Assessing the Efficacy of Solar PV in Trickle Irrigation: A Predictive Approach

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ABSTRACT

Trickle irrigation is widely recognized as an efficient method for water application in agriculture. In India, where water scarcity is a significant issue, trickle irrigation emerges as an attractive option for water conservation. Additionally, solar photovoltaic (PV) power is rapidly gaining popularity worldwide as the most viable renewable energy source for irrigation. Unlike conventional electricity, the performance of trickle irrigation systems powered by solar PV is highly variable due to the intermittent nature of solar energy supply. Therefore, designing a compatible trickle irrigation system that aligns with energy generation and the desired performance of water application to crops is crucial. This paper introduces an integrated mathematical model designed to simulate and predict the performance of trickle irrigation systems under various operating conditions. The model's accuracy is validated through field experiments. The root mean square error (RMSE) for the solar PV output power and pump discharge in the developed model is within 5%. The coefficient of determination (R^2) for the experimental pump model is 0.97, indicating a high level of accuracy. The results demonstrate a satisfactory agreement between the predicted and measured parameters, validating the model's effectiveness in simulating the performance of solar-powered trickle irrigation systems.

Keywords: Irrigation, Modeling, Photovoltaic, Pump, Solar energy.

1. INTRODUCTION

The demand for energy and water is growing rapidly with the increasing population, urbanization, and modernization. Realizing finite resources of conventional energy and their environmental issues, alternative renewable energy (RE) options have been promoted in wider scale throughout the world (Panwar et al., 2011). Solar photovoltaic (PV) energy is emerging as the most reliable RE option of pumping water for irrigation. Similarly, trickle irrigation is identified as the most efficient method of water application to the crop worldwide. This method is popular in water scares countries in Asia and Africa especially for horticultural crops. Principally, proper design and layout of trickle irrigation system (TIS) are most important to reach out its full potential. Several studies on the performance variation of the solar PV system and TIS under different operating conditions are available in the literature (Baiamonte 2018; Bora et al., 2016; Keller and Karmeli 1974; Limmanee et al., 2016; Renu et al., 2017).

The solar PV system is highly affected by the intermittent nature of weather parameters like solar radiation and temperature. Therefore, power generation is not uniform throughout the day and varies with the season. The performance of TIS can be affected by the pressure and discharge variation. TIS design and layout should be compatible with the power generation of the solar PV system when integrated and having no energy storage. The selection of optimal and compatible system design is possible by simulating its performance for varying conditions. Therefore, this paper attempts to present a performance prediction model for a solar PV operated TIS in which the pump discharge has been predicted for varying power and head conditions. This flow rate then matched with the pre-determined performance of TIS at different flow rates and accordingly the TIS performance for solar power is predicted.

2. METHODOLOGY

2.1 Description of the Study Area

The study was conducted at the farm site of the Land and Water Resources Engineering, Department of Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur. The location of study area is depicted in Fig.1. The study area lies on the latitude of 22o20’30” (22.33°N) and longitude of 87o20’0” (87.32°E), located in the West Midnapore district of the state of West Bengal (India).

The study location is situated at about 48 m above mean sea level. The study area falls under the sub-humid subtropical climate zone of India. The average annual rainfall of study area is approximately 150 cm. Soil of the location is characterized as red lateritic with sandy loam in texture, which is taxonomically grouped under ‘Haplustalf’. The average annual solar insolation at latitude angle of the study area is 4.94 kWh/m^2. The average daily temperature varies between 21 ^{o}C in Dec/January to 38 ^{o}C in May/June (Hadole et al., 2022).

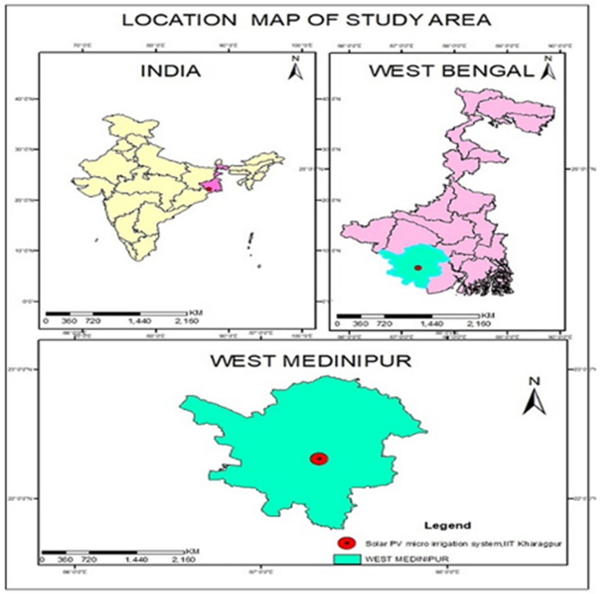

Fig. 1. Location map of study area

2.2 Description of the Experimental Set-up and Data

The solar PV-operated TIS consists of a solar PV system, a pumping system, and the TIS itself. The system employs a stand-alone single-axis sun-tracking solar PV array, which converts sunlight into direct electricity. This electricity is regulated by a controller that maintains a constant voltage for the pump by adjusting the motor's frequency and speed based on the available solar power. The pumped water is then supplied to the TIS for crop irrigation. The detailed specifications of the entire system are given in Table 1 and Table 2, and the Conceptual block diagram and field installation of the solar PV power-operated TIS is depicted in Fig. 2 and Fig.3, respectively.

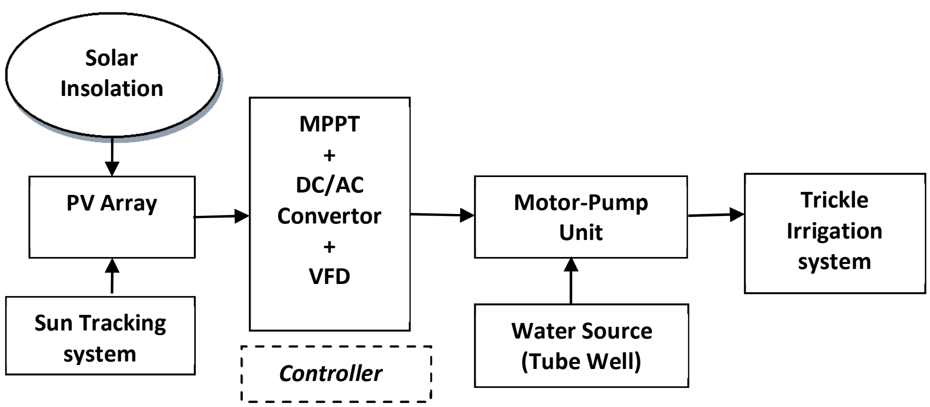

Fig.2. Block diagram of solar PV operated trickle irrigation system

Table 1: Experimental Specifications of Trickle Irrigation System

Sl. No	Particular (Unit)	Value/details
1	Main line (mm) – 01 nos.	63
2	Sub-main (Φ, mm) – 05 nos.	50
3	Lateral (Φ, mm)	12
4	Emitter (L/h)	4
5	Plot size (m × m)	40 × 20
6	No. of plot	10
7	Crop	Vegetables

Table 2: Experimental Specifications of Solar PV Pumping System

Sl. No	**Particular (Unit)**	**Value/details**
1	Rated power of module (W)	320
2	Number of modules in series, M_s	16
3	Number of modules in parallel string, M_p	01
4	Solar PV system capacity (W)	5120
5	Tilt angle	Fixed (at latitude angle)
6	Orientation	N-S
7	Pump Type	3 phase-AC/submersible
8	Pump size (hp)	5
9	Rated pump voltage (V)	415
10	Rated pump current (A)	10
11	Frequency (Hz)	50
12	Rated pump flow rate (L/s)	5.45
13	Rated head (m)	50

Fig. 3 Solar PV and Trickle irrigation system IIT Kharagpur (Hadole et al., 2021)

The study is divided into three parts: i) the model formulation ii) field experimentation and iii) validation of the prediction model.

2.3 Model Formulation

2.3.1 Motor-Pump Subsystem Evaluation and Model Development

The motor-pump characteristics were modeled based on experimental evaluations conducted during winter season of 2019 to 2021. During this period, instantaneous measurements of pump flow rate, solar power, and head were recorded at 15-minute intervals, with the pumping head ranging from 18 m to 24 m. A total of one hundred samples were randomly selected for regression analysis, resulting in a regression equation that correlates instantaneous solar PV power (P, kW) and head (H, m) to discharge (Q, lps) for the motor-pump subsystem. This equation is utilized to predict flow rates under varying power supply and head conditions. The model's accuracy is assessed using the root mean square error (RMSE), calculated as follows:

$$RMSE = [\frac{\sum_{i=1}^{N}(P_i - M_i)^2}{\sum_{i=1}^{N} {M_i}^2}]^{0.5} \times 100 \quad (3)$$

Where M_i and P_i are i^{th} measured and predicted values respectively, and N is the number of measurements.

2.3.2 Trickle Irrigation System Performance Evaluation

The performance of a conventionally designed Trickle Irrigation System (TIS) is evaluated at various flow rates and inlet pressures by operating the system with conventional grid power. Flow rates and inlet pressures are controlled using a flow control valve and measured with a flow meter and pressure gauge. The evaluation focuses on emitter discharge and uniformity coefficients at different operating conditions. The emission uniformity (EU) is calculated using the formula:

$$EU = \frac{q_n}{q_a} \times 100 \quad (4)$$

Where, EU represents the emission uniformity (%), q_n is the average discharge from the lowest 25% of emitters (L/h), and q_a is the average discharge of all emitters (L/h). The results from these field investigations are then compared with model-predicted hourly flow rates to forecast the performance of the solar PV operated TIS.

3. Results and discussions

The average hourly solar PV power measured during 2019 to 2021 is shown in Fig. 4.

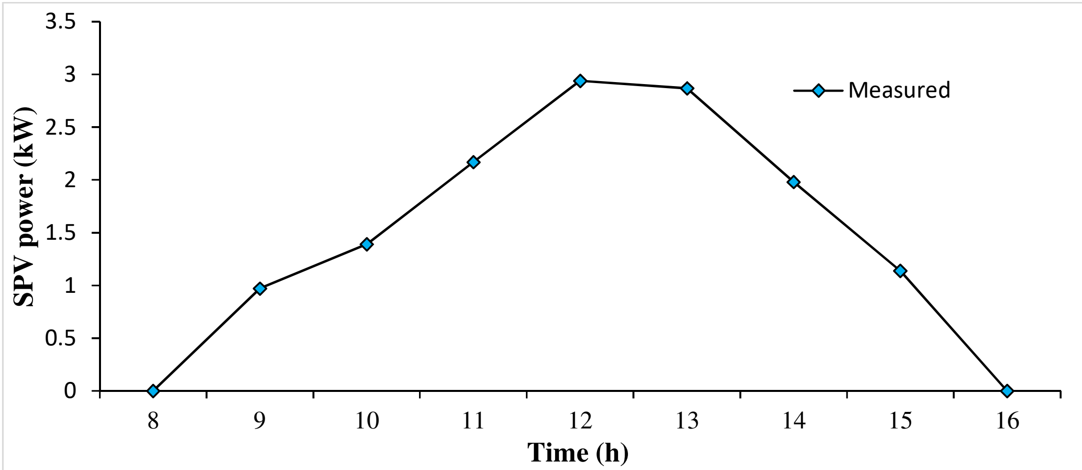

Fig. 4. Average measured solar PV power output

This level of accuracy is crucial for applications in irrigation systems, where precise power output predictions can significantly impact the efficiency and reliability of water delivery.

3.1 Evaluation of Motor-Pump subsystem

The regression equation developed for the motor-pump subsystem, represented by Eq. (4), establishes a direct relationship between instantaneous solar PV power (P), head (H), and pump discharge (Q). The equation is valid for specific operational conditions, namely solar power ranging from 1.2 kW to 3.5 kW and head values between 18 m and 24 m. This specificity is important as it delineates the operational boundaries within which the model can be reliably applied.

$$Q = c + aP + bH \tag{4}$$

The parameters obtained from the regression analysis, as shown in Table 3, provide valuable insights into the behavior of the motor-pump subsystem. The coefficient *c* (6.3386) represents a constant that influences the discharge, while *a* (2.2355) indicates the sensitivity of discharge to changes in solar power. Conversely, the negative coefficient *b* (-0.2834) suggests that as the head increases, the discharge decreases, which is consistent with the principles of fluid dynamics where higher head results in reduced flow rates.

The coefficient of determination R^2 of 0.97 indicates that 97% of the variability in pump discharge can be explained by the regression equation, which is an excellent fit. This high R^2 value reinforces the reliability of the regression equation for predicting pump performance under varying solar power and head conditions.

Table 3: Regression analysis results

Sl. No.	Parameter	Value
1	*c*	6.3386
2	*a*	2.2355
3	*b*	-0.2834
4	R^2	0.97
5	Standard error	0.0027

The results demonstrate that the proposed regression equation for the solar PV powered motor-pump subsystem is both accurate and reliable. The strong correlation between simulated and measured outputs, along with the robust regression analysis, supports the model's application in optimizing irrigation systems powered by solar energy. This predictive capability is essential for enhancing the efficiency of water management in agricultural practices, particularly in regions where water resources are limited.

This model is used to predict the instantaneous pump discharge at solar output power and operating head. The Fig.5 shows the comparison of predicted (Qs) and measured (Qm) pump discharge for 20 m, 22 m, and 25 m head. It shows that the predicted values closely match with the measured values. The RMSE for 20, 22, and 25 m head was found as 2.24 %, 3.20 %, and 4.54 %, respectively.

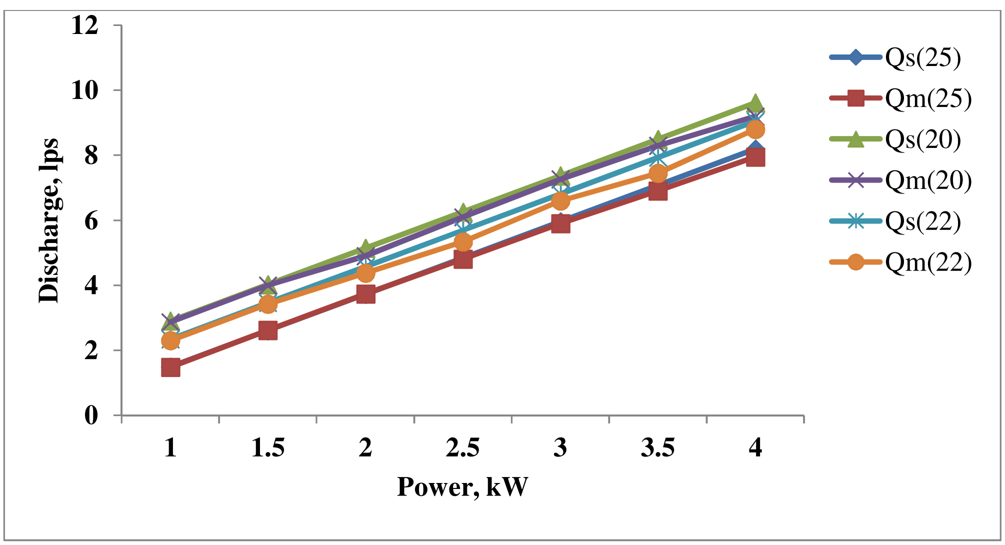

Fig. 5. Comparison of the simulated and measured pump discharge

3.2 Performance evaluation of a trickle irrigation system

The field performance of the Trickle Irrigation System (TIS) at various flow rates is detailed in Table 4 and Table 5. These tables provide insights into the relationship between flow rates, inlet pressures, emission uniformity (EU), and average emitter discharge. Table 4 presents the measured inlet pressures for different sub-mains at various flow rates. The data indicates that at the rated flow rate of 8 Ls^{-1}, the highest sub-main inlet pressure of 1.2 kg cm^{-2} is observed when all five sub-mains are operated simultaneously. As the flow rate decreased, the inlet pressure also decreased, which affected the operational capacity of the sub-mains. This relationship indicates that maintaining a higher flow rate is essential for ensuring adequate pressure across all sub-mains.

Table 5 shows the relationship between inlet pressure, emission uniformity, and average emitter discharge. The results indicate that higher inlet pressures correlate with improved emission uniformity and higher average emitter discharge.

Table 4: Measured results of flow rate vs. Inlet pressure (approx.) of different sub main.

Flow rate	**Inlet pressure (kg/cm^2)**				
(lps)	***Submain I***	***Submain II***	***Submain III***	***Submain IV***	***Submain V***
8.0	1.2	1.2	1.15	1.15	1.15
7.5	1.15	1.105	1.105	1.1	1.1
7.0	1.15	1.05	1.05	1.0	1.0
6.5	1.15	1.15	1.0	1.0	0.8
6.0	1.15	1.15	1.05	0.9	0.6
5.5	1.1	1.1	1.0	0.85	0.5
5.0	1.1	1.1	1.0	0.7	-
4.5	1.05	1.05	0.9	0.5	-
4.0	1.05	0.9	0.8	-	-
3.5	1	0.8	0.6	-	-
3.0	1	0.7	0.5	-	-
2.5	0.9	0.8	-	-	-
2.0	0.8	0.5	-	-	-
1.5	0.6	-	-	-	-

This suggests that maintaining a higher inlet pressure is crucial for achieving uniform and efficient water distribution through the emitters. The operational limits of the TIS are highlighted, as lower flow rates can render some sub-mains inoperable, indicating that the system's design and capacity are critical for ensuring consistent performance across all sub-mains.

Table 5: Inlet Pressure vs. emission uniformity and average emitter discharge

Inlet Pressure (kg/cm^2)	**EU (%)**	**Avg. emitter discharge (L/h)**
1.2	96	4.1
1.15	95	4.05
1.1	93	4.0
1.0	92	3.95
0.9	90	3.84
0.8	88	3.60
0.7	85	3.22
0.6	82	2.98
0.5	80	2.65

The results from Table 4 and Table 5 provide a comprehensive understanding of the performance of the TIS under different operating conditions. The developed model's predictions were validated against field data, demonstrating a strong correlation with measured values. The RMSE for solar PV output power and pump discharge was found to be within 5%, and the coefficient of determination (R^2) for the experimental pump model was 0.97, indicating high accuracy in the model's predictions. This validation confirms the model's effectiveness in simulating the performance of solar-powered trickle irrigation systems.

4. Conclusions

This study analyzed the field performance of solar PV powered TIS and developed a pump model for predicting its performance, demonstrating its utility in managing irrigation water supply across different crop plots. The findings underscore the importance of aligning system design with energy generation capabilities to achieve optimal irrigation performance. By utilizing the developed model, agricultural practitioners can enhance the efficiency of water application in trickle irrigation systems, ultimately contributing to improved crop yields and sustainable water management practices.

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