyed to the plant root zone via a 63 mm main pipe (Figure 1a). Main and drip lines were used to deliver water to the root zone of the plants. In both the control and automation irrigation systems, the main pipes are Ø 63 mm, while the drip irrigation pipes are Ø 16 mm PE (Figure 1d), with emitters spaced 33 cm apart and the emitter discharge rate was determined by measuring the amount of water collected in measuring containers placed under three emitters—at the beginning, middle, and end of three laterals. The average flow rate was found to be 4 L/h.

The solar panels have been mounted onto the supporting structure designed in a Venlo roof system configuration (Figure 1c and Figure 2) and the structure was oriented in the southeast and northwest directions. In this way, the solar panels have obtained the necessary energy from sunrise to sunset and have continuously provided required energy for the submersible pump and control unit.

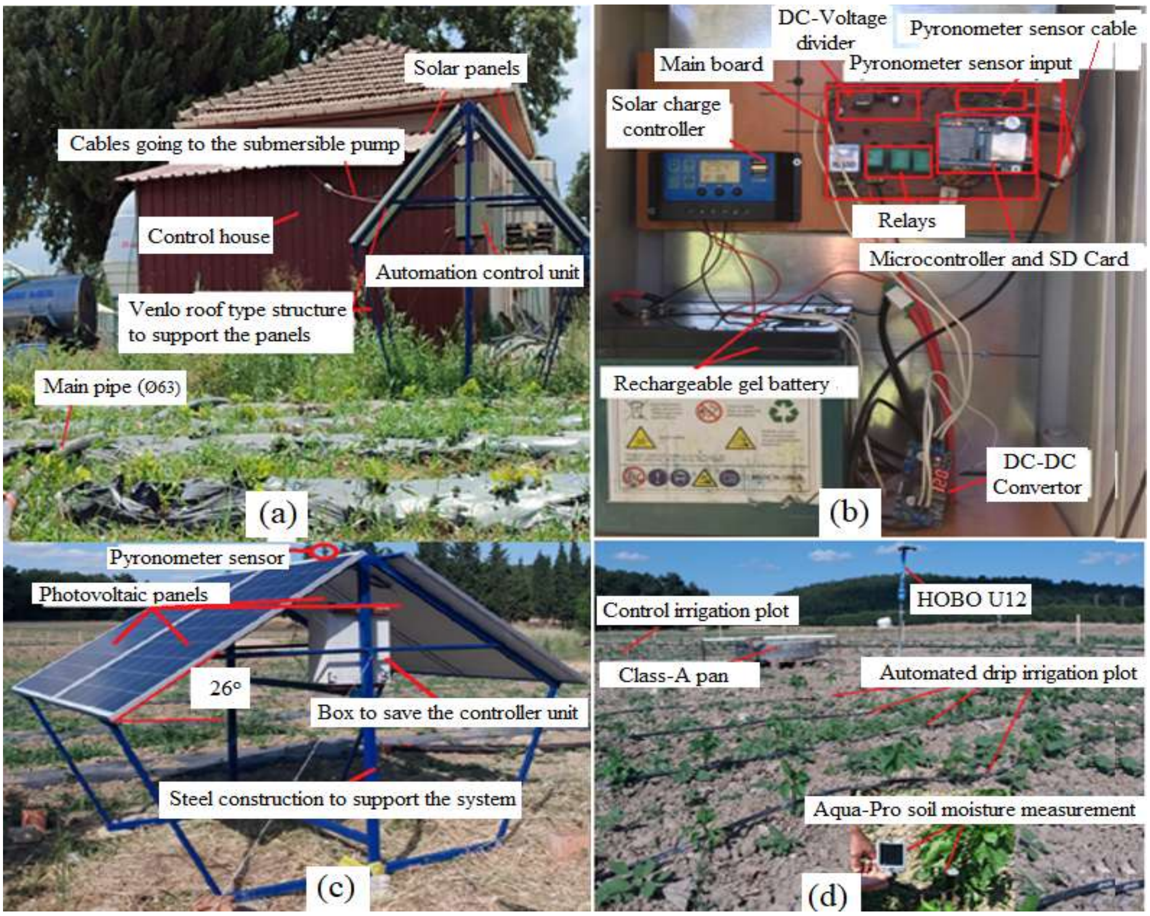

Figure 1- The layout of the solar powered automatic drip irrigation system (Dardanelles Campus)

In the study, two independent irrigation systems have been installed, one of which is a manually controlled drip irrigation system powered by the city grid and called as a control treatment, while the other solar-powered automatic drip irrigation system and called as an automatic irrigation system. Each system used a different submersible pump, the submersible pump used for the control treatment is an electrically powered pump employed for irrigating plants grown at the Dardanelles Campus and in terms of control, the pressure in the main pipe has been maintained around 1.5 atm using a by-pass valve located on the well. The average discharge of the three emitters has been determined on each line for each treatment.

In the control treatment, evaporation measurements taken every four days from the Class-A pan placed in the experimental area were used to determine plant water consumption values. Based on these values, the irrigation duration was calculated, and irrigation water was applied to the root zones of the plants using a drip irrigation system.

In the automatic system, the required energy was provided by solar panels. To ensure continuous, uninterrupted operation of the electronic circuit connected to the microprocessor and the algorithms stored in the microprocessor's memory, a rechargeable gel battery was used (Figure 1b). This battery was charged by the solar panels. The submersible pump used in the automation system is powered by solar panels. Daily radiation data were obtained from a pyranometer sensor, placed at the highest point of the support system in such a way that it would not be affected by the shade (Figure 1c). Throughout the irrigation season, the amount of water required by the plants, from the seedling stage to the harvest period, was applied to the root zone according to the treatments. A fertilizer tank was connected separately to each irrigation system, enabling fertigation with irrigation. The experimental setup is illustrated in Figure 2.

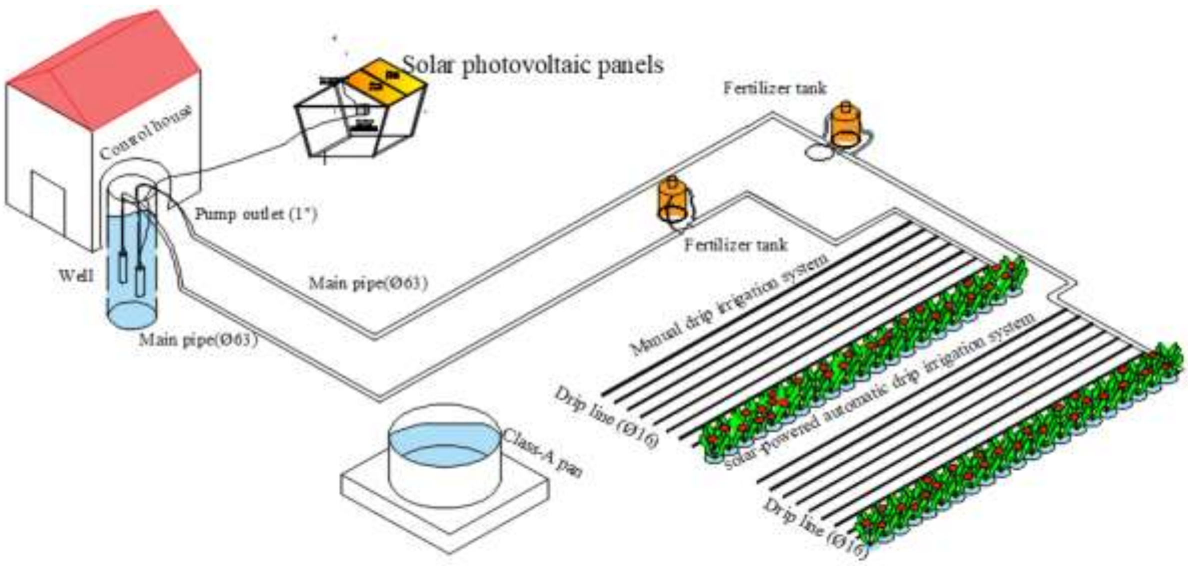

Figure 2- Layout of the experiment components

The system ensures accurate plant water consumption calculation by integrating solar radiation data from a pyranometer with monthly empirical equations (Yıldırım et al. 2016) in Table 1. These equations, tailored for each month, were programmed into a microcontroller which converted real-time solar radiation measurements into corresponding evaporation values. The microcontroller then computed the evapotranspiration and determined irrigation amounts accordingly.

Table 1- Reference plant water consumption values corresponding to solar radiation values (Yıldırım et al. 2016).

Months	*Equations*	R^2
May	$Ep=0.31R_s-1.984$	0.998
June	$Ep=0.305R_s$	0.984
July	$Ep=0.335R_s-1.279$	0.995
August	$Ep=0.222R_s$	0.971
September	$Ep=0.314R_s+0.018$	0.998

These equations were programmed into the microprocessor (ATmega328), allowing the system to operate automatically in a closed-loop manner. The energy required for the microprocessor was supplied from rechargeable gel batteries, while the submersible pump was obtained it from the solar panels. After the required software was loaded into the microcontroller's memory, the irrigation process was controlled by the microcontroller.

Yıldırım et al. (2018) stated that a 0.37 kW centrifugal pump, under Canakkale conditions, could perform irrigation using solar radiation, with a solar panel (220 W) consistently producing 150 W of power between 05:00 a.m. and 21:00 p.m. They indicated that irrigation could be conducted during these hours. With the information and software provided to the electronic board, irrigation was performed daily at 10:00 a.m. based on radiation values obtained from the previous day, throughout the entire irrigation season in the solar-powered automatic drip irrigation system. Additionally, necessary data was recorded on a microSD card placed on the main board.

Data transmitted by the pyranometer sensor to the main board was stored hourly and converted by the microcontroller into daily radiation values using the equation provided by Monteith (1977). Using the equation specified for the given month, the reference crop water consumption was determined, and the irrigation duration was calculated.

2.2. Irrigation program

The amount of irrigation water required is calculated and applied to the plant root zone by the system. The equations used in both systems are given below.

$$ET_c = K_c \ x \ K_p \ x \ E_p$$

Where; ETc, Actual plant water consumption, mm; Kc, Crop coefficient; Kp, Pan coefficient; Ep, Evaporation from Class-A pan, mm

In the experiment, the pan coefficient (Kp) was taken as 0.85 for the experimental area, Canakkale. The crop coefficients (Kc) were taken as 0.4 for the 1st stage of plant growth, 1.00 for the 3rd stage, and 0.85 for the 4th stage of plant growth (Güngör et al. 1996).

Soil moisture values were determined in real-time using an Aqua-Pro soil moisture meter with probes and a reader head at different depths. The values obtained were correlated with the soil moisture percentages derived gravimetrically from soil samples taken at the same depths. A soil moisture calibration curve with 92% accuracy was developed and utilized for this purpose during the trial period. Available soil moisture for each depth of 30 cm from 0 to 90 cm was determined by Aqua-Pro soil moisture instrument in the control treatment after and before irrigation and in the automated system after irrigation by using the equation (Güngör et al. 1996) given below.

$$d = \frac{(FC - ASW)}{100} x\gamma_s \ x \ D \ x \ P$$

Where; d, depth of water to be applied to the field (mm); FC, field capacity (%); ASW, available soil moisture; γs , soil bulk density (g cm^{-3}); D, required depth to be refilled up to field capacity (mm), P= percentage of wetted area (%).

The amount of irrigation water to be applied, in volume, is determined using the plant water consumption values and the irrigated area through the following equation:

$$V = ET_c \ x \ A$$

Where; V, Volume of irrigation water to be applied, L; A, Irrigation area, m^2

Using the flow rate of the pump, the duration required to supply the necessary irrigation water is calculated using the following equation:

$$T(min) = \frac{V(L)}{Q(L/min)}$$

Where; T, Irrigation duration, minutes; Q, Pump flow rate, L/min

2.3. Fruit quality parameters

For the measurement of plant parameters, all weights were measured using a scale with 0.01 g precision, and diameter measurements were taken with a digital calliper with 0.01 mm precision. Soluble solid content (SSC) was measured using a handheld refractometer (Tech-Jam International Inc., Tokyo, Japan) from the juice extracted from fruits in each group. To examine changes in titratable acidity (TA), 20 mL of juice from fruits in each group was taken and diluted to 100 mL with distilled water. From this diluted sample, 20 mL was taken, and 1-2 drops of phenolphthalein were added. Using a 50 mL digital burette, NaOH (sodium hydroxide) was used for neutralization, and the value obtained was substituted into the equation to calculate the percentage of titratable acidity.

For leaf area measurements, a CI-202 leaf area meter from CID, Inc. was used, and the leaf area was determined in cm^2. All leaves from the plant were separated from the stem, and the total leaf area of each plant was measured with the leaf area meter. The weights of the leaves and stems were measured separately using a precision scale. The total leaf area of a plant was divided by the area in which the plant was grown to determine the leaf area index (LAI).

The results obtained from plants grown under automatic and controlled irrigation treatments were analyzed using the SPSS statistical package. An independent two-sample t-test was applied to determine the differences between the two treatments.

2.4. Financial analysis

Financial analysis is essential to determine whether investing in a solar energy system is economically viable. This analysis involves considering factors such as the price of electricity sold, net metering tariffs, the inflation rate for energy prices, and general installation and operating costs (Biberci 2023). In the economic analysis of this study, the cost values of a 0.37 kW brushless, 24V DC-powered pump for the automatic system and a 0.37 kW asynchronous electric motor for the electric pump were used.

Basic Payback Period is the time it takes for an investment to recover its initial cost from the savings or revenues generated

$$Basic \ Payback \ Period(BBP) = \frac{Initial \ investment}{Annual \ savings}$$

Net present value (NPV) is a method used to evaluate the profitability of an investment by comparing the present value of future cash flows to the initial investment.

$$Net\ Present\ Value\ (NPV) = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

Where; C_t, Cash flow in month; t, months; r, Discount rate (assumed at 10% for this analysis); T, Growing period (assumed 5 months); C_0, Initial investment

3. Results and Discussion

3.1. Changes in temperature, humidity and radiation

Temperature, humidity, and radiation values measured at the site are presented in Table 2. During the trial period, temperature values fluctuated between an average of 22.7-28.4 °C, while humidity values varied between 57.4-69.9%. Solar radiation values, provided as ten-day averages between June 11 and September 20, reached its peak value of 29.4 MJ/m²/day during the period of July 10-20, while temperature was at the peak value of 28.4 °C. It then was very stable around 25 MJ/m²/day until the end of August. It showed a declining trend, decreasing to 14.7 MJ/m²/day till September 20th. During the third quarter of June, plant water consumption was 22.5 mm. From the first to the second quarter of July, there was an increase in solar radiation to 29.4 MJ/m²/day. As shown in Table 2, this increase was associated with a significant rise in evapotranspiration, which reached 182.3 mm. After July 21 to the end of August, the solar radiation level was almost steady state. During this period, temperature was 27.4 °C, humidity was 57.5%, and radiation was 25.3 MJ/m²/day. In August, with temperature at 27.2 °C, humidity at 62.9%, and radiation at 24.2 MJ/m²/day, therefore plant water consumption increased to 222.5 mm. In the first quarter of September, a decrease in temperature and radiation led to a reduction in plant water consumption up to 77.9 mm.

Table 2- Averages of temperature, humidity, and radiation values measured at the site in 2023

Decades	*T (°C)*	*RH (%)*	*Rs (MJ/m²/gün)*
1-10 June	24.2	64.2	
11-20 June	22.7	69.9	24.8
21-30 June	24.9	63	23.2
1-10 July	26.4	61.4	25.3
11-20 July	28.4	57.4	29.4
21-31 July	27.4	57.5	25.3
1-10 August	26.6	61.7	23.5
11-20 August	27.8	64.5	24.3
21-31 August	27.1	62.4	24.7
1-10 September	25.1	65.2	19.2
11-20 September	22.7	60.8	14.7
21-30 September	24	61.5	

3.2 Evaporation, evapotranspiration and irrigation amounts

The evaporation amount from the Class-A pan during the trial period was 746.2 mm (Table 3), and the calculated crop evapotranspiration value was 505.1 mm for the period. During the season, the amount of irrigation water applied under the control irrigation was 492.7 mm which was very close to the actual crop evapotranspiration, while the automated irrigation system applied 602.4 mm. The data indicate that the automated irrigation system resulted in 21.7% over-irrigation compared to crop evapotranspiration. Hence, the automation system has performed excessive irrigation, particularly in months of June and September. This indicates that the evaporation equations (Table 1) used for these months overestimated the actual plant water consumption.

Table 3- Evaporation, crop evapotranspiration, and irrigation amounts applied by automation and control irrigation methods (mm)

Year of 2023	*Evaporation over a specified period (mm)*	*ETc (mm)*	*Control Irrigation (mm)*	*Automatic Irrigation (mm)*
22-30 June	66	22.5	11.9	59.2
July	312.6	182.3	193.5	198.6
August	265.4	222.5	215.1	227.9
1-17 September	102.2	77.9	72.2	116.7
Total	746.2	505.1	492.7	602.4

The daily evaporation, plant water consumption, and the amounts of irrigation water applied by both methods are illustrated in Figure 3. The daily evaporation rate started at approximately 7 mm on June 22 and peaked at around 13 mm on July 9. Until July 21, evaporation remained at a similar level, fluctuating between 10-12 mm from July 11 to August 8, despite some variations. After August 12, evaporation decreased linearly, reaching 6 mm by September 13. Plant water consumption values began at 2 mm on June 22, fluctuated between 2-4 mm until July 6, and then increased linearly to reach 8.97 mm by July 31. After this peak, there was a linear decrease in water consumption, falling to 6.38 mm by August 29, and remained around 4 mm until September 13. Comparing the irrigation water applied by both systems with the crop evapotranspiration curve on the figure provides insight into the performance of irrigation applications during these periods. Accordingly, in the control irrigation based on the Class-A pan, the required amount of water of the plants were consistently met, while the automatic irrigation system applied more water than the crop evapotranspiration for the whole growing period. When evaluating the performance of automatic irrigation based on the amounts of water applied during different periods, the following results can be drawn.

June 22 - July 11: The system applied 132.9 mm of irrigation water, while plant water consumption was 57.7 mm, indicating an over-irrigation scenario.

July 11 - July 22: The system applied 70.8 mm of irrigation water, and plant water consumption was 86.9 mm, showing very close value to crop evapotranspiration.

July 22 - July 27: The system applied 38.6 mm of irrigation water, with plant water consumption at 37.9 mm, indicating an accurate irrigation application.

July 27 - August 29: The system applied 257.9 mm of irrigation water, and plant water consumption was 253.9 mm, demonstrating successful irrigation.

August 29 - September 13: The system applied 111.6 mm of irrigation water, with plant water consumption at 80.6 mm, indicating over-irrigation during this period.

During July and August in which the peak values of crop evapotranspiration were, it successfully carried out irrigation performance by applying water equal to the crop evapotranspiration, but in June and September, the amount of irrigation water applied was more than the crop evapotranspiration.

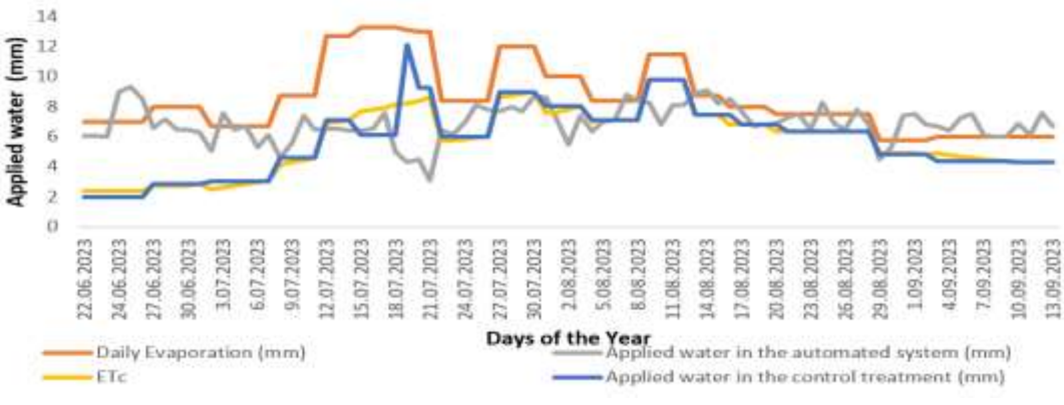

Figure 3- Daily evaporation, plant water consumption, irrigation water applied by automation, and irrigation water applied by control during the irrigation season (mm)

3.3. Soil moisture variations

Soil moisture values were measured periodically at specified intervals for both control and automation methods by using Aqua-Pro. For the control method, they were taken before and after irrigation for four-day intervals, while only one time after irrigation for the automation method. The measurement results are presented in Table 4. The field capacity of the soil in the experimental area was found to be 34.4%. From the data, it is observed that for the control irrigation method, the soil moisture level closely approached the field capacity from August 9th to August 21th according to the Class-A. After this period, until September 21th, the soil moisture level was maintained close to the field capacity. However, with the completion of irrigation before harvest on September 25th, the soil moisture level decreased to 25.2%. In contrast, during the periods when measurements were taken for the automation system, the soil moisture remained consistently at field capacity level due to the system's irrigation practices. This indicates that the system was able to perform irrigation successfully based on plant water consumption.

Table 4- Soil moisture changes for control and automation methods

Date	*Control irrigation, gravimetric water, P_w(%)*		*Automation irrigation gravimetric water, P_w(%)*
	Before irrigation	*After irrigation*	*After irrigation*
9 August	30.5	32.5	35.1
13 August	29.8	32.4	35.0
17 August	30.3	33.2	35.7
21 August	30.9	31.8	35.1
25 August	30.3	35.0	35.1
29 August	30.7	35.3	35.3
3 September	29.8	35.1	23.0
8 September	Rainfall	34.4	34.8
10 September	29.1	34.7	35.0
14 September	29.0	33.6	34.0
18 September	28.5	33.5	34.1
21 September	27.9	34.2	34.6
25 September	System closed	25.2	24.8

3.4. Effects of irrigation practices on fruit quality parameters

Fruit yield and vegetative growth parameters were given in Table 5. The yield value was 6.72 t da^{-1} in the control treatment, while it was 6.8 t da^{-1}. The results were analyzed using an independent two-sample t-test (t = 0.97, sd = 4, P = 0.913, ns) and there was no significant difference between them, therefore, the differences between the groups was due to coincidence. The findings suggest that plant development was not significantly affected by periods of under- or over-irrigation in the automated system, demonstrating successful irrigation management by the automation system.

For both applications in terms of vegetative growth and fruit quality parameters, the tests showed that differences in the following parameters were not statistically significant; leaf area (t = 0.541, sd = 4, P = 0.391, ns), fruit width (t = 0.81, sd = 28, P = 0.852, ns), fruit length (t = 0.547, sd = 4, P = 0.411, ns), fruit diameter (t = 0.536, sd = 28, P = 0.673, ns), leaf fresh weight (t = 0.553, sd = 4, P = 0.266, ns), stem fresh weight (t = 0.618, sd = 4, P = 0.946, ns), root fresh weight (t = 0.817, sd = 4, P = 0.412, ns). These results suggest that the differences observed between the control and automated irrigation methods for these parameters are not statistically significant and are likely due to coincidence.

There are many research results carried out on Kapia water respond to water. Some of them are as follows; Demirel et al. (2012), investigated the effects of four different irrigation levels on the yield of Kapia pepper by using drip irrigation in Çanakkale. They applied irrigation water amounts ranging from 30 to 567 mm over a season. The yield values varied from 4.47 to 63.64 t ha^{-1} based on the irrigation treatments. Sezen et al. (2016), examined the effect of different irrigation water applications on the yield of pepper under drip irrigation and they obtained a yield of 46 t ha^{-1} by applying 743 mm of irrigation water in the full irrigation, by saving 25% of irrigation water they obtained a yield of 44 t ha^{-1} by applying 578 mm of irrigation water, by saving 50% of irrigation water they obtained a yield of 35 t ha^{-1} by applying 390 mm of irrigation water. Köksal et al. (2017), evaluated the effects of different irrigation water levels on yield, and fruit quality of red pepper (*Capsicum annuum* L. cv. Kapija). They conducted different irrigation applications to meet 100%, 70%, and 40% of the plant's water needs. Over two years, they obtained plant water consumption values ranging from 294 to 472 mm in the first year and 163 to 508 mm in the second year. The highest yield was achieved with full water requirements and the yield was 42.43 t ha^{-1}. As seen from the literature results, plants grown in a warm climate zone have higher evapotranspiration, while there is a slight decrease in yield. Therefore, our results are very close to the findings of Demirel et al. (2012), conducted the research at the same climatic zone. The plant development and fruit quality parameters showed similar results for both the control and automation methods. These findings indicate that the automated irrigation system can be effectively used in agricultural production, demonstrating its potential for successful application in plant cultivation. Hence, the automated irrigation method has the potential to provide significant economic benefits to the producer.

Despite of over-irrigation periods, the automation system generally maintained soil moisture at field capacity. As a result, there was no significant difference in yield or vegetative plant development compared with the control irrigation treatment. These results indicate that the automated irrigation system effectively executed the commands programmed into the microprocessor's memory. However, the microprocessor's performance could be improved to better handle irrigation adjustments and minimize discrepancies in future applications.

The results showed that Control and automation irrigation treatments have yielded parallel trends in terms of plant yield and vegetative growth of Kapia pepper.

Table 5- Fruit yield and plant development parameters

Treatments	*Dates*	*Fruit (mm)*		*Leaf (g)*		*Stem(g)*		*Root(g)*		*Leaf area (cm^2)*	*Yield ($t\ da^{-1}$)*
		Width	*Length*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*		
Control irrigation	04.8.23	128.1	45.1	122	15.4	78	10.5	23	3.1	6832	
	17.8.23	172.3	69.9	-	-	-	-	-	-	-	2.46
	01.8.23	115.6	38.1	183	40.4	128	18.4	39	13.2	9986	1.32
	25.8.23	108.7	35.5	62	19	148		40	13.6	3365	2.94/6.72^{ns}
Automatic irrigation	04.8.23	124.3	38.3	115	10.7	73	9.54	21	6.28	6410	
	17.8.23	166.5	63.4	-	-	-	-	-	-	-	2.40
	01.8.23	109.7	55.1	103	23.4	93	22.1	44	149	5986	1.40
	25.8.23	114.9	33	78	25	141	36.5	44	15.1	3567	3.00/6.80^{ns}

ns: not significant

3.5. Financial analysis

We utilized the Basic Payback Period (BBP) and Net Present Value (NPV) methods to provide a cost-benefit analysis comparing manual and automated irrigation systems. The economic analysis of manually operated conventional systems and automatic irrigation systems for Kapia pepper cultivation in the experimental field was calculated, assuming production on an area of 1000 m² for each system. The economic analysis study was conducted by comparing the initial investment cost, energy, and labor expenses over a single production season. The basic payback period and net present value were obtained and given in Table 6. For this purpose, data from the year 2023 was used. The agricultural irrigation fee per 1 kWh is 2.4 TL. Assumed automated irrigation system saves 25% in operational costs annually due to reduced labor and electricity.

Table 6- Economic comparison of the conventional system and the automatic irrigation system

Comparison of financial indicators	*Units*	*Manual*	*Automated*
Cultivation labor	(TL)	8160	6120
Irrigation+Harvest labor	(TL)	27200	20400
Monthly energy cost (30 days)	(TL)	2220	0
Pump efficiency	%	85%	90%
Price of pump	(TL)	2000	5500
Price of solar panels (4 PV panels)	(TL)	0	9000
Driver	(TL)	8140	0
Discount rate	%	10%	10%
Unit price of kapia	(TL)	7	7
BPP (year)	Year	2	1
NPV	(TL)	-2340	4360

TL=Turkish Lira (1$ =24 TL in 2023).

The Basic Payback Period (BBP) for the manual irrigation system is 2 years, while it is only 1 year for the solar-powered automated drip irrigation system. In terms of Net Present Value (NPV) for a single growing season, the manual system shows a financial loss of -2340 TL, whereas the automated system generates a profit of 4360 TL. The manual system has the advantage of a lower initial investment cost and is suitable for small-scale farming. However, it comes with significant disadvantages, such as a longer payback period, negative NPV, high labor costs, and higher energy consumption. On the other hand, the solar-powered automated drip irrigation system offers a shorter payback period, positive NPV, lower labor costs, and improved energy efficiency. Despite these benefits, the primary disadvantage is the higher initial investment cost.

4. Conclusions

The prototype of the solar-powered automatic drip irrigation system has been tested to determine the performance of both the control unit, the pyranometer sensor, and the software. In the experiment, once the general strategy was defined into the memory of the microcontroller (MC), it performed the necessary calculations and activated decision mechanisms to optimally implement about when and how much water to apply depending on the feedback of the pyranometer sensor. The irrigation decision was made, and actions were carried out throughout the entire experiment. The solar-powered automatic drip irrigation system successfully maintained soil moisture and performed well in irrigation, with similar crop yields in both automated and manual treatments. Over-irrigation in June and September was due to fluctuations in evaporation equations, highlighting the need for improved calibration. Updating the monthly equations based on field-measured data will significantly enhance the system's accuracy and overall success. Furthermore, integrating real-time feedback from soil moisture sensors will allow for dynamic validation and adjustment of irrigation amounts, further improving system performance. The system demonstrated economic advantages with reduced labour and energy costs, offering a shorter payback period and positive returns. It also supports sustainable agriculture by reducing greenhouse gas emissions and optimizing water and fertilizer use. Yield and vegetative development parameters of kapia pepper were very similar in both control and automation irrigation treatments, which were also very familiar with the findings of literatures. The system has demonstrated successful performance in terms of hardware, and the slight excess in irrigation water applied by the system in June and September was due to the equations used for these months. Hence, the estimated amount of evaporation from Class-A pan, provided by Yıldırım et al. (2016), showed some fluctuations for June and September, leading to a certain amount of over-irrigation. Therefore, long-term datasets of solar radiation, temperature, humidity, wind speed, and actual evapotranspiration from Class-A pans are essential. These will enable the creation of robust predictive models and improve calibration of monthly equations. This indicates that the accuracy of calibration curves significantly impacts the system's performance. Therefore, the equations predicting evaporation from Class-A pan must be based on long-term measurements to ensure their effectiveness in predicting actual values. The need for long-term calibration of evaporation prediction equations demonstrates the importance of this approach for optimizing automation systems.

The use of these systems is becoming increasingly widespread in the agricultural sector, as in all other sectors. Due to climate change, water is becoming a scarce resource, and the incorrect use of fertilizers can lead to negative impacts such as contamination of groundwater and aquifers. To minimize these adverse effects, the use of modern irrigation systems in agriculture has become essential. The addition of automation to modern irrigation systems will enable more efficient use of these natural resources too. Hence, automated solar-powered irrigation systems can be further optimized to enhance sustainability and efficiency in agricultural production. Integration with IoT technologies, the use of machine learning for predictive irrigation scheduling, and the incorporation of real-time soil and crop sensors can significantly improve system performance. Moreover, the analysis shows that the manual system leads to financial losses due to high labor and energy expenses. On the other hand, the solar-powered automated system is more economically advantageous, with a shorter payback period and positive returns on investment. Therefore, transitioning to automated irrigation is a more profitable and sustainable option for long-term agricultural production.

Irrigation systems powered by renewable energy can significantly reduce greenhouse gas emissions. Their automatic closed-loop operation increases the efficiency of both irrigation and fertilization processes, promoting the widespread adoption of these systems as environmentally friendly solutions in agriculture. As such, closed-loop automation systems can be considered an effective strategy for sustainable water management in agriculture.

For future work, stronger long-term correlations will be established between solar radiation, temperature, humidity, wind speed, and measurements from a Class A evaporation pan to estimate monthly plant water consumption more accurately. Integrating these data-driven correlations into the microprocessor will further enhance the water application performance of the automatic irrigation system.

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