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Research Article

Determining the Irrigation Performance of Solar Panels Operating with a Sun Tracking System

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Abstract

In the study, utilizing the relationship established between plant water consumption and solar radiation, an irrigation system was attempted to be automated through a Programmable Logic Control (PLC) controlled program for tomato plants grown in an open field. The system has obtained its required energy through solar panels, utilizing solar energy as its power source. The performance of the system has been attempted to be evaluated through the yield and quality parameters of the cultivated plants by yield, mean fruit weight and width, titratable acidity, total solids, pH, leaves (fresh+dry) weights, stem (fresh+dry) weights, leaf area, plant height. The PV panels used in the system were equipped with a solar tracking system to pump more water at a lower cost. This has led to an increase in the efficiency of the panels.

The solar radiation values obtained with a pyranometer sensor during irrigation were processed through the software written in the PLC's memory. The amount of water consumed by the plant the next day was calculated, and it was attempted to be automatically supplied to the plant's root zone at 10:00 am. The system has been made continuous by being controlled with automation and SCADA. The development of the plants, temperature, humidity, and radiation levels were measured, and the system's irrigation performance was determined according to the moisture level change in the soil.
Keywords: Irrigation, Irrigation Automation, Solar Radiation, Programmable Logic Controller

Güneş Takip Sistemli Solar Panellerinin Sulamadaki Performansının Belirlenmesi

Öz

Bitki su tüketimi ile solar radyasyon arasında kurulan ilişkiden yararlanarak, yazılan program dahilinde Programlanabilir Logic Kontrol (PLC) aracılığıyla açık alanda yetirilen domates bitkisinde sulama otomatik olarak yaptırılmaya çalışılmıştır. Sistem, kullandığı enerjiyi solar paneller aracılığıyla sağlayarak gerekli enerji güneşten sağlanmıştır. Sistemin performansı yetiştirilen bitkilerin verim ve kalite parametreleri; verim, ortalama meyve ağırlığı ve genişliği, titre edilebilir asit, kuru madde, pH, gövde ve yaprak yaş ve kuru ağırlıkları, yaprak alanı elde edilmiştir. Buradaki PV paneller güneş takip sistemi ile donatılarak düşük maliyet ile daha fazla su pompalanmış ve bu şekilde panellerin veriminin artması sağlanmıştır.

Sulamada pyronometre sensörü ile elde edilen solar radyasyon değerleri PLC'nin hafızasında yazılan yazılım sayesinde işlenerek bir ertesi gün bitkinin tükettiği su miktarı hesaplanıp, saat 10.00'da otomatik olarak bitki kök bölgesine verilmiştir. Oluşturulan sistem otomasyon ve Scada ile kontrol edilerek süreklilik kazandırılmıştır. Bitkilerin gelişimi, sıcaklık, nem değerleri, radyasyon miktarı ölçülmüş ve bu değerlerle sistemin sulama uygulama performansı topraktaki nem değişimine göre belirlenmiştir.
Anahtar Kelimeler: Sulama, Sulama Otomasyonu, Solar Radyasyon, Programlanabilir mikroişlemci

Introduction

In one-way, agricultural practices and machinery continue to advance on the other hand the energy demand in agriculture is also increasing. This includes energy used for irrigation, crop drying and processing, as well as powering farm machinery and equipment. The use of renewable energy sources such as solar, wind, and biomass can help to reduce the reliance on fossil fuels in agriculture and promote more sustainable practices. Due to the increase in energy costs in today's world, the use of alternative energy sources is being considered in agriculture, as in many other sectors so that some studies are being conducted on the use of alternative energy and solar energy is the most widely used alternative energy source in agriculture in recent times. The average efficiency of solar panels that convert solar energy into electricity is around 20%, and to achieve higher efficiency, it is important to ensure that the sunlight is perpendicular to the panel. Our world, which is increasingly polluted by fossil fuels in energy production, has entered an irreversible state of pollution. However, with the development of technologies, the efficiency values of the energy produced have also increased, in addition to the diversity of alternative energy sources. The production and installation of PV panels for solar energy are rapidly increasing, and the energy production values of the panels also vary. However, it is possible to increase the efficiency of the panels with different methods and techniques. One of these methods is to ensure that the sunlight is perpendicular to the panels from sunrise to sunset throughout the day. Many scientific studies are being conducted to increase irrigation efficiency in automatic irrigation systems.

Shull and Dylla (1980) used gypsum blocks as sensors in sprinkler irrigation systems and enabled the system to operate automatically based on the information obtained from the sensors. Frankovitch and Sarich (1991) attempted to control the operating time of the pump in an irrigation system by using an electronic switch. It is possible to see that highly complex technologies have been developed in recent times for delivering irrigation water to the plant root zone, but the number of producers using these technologies is extremely limited. Therefore, many researchers are trying to develop simple automatic irrigation systems that can be used by many producers. Caceres et al. (2007) developed a "control tray" that controls the irrigation system in greenhouses. This system consists of a sensor that detects the water level and a relay that activates the pump, making it a very simple system. Yıldırım and Demirel (2011) provided irrigation automation by using a sensor that detects the moisture level in the soil and a processor that controls the activation of the relays. Yıldırım et al. (2016) suggested that there is a strong relationship between solar radiation and evaporation, and this relationship can be utilized to automate irrigation systems.

In this study, a prototype of automatic irrigation system was developed using the relationship between plant water consumption and solar radiation to automatically activate the irrigation system. Therefore, this event can prevent the wastage of energy and water.

Material and Methods

This study was established in May 2022 in the Dardanellas Research Center of Çanakkale Onsekiz Mart University Faculty of Agriculture. The area is located at 40.08 N latitude, 28.20 E longitude, and 3 m above sea level.

Irrigation system and Plant Growth Medium

The irrigation system established in the experiment is given in Figure 1. PLC has been used in the control mechanism. The irrigation system has a submersible pump flow rate of 2 m3 h-1 and a manometric height of 64m. The outlet of the pump is connected to the main pipe with a socket that is joined to a plastic hose with a diameter of 1” and a main pipe with a diameter of Ø 63, and the water is conveyed from the main pipe to Ø16 PE lateral pipes and then given to the plant root zone with drippers that have a discharge of 4 L h-1.

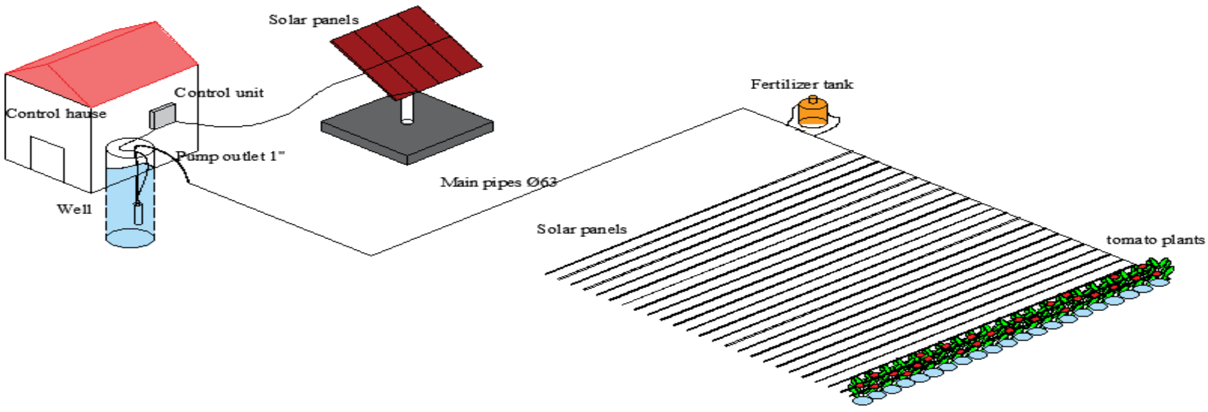

Figure 1. Field application of the drip irrigation system powered by solar panels.

In this study, irrigation applications were carried out through PLC by obtaining cumulative evaporation (mm) values corresponding to cumulative solar radiation (W m-2) values, determined based on equations given by Yildirim et al. (2016) established between solar radiation and plant water consumption on a monthly basis.

The PLC, submersible pump, and pyranometer sensor used in the experiment were placed at the site, and the solar panels carrying system was installed on the experimental site at Dardanellas, as shown in Figure 2.

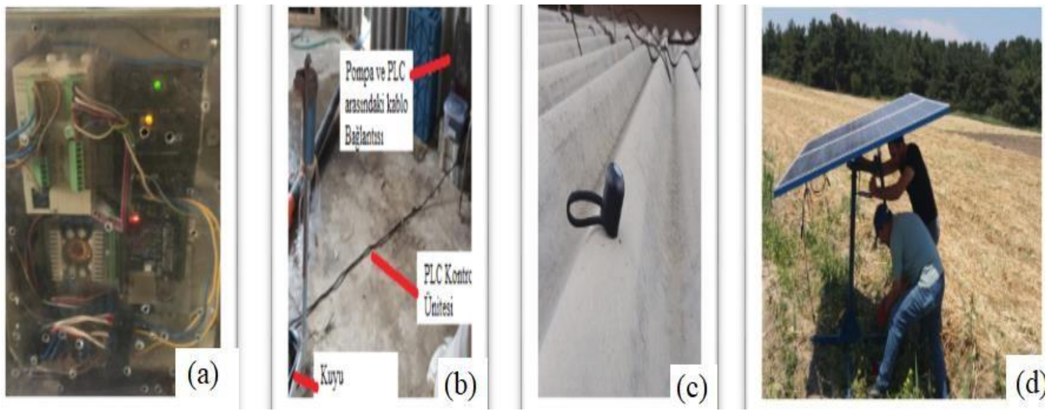

Figure 2. Irrigation automation: a) PLC, b) Connection between PLC and submersible pump, c) Pyranometer sensor, d) Solar panels.

After the necessary software and hardware connections were made for the PLC control unit that enables the automatic control of the irrigation system, the submersible pump was placed inside the control house to avoid being affected by possible precipitation or adverse conditions and also the pyranometer sensor was placed on the roof of the control house and connected to the analog input of the PLC via cable. The solar panels that will supply energy to the system were placed in a shaded-free area close to the control house, which is near the PLC control unit.

The physical and chemical properties of the soil in the area where plant production is carried out were obtained from a previous study conducted at the same location. The soil contains 1% organic matter, has a pH of 7.92, an electrical conductivity (EC) of 0.415 dS m-1, a field capacity of 34.4%, and a wilting point of 19.1% Yıldırım and Bahar (2017). Soil preparation and pipe placement at the experimental site were carried out between May 10th and May 15th, 2022. Three different plots were created at the experimental site, each with dimensions of 2.8x10 m and a distance of 2 m between each plot. Samples were taken from the middle rows of each plot. For the experiment, table tomatoes (*Lycopersicumesculentum* L.) were grown with a planting distance of 70x33 cm between each plant (Figure 3).

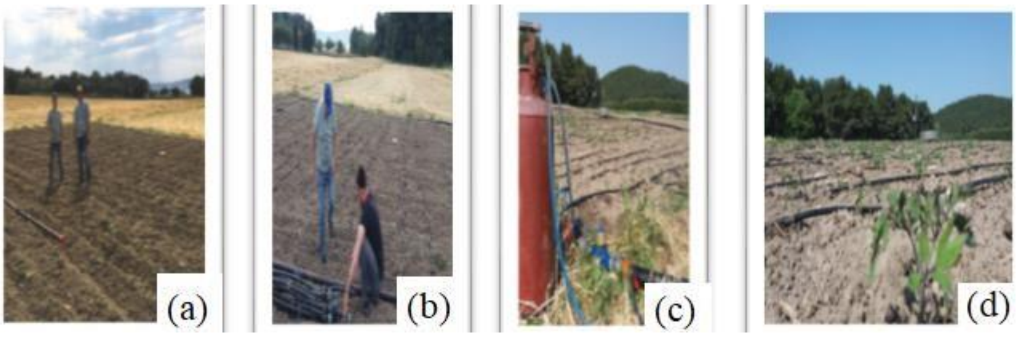

Figure3. Irrigation layout a) land preparation b) main pipes construction c) Fertigation tank and lateral pipes d) tomato seedlings and irrigation

Tomato seedlings were transplanted into the experimental area after land preparation was completed on May 18, 2022. The initial irrigation was provided by the pump located in the field.

The changes in the angle of incidence of sunlight on Earth throughout the year are due to the Earth's orbit around the Sun. These changes in angle cause the seasons to change at different times of the year. During the summer season in the Northern Hemisphere, the Northern Hemisphere receives more direct sunlight because the Earth's axis is tilted towards the Sun. This results in longer days and shorter nights in the Northern Hemisphere. Conversely, during the winter season in the Northern Hemisphere, the Northern Hemisphere receives less direct sunlight because the Earth's axis is tilted away from the Sun. This results in shorter days and longer nights in the Northern Hemisphere. Therefore, A sundial is a device that uses the position of the sun to reflect the time. Solar clocks have been developed and used in history by utilizing the solar angles based on the position of the sun at different time intervals. The sun clock established by the Faculty of Agriculture of Çanakkale Onsekiz Mart University can be seen in the Figure 4a.

The sun tracking systems in irrigation systems powered by solar panels provides an important advantage. Therefore, in this study, solar panels were moved according to the sunlight at different times.

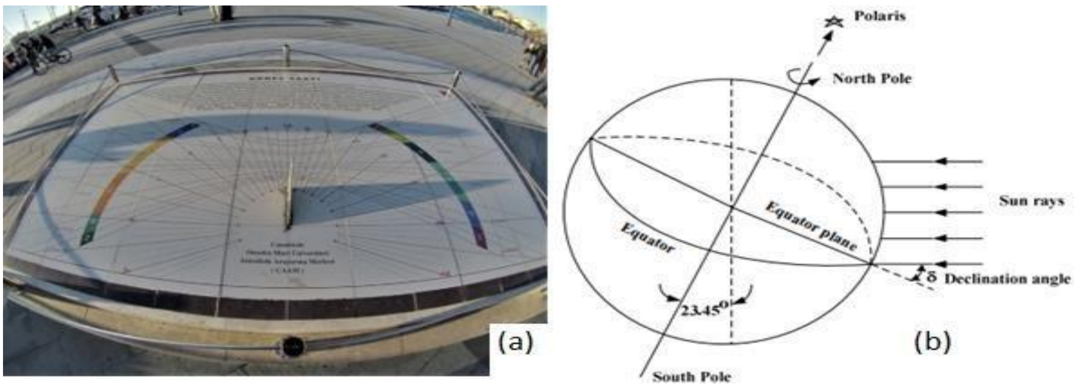

Figure4. The sundial application (a) (Çanakkale) and variation of solar declination angle(b) (Declination angle). (b was taken from Karanfil et al., 2015)

Latitude(ø), Declination(δ) and Hour Angles(ω)

The shape of the Earth being an ellipsoid and the sun's rays not always hitting the equator at right angles while revolving around the sun. The sun only comes at a right angle twice a year during the year, varying between -90º ≤Ø≤ 90º and passing through the equator. This is shown in the Figure 4b. Turkey is located at 36º-42º north latitude and at 26º-45º east longitude (Bakirci, 2012). Declination angle (δ) is the angle between the sun lights and equator plane. Looking at the solar declination angle values with respect to the center of the Earth in Figure 4b, when the northern hemisphere is considered positive and the southern hemisphere is considered negative, it can be observed that the angle values fall between -23.45º and 23.45º (Duffie and Beckman, 2013). The equation (1) shows the calculation of the declination angle on any given day of the year, where the value of n is the number of days from January 1st (Kentli. and Yılmaz, 2012).

$$\delta = 23{,}45\ \sin\left(\frac{360.(284+n)}{365}\right)^{\circ} \qquad (1)$$

Hour angle (ω) is the angle between the longitude of sun lights and the longitude of the location. The angle before noon is minus (-) and after noon is plus (+) and is zero (0) at noon. However, this is not the case for local time. For example, if we take the summer months in Çanakkale region, the time when the sun is directly overhead is around 1:00 pm. This situation is related to the local time we use. Equation (2) is given below. Assuming one full rotation is equal to 360 degrees, the angle of incoming sunlight moves through a 15-degree increment in one hour (Okundamiya M. S. , et al 2011).

$$\omega = 15.(GS - 12) \qquad (2)$$

Sunset angle (GB°), When looking at the sundial, noon time when the sun is exactly overhead is considered as zero, and the angle value that the sun has scanned until sunset is called the setting angle, and its symmetry represents the rising angle. This angle is given in equation (3). The working principle of solar tracking panels is given in Figure 5.

$$GB^{o} = cos^{-1}(-tan(\delta)tan(\varphi)) \qquad (3)$$

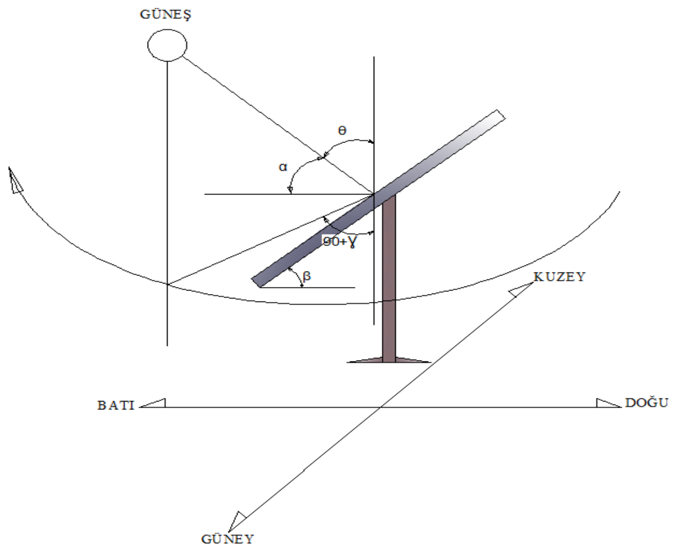

Figure 5. The control of the tracking angles of solar panels with tracking systems.

Zenith (θ) and Azimuth (γ) Angles

Zenith angle (θ) is the angle between the line to the sun and the vertical axis. In the calculation of the angle values shown in Figure 5, equations (4), (5), (6), and (7) are used (Ourraoui I, et al.2022).

$$\cos\theta = \sin\varphi \sin\delta + \cos\delta \cos\omega \qquad (4)$$

$$\alpha = \sin^{-1}[\cos\delta \cos\varphi \cos\omega + \sin\delta \sin\varphi \qquad (5)$$

θ = Zenitangle,
δ = Declination angle ,

φ = Latitude angle,
ω = Hour angle
θ = 90-α,
α: Sun elevation angle

$$\theta = \cos^{-1}[\mathrm{Cos}(\delta)\,\mathrm{Cos}(\varphi-\beta)\,\mathrm{Cos}(\omega) + \mathrm{Sin}(\delta)\,\mathrm{Sin}\,(\varphi-\beta)] \quad (6)$$

β = The angle of inclination that is considered with respect to the horizontal plane.,
δ = Declination angle ,
γ = Azimuth angle,
ω = Hour angle
φ = Latitude angle,

Azimuth angle (γ) is the angle between the north or south position of the sun and the direct solar radiation and this angle is assumed to be negative (-) from south to east and to be positive (+) from south to west. (γ)) is 180º at noon. Azimuth angle is calculated by the following equation (7) given below (Ourraoui I, et al.2022).

$$\gamma = \sin^{-1}[\frac{\mathrm{Cos}\,(\delta)\mathrm{Sin}\,(\omega)}{\mathrm{Cos}\,(\alpha)}] \quad (7)$$

Software

The purpose of installing a sun tracking system is to increase the energy efficiency of solar panels, which typically varies in the range of 20-25%. By ensuring that the sunlight falls perpendicularly on the panels throughout the day, the system can provide an additional efficiency increase of up to 30% on top of the current efficiency.

PLC (Programmable Logic Controller) has been used as the microcontroller. PLCs are preferred in industrial automation due to their low probability of failure and their resistance to electromagnetic noise. In the project, a PLC model (Delta 14SS2) was chosen, and an analog module (dvp-06xa) with a 12-bit resolution was also used. The program used for the Delta PLC program is "ISP Soft." A part of the program is shown in Figure 6a-b.

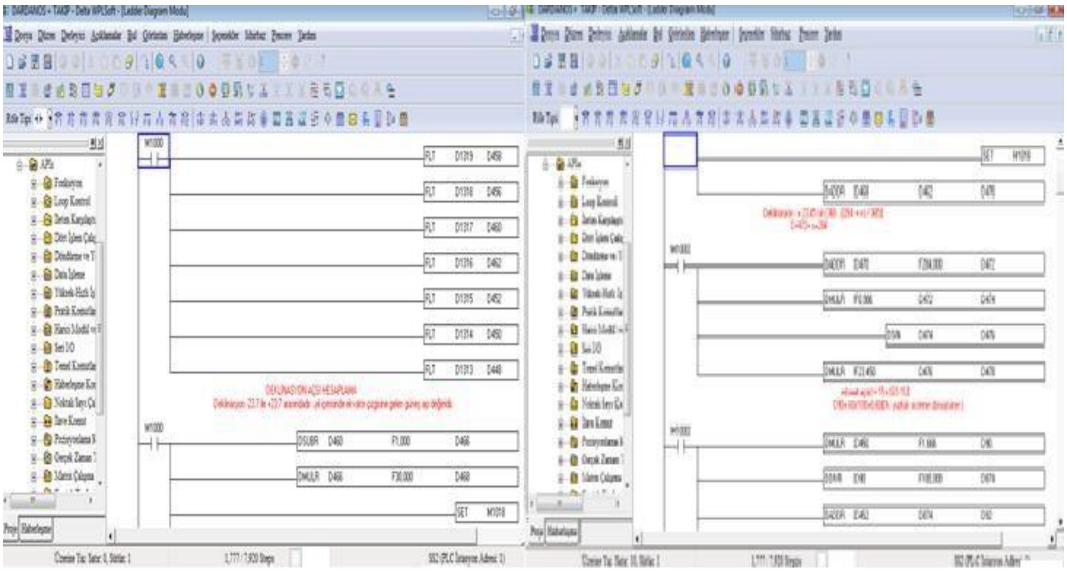

Figure 6. A part of the declination (a) and hour angle (b) calculation program made with Delta PLC "WPL Soft" program.

The microcontroller (PLC) program was used to calculate the angle of incidence of sunlight on the solar panels based on the latitude and longitude of the location where the panels are located, as well as the date, time, and minute. This ensured that the solar panels were oriented perpendicular to the incoming sunlight using the calculated angle values. In Figure 7b uses local time as the time zone used in the calculation of the angle at which the incoming sunlight reaches the location of the panels. In the calculation of local time, equation (2) was used to convert the real-time clock value to local time using PLC. In Figure 7, in addition to calculating the angle of incidence of the sunlight, an automatic irrigation system has been designed for the agricultural land in the Dardanellas area by considering radiation values and plant water consumption amounts. According to this design, a PLC program has been written and the flow diagram of the program is given in Figure 8.

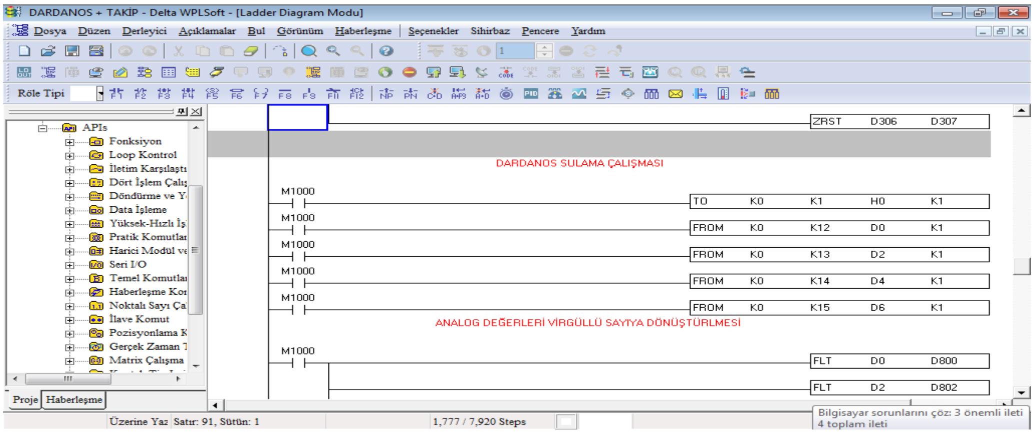

Figure 7. A part of the Dardanellas irrigation automation program made with Delta PLC "WPL Soft" program.

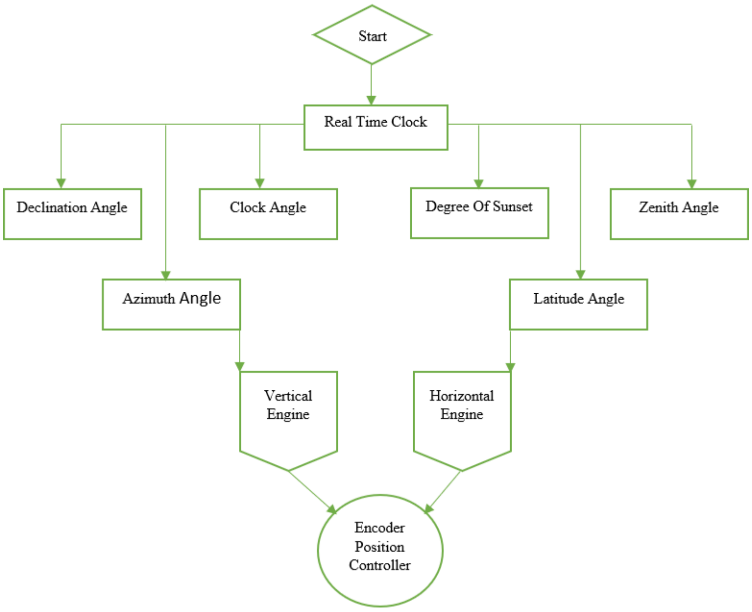

Figure 8. Flow diagram using Delta PLC "WPL soft".

The PLC program in the flow diagram shown in Figure 8 was designed using the given formulas to calculate the solar incidence angles based on real-time and date values. After the calculations, the vertical and horizontal motors were moved to position the PV panels at the angle they should be according to the calculation.

Results and Discussions

In the study, the irrigation program was calculated daily based on the solar radiation values determined by Yıldırım et al. (2015), and the calculated amount of irrigation water was applied to the system the next day at 10.00 am by triggering the pump. Furthermore, the evapotranspiration values, which consisted of class A pan, were measured and recorded together with the parameters of temperature, humidity, and pyranometer sensors of the HOBO U12 device at the site. The temperature, humidity, solar radiation, and photosynthetically active radiation (PAR) measurements obtained from the field are given in Figure 9. PAR values were calculated according to Kara and Yıldırım (2015).

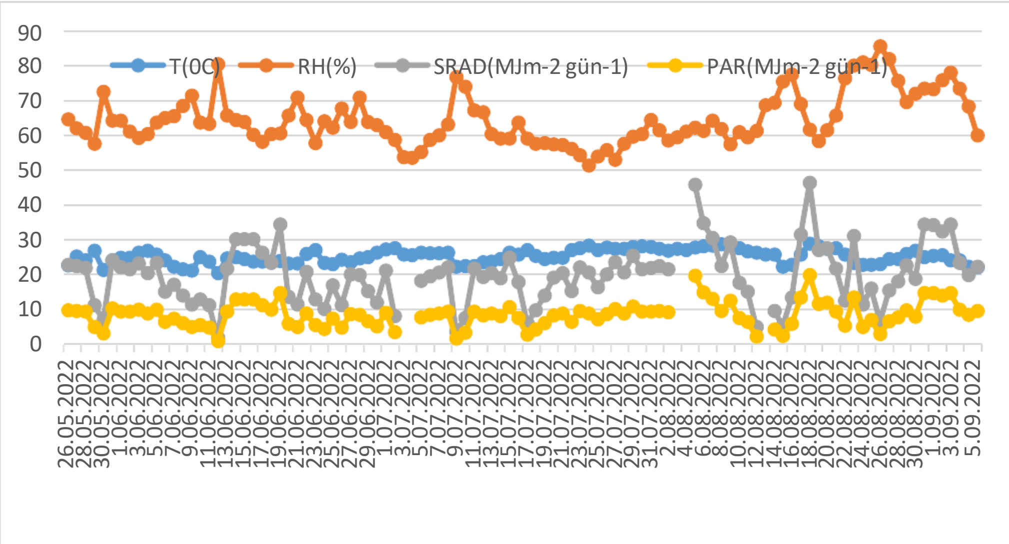

Figure 9. The temperature, humidity, solar radiation (SRAD), and photosynthetic active radiation (PAR) values at the site

During the May-August period in the experimental area where crop production was carried out, the average temperature varied between 20-30°C. The solar radiation values were around 20 MJ m-2 day-1 in July and August, however, on August 22-24, an excessive amount of rain occurred. On August 22, there was a hail along with the rain. Due to the rainy and cloudy weather conditions that lasted for 4 days, various diseases, especially mildew, caused significant losses in plant and yield, and as a result, plant sampling could not be performed and no yield was obtained after this date. On August 22, when the rain started, the temperature was recorded as 22.9°C, the humidity was 81%, and the incoming radiation was measured as 11.5 MJ m-2 day-1.

The irrigation automation system was installed and activated on June 16th. The system was operated as a closed loop thanks to the software stored in the PLC memory. Soil moisture values were determined both by Aqua-pro soil moisture meter and gravimetrically during the operation of the system. The changes in soil moisture according to the irrigation performed by the irrigation system are given in Figure 10. When the soil moisture dropped to 31.1% on July 4th according to the soil moisture measurements, irrigation was applied for the duration determined by the system, and the soil moisture was brought back to field capacity level. Daily irrigations were performed based on the solar radiation value of the previous day, ensuring that they were carried out at 10:00 am every day. On July 8th, it was observed that the current soil moisture level had dropped to 31.1%, and the system provided irrigation to bring it back to field capacity level, as determined by subsequent soil moisture measurements. The system was observed to irrigate on July 12th when the soil moisture level dropped by 33.4% and on July 16th when it reached a level of 31.5%, bringing the soil moisture back to field capacity. As seen, irrigation was started when about 20% of the soil moisture was depleted until July 16th. The basic principle of drip irrigation system, which is to irrigate little but often, was successfully implemented. The system has successfully carried out the irrigation according to the defined software until July 16th. The plant growth between May 18th and July 20th is visually presented in Figure 11. As seen from the Figure 11, tomato seedlings have continued their development normally thanks to the irrigation performed by the system.

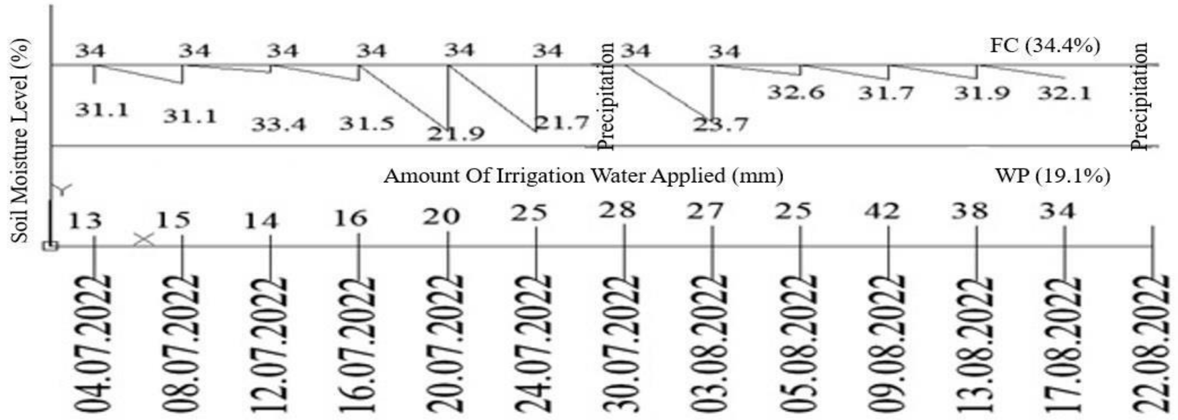

Figure10. The performance of the automatic irrigation system.

Figure 11. Plant development during (a) transplanting to field (May 18) and (b) completion of vegetative growth (July 20).

The system continued to operate between July 20th and July 24th, but it was observed that the soil moisture values indicated by the soil moisture measurements decreased to 21.9% and 21.7% respectively. In drip irrigation, plants that are sensitive to water stress and moisture should not be allowed to drop more than 50% of the whole soil moisture, otherwise yield losses due to water stress may occur in the plants. Therefore, the fact that the soil moisture has fallen below the value of 26.7%, which represents the 50% limit of the available soil moisture, indicates that the plant is under a water stress caused by irrigation. During these dates, the average temperature was 24.9°C, the humidity was 57.2%, and the Class A pan evaporation was 48 mm between July 16th and July 20th and 56 mm between July 20th and July 24th. It can be seen that the moisture deficit is high and the amount of evaporation is high, indicating that plant water consumption is high due to the high evapotranspiration demand and low soil moisture content.

For these reasons, it has been determined that the soil moisture level has consumed more than 50% of the available moisture and was measured as 21.9% and 21.7% in the soil. On both dates, the irrigation carried out by the system has brought the soil moisture back to field capacity level. Therefore, the system has shown significant success in determining the irrigation duration. Although the system has brought the soil moisture to the field capacity level on these dates, the decrease in moisture to these levels raises the possibility of developing stress in the plant.

The system was not operational between July 24th and July 30th due to rainfall, and then it was manually operated on July 30th to bring the soil moisture to field capacity level. The system continued with closed-loop irrigation after that. According to the soil moisture measurement conducted on August 3, the current soil moisture value was determined as 23.7%, and it was observed that it fell below the 50% limit value of the available soil moisture, which is 26.7%. This situation indicates that using the system on a large scale can cause water stress in plants and may result in certain losses in crop yield. The system worked successfully between August 3 and August 17, and the soil moisture values were around 31-32%, which means that approximately 19% of the available soil moisture was consumed. This indicates that there was no water stress in the plants. It is observed that the automatic irrigation process of the system was highly successful in promoting plant growth during the dry period. During experiment dates, irrigation was carried out for approximately 50 decars (da) (1 da=1000 m^2) from the same well in the Dardanellas Research Center.

The system's performance was successfully maintained until the last week of August. The reason why the agricultural production season could not be sustained until the end is that only one available well with a very low capacity of approximately 3-4 m3 was used in the agricultural production activities carried out in an area of about 50 da. It is not possible to carry out irrigated crop production in all areas with this water source, as the well has a very low capacity of approximately 3-4 m3 and it is used for the crop production activities in approximately 50 da of land. During the months when our experiment was carried out, there were problems with the water source due to irrigation of an area exceeding the capacity within the area where the experiment was conducted. Due to excessive watering of other areas, there was not enough water left in the well, and our system automatically turning on and off, caused the pump to operate in a dry environment since the water level in the well was 1 m above the bottom where our pump was located. As the system's operation in this way could damage the pump, the irrigation process was continued manually until September 15 with the pump according to the water level in the well. Due to the excessive rain that occurred between August 20th, and the closed weather conditions, diseases such as mildew and powdery mildew appeared on the tomatoes. As a result, the tomato fruits could not be harvested after this date, causing a significant loss in yield. The values related to the vegetative growth and fruit yield of the plant, determined by the samples taken and the harvest before this date, are given in Table 1 and 2.

Upon examining the tables, it can be seen that the vegetative growth parameters of the plant, such as leaf and stem weight, reached 1280 g, and leaf area values reached up to 3992 cm^2, indicating that the plant growth parameters were very healthy. This shows that the system was successful in irrigation. These values obtained show a good agreement with the values given in Yıldırım and Bahar (2017).

Table 1. Some physical parameters of tomato plants

Dates (2022)	**Leaves weight (g plant-1)**		**Stem (g plant-1)**		**Leaf area (cm2)**	**Plant height(cm)**
	Fresh	Dry	Fresh	Dry		
18.05	1.72	0.14	18.7	2.8	82.5	15
04.07	26.2	4.12	42.2	4.94	221.1	64
03.08	550	93.5	500	84.9	3842	75
16.08	650	111	630	107	3992	82

According to the values given in Table 2, the fruit weight has reached up to 136.4 g, and the plot yield values were 52 kg plot-1 on August 2 and 69 kg plot-1on August 16. After this date, although there was a significant yield on the plant, no yield could be obtained after the period of rain that occurred between August 20-24 and the weather being cloudy for four days, which caused significant diseases to develop in both the fruit and the plant. the irrigation system produced a yield of 5042 kg da-1. Unfavourable weather conditions during the last harvest resulted in a yield that was well below than the the average obtained before research studies. Excessive rain, low temperatures, high humidity, and cloudy weather for four days affected the quality and quantity of the crop and the unfavourable weather conditions prevented the last crop from being harvested.

Table 2. Fruit quality parameters

Dates (2022)	Fruit weight(g)	With (cm)	Length (cm)	Titratable acidity (%)	Total solids (%)	PH	Yield (kgplot-1)
02.08	114.3	58.6	56.7	6.6	5.0	4.7	52
16.08	136.4	65.2	63.9	7.6	5.6	5.3	69

The physical development of the tomato plant under the field conditions during the harvest on August 16 is given in Figure 12a-c.

It can be seen from Figures 12 a-b that the plant development was perfectly normal as a result of the irrigation performed by the system, As can be seen in Figure 12-c, after the rain that occurred between August 20-24, the tomato plants dried up and there was rot in the tomato fruits.

Figure 12. General view of the plants under field conditions (a-b) on August 16, 2022, and (c) after August 24, 2022.

Conclusion

When monitoring the performance of the automatic irrigation system, it was observed that it exhibited successful performance during the plant growth period. However, during the fruit development period, it was seen as an important factor that negatively affected the system performance when it started irrigating after more than 50% of the available soil moisture was consumed. Another important shortcoming of the system was evaluated as not taking into account the amount of rainfall during irrigation, even in rainy weather conditions. This was considered an important deficiency that affected the system's performance negatively. Furthermore, it is necessary to have a control system that detects the water level and disables the pump when the well water level falls below the pump level. Additionally, the relationship between solar radiation and evapotranspiration in the software controlling the system between July 16 and August 3 needs to be reviewed again, and calibration may be necessary. This has highlighted the necessity of performing calibration on the system.

This result has shown the importance of obtaining calibration values in the long term in software controlling the operation of automatic systems. Developing the software in this direction will increase the system performance and will be an important step towards further improvement of the system. Furthermore, this study can be considered as a pioneering study that can lead further research in this field studies.

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Araştırmacıların Katkı Oranı Beyan Özeti

Yazarlar makaleye eşit oranda katkı sağlamış olduklarını beyan eder.

Çıkar Çatışması Beyanı

Makale yazarları aralarında herhangi bir çıkar çatışması olmadığını beyan ederler.

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