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Drip Irrigation Application with Solar Powered Subsurface Irrigation Automation Experimental Evaluation

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ABSTRACT

In recent years, the effects of global climate change have led to a continuous decline in water resources, making it increasingly difficult to meet the growing demand for freshwater. Globally, the highest proportion of irrigation water is used in agricultural activities. In conventional farming, commonly preferred irrigation methods are often associated with unregulated and excessive water use. This has become a major factor in the rapid depletion of water resources. Controlled irrigation systems, widely implemented in modern agricultural practices, help reduce plant water consumption and ensure more efficient use of water. The advancement of computer and electronic systems has increased technological support in agricultural irrigation systems, thereby contributing to improved crop productivity. With the development of computer technologies, determining the water requirements of crops and creating soil water budgets has become significantly more accurate and important.

This study investigates the real-world evaluation of a photovoltaic solar energy-supported subsurface irrigation automation system, as well as a non-automated drip irrigation application, by utilizing the solar energy potential of Yozgat province. The solar-powered pressurized irrigation automation system consists of a direct current motor pump connected to photovoltaic (PV) solar panels and a control unit. Subsurface and drip irrigation systems were installed on designated plots. To determine the water requirement of the common bean plant, the CROPWAT program was used, and the solar-powered irrigation automation system was designed accordingly.

Experimental trials were conducted on plots cultivated with common beans, and comparisons were made between the automated subsurface irrigation system and the non-automated drip irrigation application. According to the data obtained, the automated irrigation system positively contributed to plant productivity. The solar-powered subsurface irrigation application resulted in a 73.3% increase in yield compared to the non-automated drip irrigation method. The design and implementation of the solar-powered subsurface irrigation automation system were proven to be feasible under real field conditions.

Keywords: solar energy, irrigation automation, subsurface pressurized irrigation, drip irrigation, dry bean.

INTRODUCTION

Due to the effects of global climate change, water resources are steadily decreasing, and the demand for freshwater can no longer be adequately met. As a result, various measures have been introduced to ensure more efficient and controlled use of water resources. To increase water conservation, many innovative approaches are being developed, such as utilizing rainwater, adjusting water use in agricultural irrigation according to needs, implementing controlled irrigation methods, and treating and reusing wastewater.

Research and applications in this field are still ongoing. In traditional agriculture, the irrigation methods used provide plants with more water than they need. A significant portion of this irrigation water evaporates. Controlled irrigation systems reduce plant water consumption and also ensure higher crop yields. The depletion of water resources, along with the growing population and advancing technology, has become an increasingly urgent issue. This situation makes it more difficult for all living beings to access water, which is the fundamental resource for life. In agricultural activities, excessive amounts of water are often used, and irrigation methods applied in traditional farming tend to be inefficient and unregulated (Çakmak et al., 2014). This is a significant factor contributing to the depletion of water resources. In many modern agricultural irrigation systems designed today, water is provided according to the plant's needs,

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preventing waste. As a result, water consumption in agricultural practices is reduced, and the conservation of water resources is supported. In these irrigation systems, the irrigation time is determined by measuring soil moisture using sensors, with solar energy-supported, sensor-based automatic irrigation systems replacing traditional methods (Sarı, 2019).

In smart irrigation systems, control boards, smartphones, sensors, electric motors, and GSM modems are used. These systems detect the moisture level in the soil through sensors and automatically irrigate the land at the appropriate moisture level. Compared to conventional irrigation systems, the sensor-supported irrigation application provides a 41.43% water saving, and when compared to the drip irrigation method, it saves 13.03% of water (Barkunan et al., 2019). Furthermore, solar energy-supported micro-irrigation systems yield more effective results in an area of 500 m² compared to standard irrigation methods (Kumar et al., 2015).

Solar-powered water pumping systems are among the most practical technical and economic solutions in areas where access to the electricity grid is unavailable. These systems can significantly improve the living standards and socio-economic conditions of farmers (Shamim Reza and Sarkar, 2015). A solar energy system can operate for more than 15 years (Raza, 2014). The installation cost of fixed photovoltaic (PV) panels is low, and they require minimal maintenance (Yagci, 2017).

Given the limited accessibility and high cost of other energy sources, solar energy emerges as a viable and efficient solution, particularly in applications such as agricultural irrigation, rural electrification, greenhouse heating, and water supply for livestock (Basalike, 2015). Solar-powered irrigation systems not only increase crop productivity in off-grid regions but also reduce farmers' energy expenses and contribute to environmental sustainability (Burney et al., 2010; Shah and Mishra, 2020). In addition, solar-based lighting and cooling systems enhance the quality of life in rural areas and reduce dependence on conventional energy sources (Rahman et al., 2013; IRENA, 2016).

The advancement of computer and electronic systems has significantly increased technological support for agricultural irrigation systems (Weng, 2011; El-Kader and Basma, 2013). Enhancing the efficiency of agricultural irrigation has become possible through the implementation of technological solutions. Smart systems have been widely used in monitoring and control applications across various fields such as environmental management, healthcare, and security, yielding positive outcomes (Sumriddetchkajorn, 2012; Broeders, 2013).

The advancement of computer technology has made it increasingly important in determining plant water requirements and establishing soil water budgets. The CROPWAT software utilizes climatic data to determine the optimal timing for irrigation (Kodal et al., 1993). Similar software programs are also employed to estimate the water needs of plants. These water requirements vary depending on climatic conditions and soil characteristics. Such software tools are capable of calculating plant water needs within a short period of time (İstanbulluoğlu and Şişman, 2004).

There has been limited research on the relationships between planting density, soil surface sub-surface drip irrigation lateral depth, and yield in bean crops. Thanks to the development of irrigation technology, pressurized irrigation systems are being rapidly adopted. Sub-surface drip irrigation systems not only provide water savings but also reduce labor and energy costs in irrigation. Sub-surface drip irrigation systems represent the most advanced form of drip irrigation systems. In this study, the effect of solar-powered sub-surface and surface drip irrigation applications on the yield of beans grown under the climatic conditions of Yozgat was investigated.

MATERIAL AND METHODS

Parameters of the Experiments

The research was conducted in the 2022 growing season on the campus land of Bozok

University, Yozgat Vocational School. The variety of dry beans used in the experiment was the Alberto variety (*Phaseolus vulgaris* L.). In the study, the effects of sub-surface pressurized drip irrigation and surface drip irrigation applications on the water consumption and yield of dry beans (*Phaseolus vulgaris* L.) were investigated, applying the same irrigation regime to both drip irrigation methods. Equal amounts of irrigation water were applied to the dry bean plants in both the sub-surface and surface irrigation applications. In the experiment, the Alberto variety of beans was planted. Four different irrigation methods were applied to the dry beans planted at the same sowing rate, with sub-surface irrigation at depths of 30 cm, 25 cm, and 5 cm, and surface drip irrigation. The same amount of water was applied to each plot in the experiment. In the trial, bean plants were planted with 30 cm row spacing and 33 cm plant spacing. Accordingly, each plot contained 24 plants per square meter. For each planting density and sub-surface drip depth, three experimental plots were established in each block. Each plot measured 3.00 x 5.00 meters, with a total area of 15.00 m². Within the blocks, sub-surface and surface irrigation plots were placed with three repetitions. Before planting the dry bean seeds in the experimental area, the field was plowed to prepare for planting. For each irrigation application plot, 500 grams of nitrogen, potassium (K_2O), and phosphorus (P_2O_5) fertilizer were applied per hectare.

In this study, climate data from Yozgat province, located between the meridians of 34°05' – 36°10' East and the parallels of 38° 40' - 40° 18' North, with an average annual rainfall of 418.7 mm and an altitude of 1300 m, were used. Table 1 provides the climate data for Yozgat province from 2021 to 2024 (Anonymous, 2023).

Table 1. Climatic data of Yozgat province for 2021-2024

Months	1	2	3	4	5	6	7	8	9	10	11	12
T (°C)	-2.4	0.2	-1.5	12	13	18	19	23	18	11	8	4
Tmax (°C)	2	5	3	18	19	24	25	31	25	17	13	8
Tmin (°C)	-6	-4	-5	5	7	13	13	16	11	6	3	1
n (hours)	3	4	6	4	8	8	10	8	7	7	7	3
RH (%)	77	78	74	48	60	65	58	51	49	69	70	83
U_2 (km/day)	140	153	147	167	135	143	205	147	136	136	131	111
Day. Sun. (MJ/m²/day)	10	13	14	18	22	24	28	26	22	15	10	9
P (mm/month)	100	39	62	15	47	93	1	7	9	11	22	51

RHmax and RHmin refer to the maximum and minimum relative humidity; Tmin, Tmax, and Tavg represent the minimum, maximum, and average temperatures, respectively; U is the wind speed; P denotes precipitation; and ETo is the reference evapotranspiration.

According to Table 2, the soil's sand content ranges from 27.68% to 45.15%, the clay content ranges from 19.18% to 44.72%, and the silt content ranges from 27.60% to 37.60%. The organic matter content of the soils varies between 0.6% and 1.9%, while the pH values range from 8.3 to 8.46. Electrical conductivity (EC) values were measured between 0.37 and 0.58 dS m^{-1} (Anonymous, 2024).

Table 2. Some characteristics of the trial area soils

Depth (cm)	pH	EC (dS m^{-2})	O.M (%)	Lime (%)	Sand (%)	Clay (%)	Silt (%)	Texture	Field Capacity (g g^{-1})	Wilting Point (g g^{-1})
0-35	8.3	0.40	1.9	5.8	27.68	44.72	27.60	C	37.4	25.6
35-85	8.6	0.37	0.6	6.5	42.08	27.91	30.01	CL	27.0	16.4
85+	8.4	0.58	0.6	7.8	45.15	19.18	35.67	L	22.9	11.8

The daily water balance can be analyzed using the CROPWAT model. The program calculates the reference crop water consumption based on the FAO 56 Penman-Monteith equation (Equation 1). Climatic data used includes the maximum monthly temperature (Tmax), minimum temperature (Tmin), average relative humidity (RH), wind speed (U_2), solar radiation (Rs), and precipitation data. Additionally, the latitude, longitude, and altitude values of the Yozgat climate station are input.

$$ETo = \frac{0.408.\Delta.(Rn - G) + \gamma\, 900\, T + 273\, U2\, .(es - ea)}{\Delta + \gamma.(1 + 0.34.U2)} \quad \text{(Eq. 1)}$$

ETo represents the reference evapotranspiration (mm/day), Δ is the slope of the saturation vapor pressure curve (kPa $°C^{-1}$), Rn is the net solar radiation received by the reference surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa $°C^{-1}$), T is the daily mean temperature (°C), U_2 is the wind speed at 2 meters height (m/s), es is the saturation vapor pressure (kPa), and ea is the actual vapor pressure (kPa). The parameter values in the equation were calculated using the FAO56 Penman-Monteith method (Allen et al., 1998).

$$ETc = ETo\, .kc \quad \text{(Eq. 2)}$$

In equation (2), Kc is the crop coefficient, ETc is the crop water consumption (mm), and ETo is the reference evapotranspiration (mm). The meteorological data required to calculate the reference evapotranspiration (ETo) were obtained from the Yozgat Meteorology Regional Directorate.

The foundation of the designed solar-powered subsurface pressurized irrigation applications consists of panels, a pump, a battery, a control unit, and a water reservoir. The electrical systems are placed inside a panel. The appearance of the system components is shown in Figure 1. Solar radiation reaching the Earth's surface is converted into electrical energy through solar panels. The electrical energy generated in the solar panels is supplied to the pump by the control unit when needed. The stored water can be used for irrigation purposes as required by the plants.

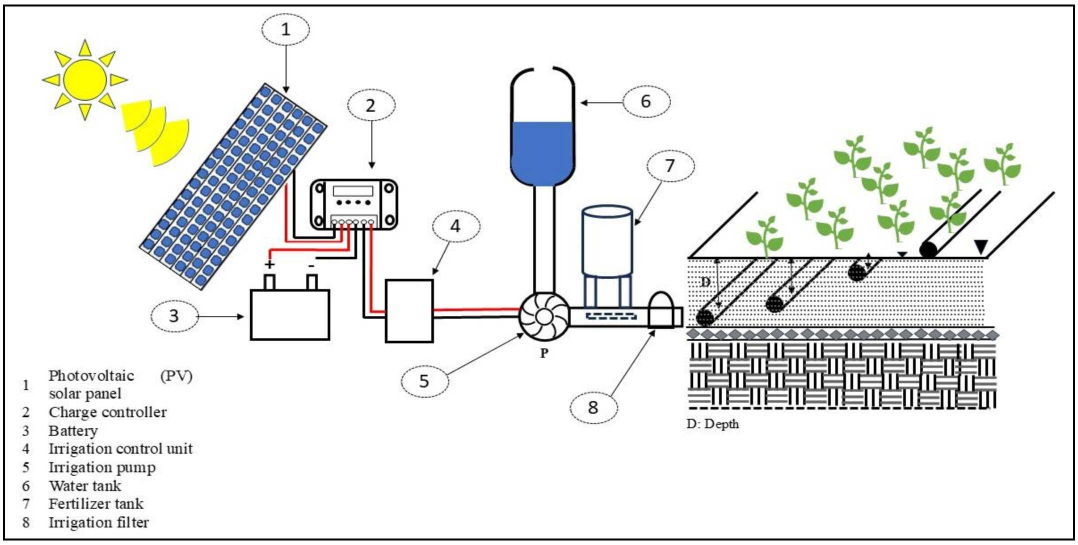

Figure 1. Photovoltaic irrigation system diagram

In the experiment, irrigation water was supplied to the system through a DC motor pump and filtration system under constant pressure. The solar panel was connected to the DC motor pump via a control unit. A 205 W monocrystalline solar panel and a 12 V DC pump were utilized. The pipeline from the water source was connected to the pump's inlet line. Pressurized water from the pump was directed to the fertilizer tank and subsequently to the subsurface drip laterals.

Different irrigation applications were implemented in the experimental plots, including subsurface (30 cm, 25 cm, and 5 cm depths) and surface (drip) methods. The lateral pipes, 16 mm in diameter with emitters spaced 33 cm apart, were installed at 30 cm intervals, using irrigation pipes with a flow rate of 1.7 L/h per emitter. Under 1 bar pressure, the emitter discharge was maintained at 2 liters. Nipple valves connected to 40 mm diameter polyethylene coil pipes were used to convey the irrigation water. Drinking water was employed as the water source in the experiment. The irrigation water from the tank was delivered to the system via the pump.

The required irrigation duration was determined using the system's pressure-flow relationship. Irrigation durations were adjusted, and constant pressure was maintained during irrigation applications. Periodic measurements were taken from the water tank, and after recording, the water consumption was calculated.

RESULTS AND DISCUSSION

Data on Irrigation Applications

Determining the required water amount for dry bean plants is related to the climatic data of the region where the plant is cultivated. In Turkey, meteorological stations are located in each province and district, providing access to climatic data for analysis. The Food and Agriculture Organization (FAO) recommends using the FAO Penman-Monteith method to calculate a plant's water requirements based on meteorological data. This method calculates the required irrigation water amount according to the plant type. The accuracy of the climatic data plays a crucial role in determining the irrigation needs of the plant. In this study, dry bean plants were used, and the evapotranspiration value (ETo) was calculated based on the crop coefficient (Kc). The ETo values, calculated from the climatic data, are presented in Table 3. Latitude and longitude data were entered into the software in degree format, with latitude at 39.82° and longitude at 34.80°. The climatic data for the experimental field, taken from the Yozgat Meteorology Regional Directorate, were used from planting to harvest. The monthly reference evapotranspiration (ETo) values for Yozgat province are 3.61 mm/day in May, 4.18 mm/day in June, 5.02 mm/day in July, and 4.96 mm/day in August.

Table 3. Yozgat/Central Climate/ETo data (ETo)

Months	Tmin (ºC)	Tmax (ºC)	RHmax (%)	U (km day^{-1})	Day length (Saat day^{-1})	Daily Solar Radiation (MJ m1^{2}.day^{-1})	ETº (mm day^{-1})
May	6.9	18.6	60.1	135	8.0	21.1	3.61
June	12.6	23.8	64.2	143	7.5	21.0	4.18
July	12.4	25.1	57.9	205	9.8	23.9	5.02
August	16.0	30.4	50.9	147	8.4	20.4	4.96

RHmax and RHmin represent the highest and lowest relative humidity; Tmin, Tmax, and Tavg refer to the lowest, highest, and average temperatures; U stands for wind speed; P refers to precipitation; and ETo is the reference evapotranspiration.

The water consumption required for the bean plant was determined using the FAO Penman-Monteith method (Uytum et al., 2013; Tahmiscioğlu, 2015). The reference value of the crop coefficient (Kc) varies from plant to plant. The Kc value changes depending on the growth stages of the plant. The Kc values calculated based on the plant’s growth stages are shown in Figure 2. It can be seen that the planting date of the crop is 15.05.2022, and the harvest date is 01.09.2022. Accordingly, the Kc value starts at 0.40, fluctuates between 0.40 and 1.15 during the development phase, reaches 1.15 during the mid-season, and decreases to between 1.15 and 0.35 during the final season. Therefore, a total irrigation schedule of 110 days is required. Of these 110 days, the first 20 days are considered the initial stage, 30 days are the development phase, 40 days are the mid-season, and the last 20 days represent the final growth stage of the plant.

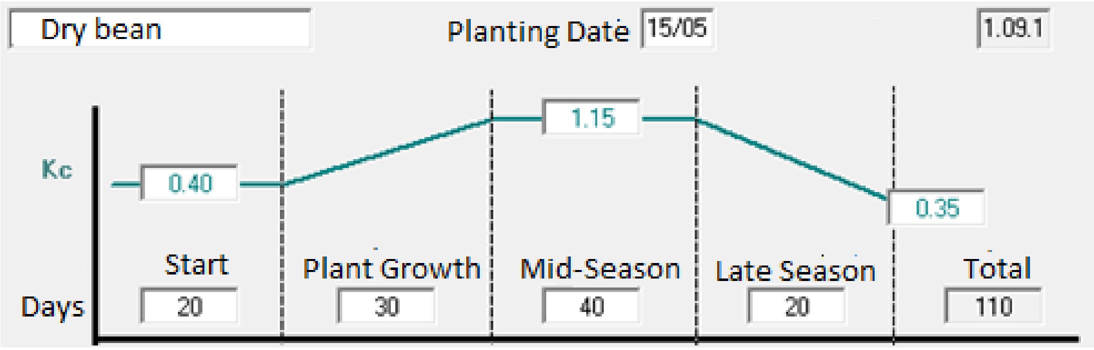

Figure 2. Yozgat/Central dry bean plant kc values and growing stage

For bush-type bean varieties, the crop coefficient (Kc) values for the initial, mid-season, and harvest periods are 0.4, 1.15, and 0.35, respectively. For pole-type beans, the crop coefficient during the mid-season should be increased to 1.20. The required water amount for beans, which have a growing period of 60-120 days, varies between 300 and 500 mm depending on the climate in order to achieve the highest yield (Doorenbos and Kassam, 1986; Suheri et al., 2020). In dry beans, the roots reach a maximum depth of 0.9 m, and the effective root depth is considered to be 0.6 m. When the daily plant water consumption requirement is 5 mm, irrigation is necessary when 45% (p = 0.45) of the total available water in the effective root zone is consumed (Allen et al., 1998).

Based on the data obtained from the plant's growing period, the water requirements for the bean plant during the initial, development, mid-season, and final season were calculated. Accordingly, the total water requirement for the plant is shown in Table 4. In Table 4, the starting month for the crop is determined as May. Depending on the months, the plant's stages are categorized as 1, 2, or 3. Based on the cultivation stage, the plant's growth is divided into the initial period, development period, mid-season, and final season. According to climatic data, the required daily net water consumption for the dry bean plant was determined. According to Table 4, the required water amount for the plant in all stages is 434.4 mm per decade (dec^{-1}).

Table 4. Water requirement of bean plants depending on their growth stage

Months	Phase	Status	kc	ETc g^{-1}	ETc d^{-1}	Effective precipitation mm	Water requirement mm d^{-1}
May	2	Initiation	0.4	1.44	8.7	8.7	1.4
May	3	Initiation	0.4	1.52	16.7	18.5	0
June	1	Growth	0.47	1.88	18.8	26.1	0
June	2	Growth	0.71	2.99	29.9	31.7	0
June	3	Growth	0.97	4.31	43.1	21.3	21.9
July	1	Middle	1.15	5.44	54.4	1	53.4
July	2	Middle	1.16	5.8	58	0	58
July	3	Middle	1.16	5.78	63.6	0.1	63.5
August	1	Middle	1.16	5.83	58.3	1.7	56.6
August	2	Last	1.01	5.11	51.1	2.5	48.7
August	3	Last	0.59	2.75	30.2	2.6	27.6
September	1	Last	0.35	1.47	1.5	0.3	1.5
				Total	**434.4**	**114.6**	**332.5**

The results obtained from the solar energy-supported subsurface and surface irrigation are explained and discussed in this section. Between May 25, 2022, and June 20, 2022, the water requirement of the bean plant was met by effective precipitation. According to the values calculated in Table 4, it was understood that the total water requirement of the bean plant during the growth stage was 9.18 mm per day.

The yield variation of dry bean plants under different depths of subsurface irrigation automation and drip irrigation is shown in Figure 3. Yields were obtained from the plots according to the irrigation practices. The yield values of each method show approximately slight differences from each other. Subsurface irrigation applications resulted in higher yields compared to surface drip irrigation.

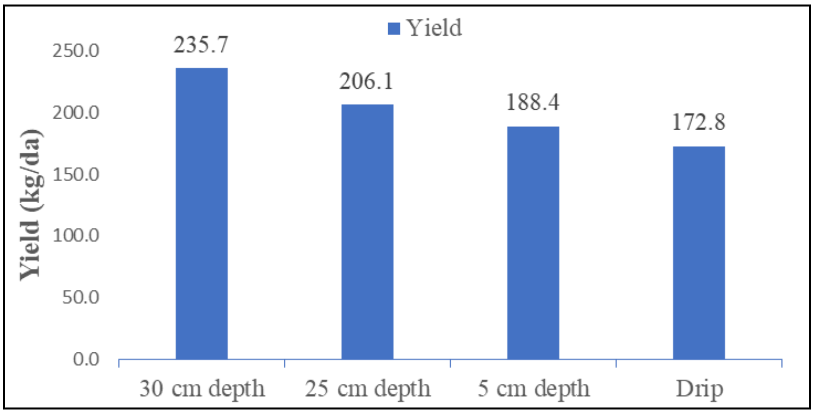

Figure 3. Variation in yield of dry bean plant with different depth subsurface irrigation and drip irrigation

Table 5 shows the evaluation of the yield data using the SPSS program. A statistically significant difference was found between the irrigation applications. There is a significant difference between the irrigation automation applications at 30 cm and 5 cm depths and the drip irrigation application. When comparing the methods in terms of yield amount, the highest yield was obtained from the subsurface irrigation automation application at 30 cm depth. This experiment concluded that the laterals placed at 30 cm depth produced the highest yield per square meter.

Table 5. SPSS results according to the efficiency factor of irrigation methods

Irrigation method	1st repetition	2nd repetition	3rd repetition
30 cm	231.94[a]	226.34[a]	248.67[a]
25 cm	227.1[a.b]	219.4[a.b]	171.73[a.b]
5 cm	195.02[b]	183.86[b]	186.2[b]
Drip irrigation	172.49[b]	186.51[b]	159.34[b]

The indices a and b are used to indicate the statistical difference between mean values within the same column according to Duncan's multiple comparison test ($p < 0.05$).

The water requirement of the bean plant was recorded as 5.8% for the initial stage, 21.13% for the growth stage, 53.93% for the mid-season stage, and 19.06% for the final stage, showing positive results. These values were compared with the rainfall in the experimental area. This irrigation practice is considered more successful and efficient compared to conventional irrigation methods, offering significant contributions to agricultural production by enhancing water use efficiency, optimizing crop yield, and supporting environmental sustainability.

CONCLUSIONS

As a result of this study, the most suitable irrigation method for dry beans was determined using a solar energy-supported subsurface pressurized drip automation system under Central Anatolian climate conditions. Solar energy-supported subsurface drip irrigation applications were established for bean irrigation. This study clearly demonstrated that applying irrigation water below the soil surface leads to efficient water use in irrigation systems. Additionally, the CROPWAT program can calculate the optimal irrigation water amount for the crop using the necessary data. The most appropriate irrigation practice was achieved without any yield loss.

Different modules can be added to solar energy-supported pressurized irrigation systems to enable remote monitoring of irrigation systems. Increasing the number of soil moisture sensors in agricultural fields and integrating additional sensors such as rainfall, temperature, and pressure sensors into the system components can multiply the data collected. As a result, improvements in irrigation and crop productivity can be achieved. Moreover, mobile devices and remote-controlled systems allow farmers to perform data analysis without physically visiting the field.

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