Analysis of Discharge in Subsurface Drip Irrigation System Operated by Boat-Based Solar Energy

Abstract

The sustainable use of water in agriculture is a critical concern in the face of depleting groundwater resources, erratic rainfall patterns, and growing food demands. Subsurface drip irrigation (SDI), when combined with solar energy, offers a viable technological intervention to enhance water productivity, reduce operational costs, and promote environmentally conscious farming. This research presents a field-based study on a subsurface drip irrigation system powered by a boat-based solar pump installed at the riverbanks of Burhi Gandak, near Pusa, Samastipur in Bihar. The study evaluates spatial and temporal variations in emitter discharge under real-world field conditions using an engineering-based methodology. A total of 45 discharge observations were recorded across multiple laterals and emitter positions. The overall average discharge was found to be 1.876 lph, with minimal deviation suggesting good hydraulic performance. The findings underscore the potential of integrating renewable energy with micro-irrigation systems to support sustainable agriculture in energy-deficient, water-stressed environments.

Keywords

Subsurface drip irrigation (SDI), solar irrigation, emitter discharge, spatial variation, temporal analysis, micro-irrigation, solar pumping

1. Introduction

Water is an essential and limited input resource for agricultural productivity. The growing challenges posed by water scarcity, climate variability, and increasing population demand necessitate a shift from conventional irrigation systems toward more efficient and precise water management strategies. Traditional irrigation practices in India, such as flood and furrow irrigation, are characterized by poor water use efficiency, typically below 40%. In contrast, micro-irrigation systems like drip and sprinkler irrigation have shown the potential to raise water use efficiency (WUE) up to 80-95% by delivering water directly to the root zone with minimal losses.

Subsurface drip irrigation (SDI) is a variation of drip irrigation where water is delivered below the soil surface through a system of buried pipes and emitters. This approach minimizes evaporation losses, reduces weed growth, and enhances root-zone moisture availability. SDI has been successfully adopted in arid and semi-arid regions for high-value crops, improving crop yield and quality while conserving water. A major challenge to widespread adoption of SDI in rural and remote areas is the dependency on electricity or diesel for pump operation. Solar-powered irrigation systems (SPIS) overcome this challenge by using renewable energy to drive pumps, making irrigation accessible even in off-grid locations.

The present study investigates the integration of SDI with a boat-mounted solar pump to serve a bamboo plantation near the Burhi Gandak river in Bihar. This configuration serves dual purposes: it utilizes river water sustainably and provides a decentralized energy source for irrigation. This paper presents an in-depth evaluation of the hydraulic performance of this unique SDI system. Specific focus is given to average emitter discharge, spatial and temporal variability, and implications for system design and field application. The study aims to determine average emitter discharge in the subsurface drip irrigation system and to analyze spatial and temporal variations in discharge performance.

2. Literature Review

Micro-irrigation technologies have evolved over the last century, with early experiments dating back to Germany in the late 19th century (Karmeli et al., 1975). The advent of plastic tubing and pressure-compensating emitters in Israel and the United States catalyzed large-scale adoption in arid zones (Schwab et al., 1981). Studies by Ayars et al. (1987) and Behera & Sachoo (1988) highlighted the advantages of SDI in saline soils and under water-limited conditions, finding notable improvements in yield and soil health.

Cherian, K.S; George, T.P (1996) concluded that the discharge rate from the trickle system with a distributor was higher than that from micro tubes of the same length. Several combinations of length, discharge and pressure were selected for the design of local (Kerala, India) trickle irrigation system. Jaiswal et al (1996) conducted the study on the levelled field of College of Agriculutral Engineering and Technology, Dr. P.D.K.V., Akola, India to determine the optimal length of lateral line for various emitter spacing's. It was revealed that optimal length of lateral line for 10% flow variation and 20% pressure variation were 20, 35, 52, and 65 m with 0.6, 1.8 and 2.4 m emitter spacing's respectively. The optimal lengths of lateral with acceptable 20% flow variation and 40% pressure variation were 28, 45, 65, and 80 m with emitter spacing's of 0.6, 1.2, 1.8, and 2.4m respectively.

Azab and Sirhan (2006) carried out an experiment at steep slope area planted with trees in different elevation terraces. The difference in elevation between upper and lower terraces at the area of study was about 8m irrigated by drip irrigation system. The system of irrigation has a problem in distribution uniformity of water resulted from initial filling of the pipes and drainage of water after stopping irrigation. Therefore, the lowest terrace receives the highest while the upper terrace receives the lowest amount of water. The distribution uniformity of the system is affected also by research was to reduce the water flow variation between terraces by changing the distribution, length and distance between laterals on manifold to solve the existing problems. The results indicated that the flow variation between terraces was reduced from 40% in the traditional design to 8% after the new design.

Mahesha et al. (2006) reported that in surface drip irrigation system, the distribution uniformity can be evaluated by direct measurement of emitter discharge rates. The main factors affecting distribution uniformity of drip irrigation system are variations in manufacture of the emitters and pressure regulators, variation in pressure caused by the changes in elevation, frictional head loss throughout the pipe network, emitter sensitivity to pressure, and irrigation temperature. The present study was conducted to assess the emitter sensitivity to operating pressure and lateral slopes. A total of seven commercially available drip emitters of different capacities ranging from two to eight lph, were studied to develop the pressure-discharge and slope-discharge relationship. The discharge performance of the emitters was tested with different operating pressure at 0.5, 0.75, 1.00, 1.25 and 1.50 kg/cm^2 operating pressure. The emitter exponents (x) obtained for emitters were found to be between 0.42 and 0.59. The emitters are of non-pressure compensating nature and had turbulent flow regime. The regression equation was developed for the pressure discharge and slopes discharge relationship.

Zhang et al (2007) reported that in order to imitate accurately flow deviation in drip irrigation system, based on the hydraulic theory, the variation regulation of the head loss of the lateral under different slopes was analyzed, and the dripper distribution of maximal and minimal working pressure under different slopes were determined. Taking into account of hydraulic variation and terrain slope a formula to compute the flow deviation of single lateral and the method for calculating flow deviation in blocks were deduced. Compared with calculation method in technical standard of micro-irrigation projects, calculation result is more consistent with actual situation. It can provide the more accurate technological guidance for designers, and makes that the practical operational targets keep pace with the designed target in drip irrigation system.

HaiJun et al (2009) conducted a laboratory experiment to investigate the mean discharge, distribution uniformity coefficient and clogging pattern of a single-wing labyrinth emitter, an integral labyrinth emitter and clogging pattern of a single-wing labyrinth emitter, integral labyrinth emitter and a pressure- compensation emitter with the application of tape water and reclaimed water. The main reasons of emitter clogging were analysed. Results indicated that the mean discharge and Christiansen uniformity coefficient of the three types of emitters were obviously lower for reclaimed water in comparison for tap water. The reduction percentages of the mean discharge and distribution uniformity coefficient were the compensation emitter. Chemical precipitation (main parts: $CaCO_3$ and $MgCO_3$) was the main reason for emitter clogging, which was partially due to higher ions concentration low discharge, small flow –path dimension and higher emitter discharge exponent were also subject to clogging. The pressure-compensation emitter is recommended for drip irrigation system with the application of reclaimed water.

Persad et al (2011) investigated on the use of solar energy for powering the pumps of a drip irrigation system. The work showed encouraging results for the two-acre area plot of land with hot peppers as the crop planted. Small area of 3-5 meters was needed to house the solar panels and the cost was not high. Pendergast et al (2013) conducted a study on the benefits of oxygation of subsurface drip-irrigation water for cotton in a Vertosol. Australian cotton (Gossypium hirsutum L.) is predominantly grown on heavy clay soils (Vertosols). Cotton grown on Vertosols often experiences episodes of low oxygen concentration in the root-zone, particularly after irrigation events. In subsurface drip-irrigation (SDI), cotton receives frequent irrigation and sustained wetting fronts are developed in the rhizosphere. The efficacy of oxygation, delivered via SDI to broadacre cotton, was evaluated over seven seasons (2005–06 to 2012–13). Oxygation of irrigation water by Mazzei air-injector produced significantly ($P < 0.001$) higher yields (200.3 v. 182.7 g m–2) and water-use efficiencies. Averaged over seven years, the yield and gross production water-use index of oxygated cotton exceeded that of the control by 10% and 7%, respectively. The improvements in yields and water-use efficiency in response to oxygation could be ascribed to greater root development and increased light interception by the crop canopies, contributing to enhanced crop physiological performance by ameliorating exposure to hypoxia. Oxygation of SDI contributed to improvements in both yields and water-use efficiency.

Olusola et al (2018) conducted a study to develop an automated solar-powered irrigation system. This will provide a cost-effective solution to the traditional irrigation method. This project is aimed at designing a system that harnesses solar energy for smart irrigation and allows for more efficient way to conserve water on the farmland. The system developed is portable and is designed to be adaptable to existing water system. The system incorporates wireless communication technology established using NRF module. For easy operations, the system can be controlled via an Android app-enabled with Bluetooth network. The user experience allows selection of either manual control for scheduled irrigation or automatic control using wireless sensors.

Mansour and Alijughaiman (2020) documented the assessment of surface and subsurface drip irrigation systems with different slopes by Hydrocalc Model. The HydroCalc simulation model is considered one of the designs, planning and evaluating the hydraulic parameters of irrigation systems, and using this model added more advantages to the measurements of hydraulic evaluations of irrigation system. Field trials were conducted in the research farm and production centre of the National Research Centre at El-Nubaria, El-Behaira Governorate, Egypt. In the field of irrigation system management, in the drip irrigation, automatic system, the use of sensors installed in the soil determines the water needs. So as to adjust the water added amounts depending on the timetable for the process of irrigation field, which varies from one crop to another. The results could be summarized as follows: using a lateral line length of 60 meters, the friction loss values expected and calculated which were estimated under drip surface and subsurface irrigation systems; subsurface was greater than the surface drip irrigation. The correlation coefficient between the values of the compressor losses due to friction were greater than 0.9. This shows a strong correlation between the predicted values, which were estimated. Significant differences were found between the treatments and the interactions between irrigation systems.

These studies collectively affirm that integrating solar power with SDI can significantly contribute to climate-resilient, resource-efficient agriculture.

3. Materials and Methods

3.1 Site Description

The field study was conducted in the bamboo plantation field located at the riverbank (riparian/dhab area) of the Burhi Gandak river at Pusa, Samastipur (Bihar), under the jurisdiction of RPCAU. The region falls under the semi-arid agro-climatic zone. The site has sandy-textured soils with high infiltration rates and an alkaline pH, which poses unique challenges for irrigation design. The average annual rainfall is 1123 mm, and mean daily temperatures range from 19°C in winter to 38°C in summer. The experimental period fell during April-May 2022, with ambient temperatures averaging 28–29°C.

3.2 System Specifications:

- Pump: 2 HP submersible, boat-mounted, drawing river water.
- Filters: Hydro-cyclone filter (65mm, 4 kg/cm²) and screen filter (120 mesh).
- Pipelines: PVC mainline (75 mm), submain (63 mm), laterals (16 mm).
- Emitters: Inline, non-pressure compensating, 4 lph nominal discharge.

3.3 System Configuration

The subsurface drip irrigation system was powered by a 2 HP solar submersible pump mounted on a floating platform. The pump directly extracts water from the river and feeds it into a filtration unit comprising a hydrocyclone filter followed by a screen filter. These ensure removal of suspended solids and protect the emitters from clogging.

The mainline (75 mm PVC) was buried underground and connected to submains (63 mm PVC), which further branched into laterals (16 mm PVC). Inline drippers with a nominal discharge capacity of 4 liters per hour (lph) were spaced at uniform intervals of 50 cm. The entire layout was designed to simulate practical field conditions of medium-scale bamboo farming.

3.4 Data Collection

Emitter discharge measurements were recorded from laterals 3, 4, and 9 (L3, L4 and L9). On each lateral, emitters at positions of Plant 1 (near submain), Plant 3 (middle), and Plant 5 (farthest) were selected. Observations were taken on five alternate days, with discharge recorded at three time intervals per day (morning, noon, and afternoon). Water discharged from emitters was collected using a calibrated 1-liter measuring cylinder, and timing was recorded with a digital stopwatch. Measurements were taken over 3-, 4-, and 5-minute intervals to increase accuracy.

3.5 Discharge Calculation and Variability Analysis

In the present study, the emitter discharge was computed by using the following basic formula:

Discharge (lph) = (Volume collected in liters) / (Time in hours)

Temporal variation was analyzed by comparing discharge values across days and time slots for each emitter. Spatial variation was assessed by comparing discharges at different distances from the submain within each lateral. Statistical tools such as average, standard deviation, and coefficient of variation (CV) were used to quantify performance. According to Bureau of Indian Standards IS 13487:1992, a CV below 10% indicates good distribution uniformity.

4. Results and Discussion

4.1 Emitter Discharge Performance

The emitter discharge data revealed that all emitters performed close to their rated discharge of 4 lph, though field-measured values ranged between 1.650 lph and 2.187 lph due to low pressure head availability, subsurface installation losses, minor clogging, and pressure drop. The overall average discharge was calculated as 1.876 lph across 45 readings. Fig. 1 depicts the variation in emitter discharge at various positions across the selected laterals while Fig. 2 illustrates the discharge uniformity across Laterals 3, 4, and 9. All CVs are well below the 10% threshold, confirming good hydraulic performance.

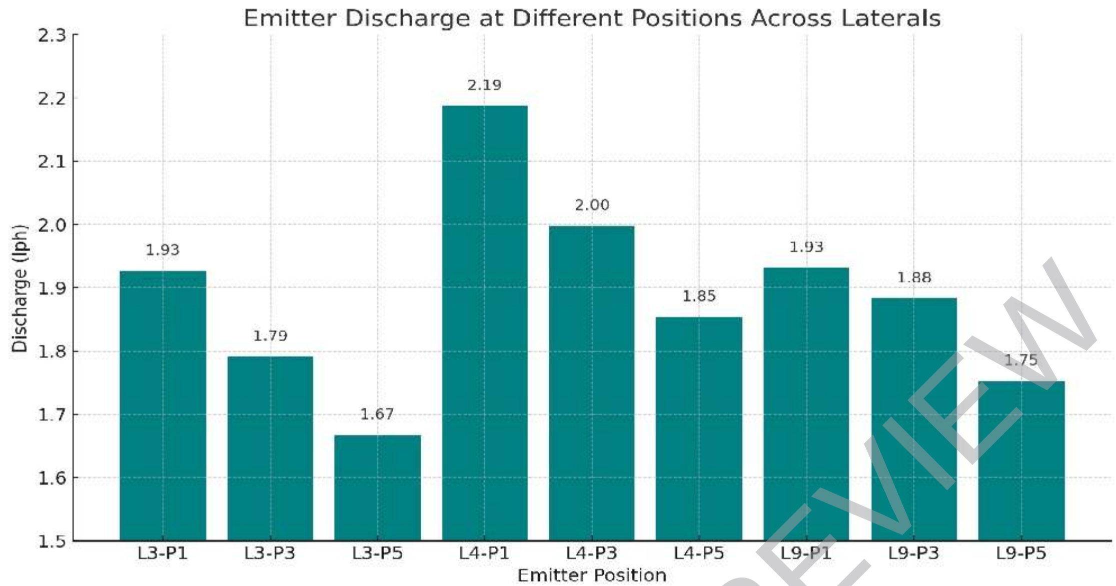

Fig. 1 Variation in emitter discharge at various positions across the selected laterals

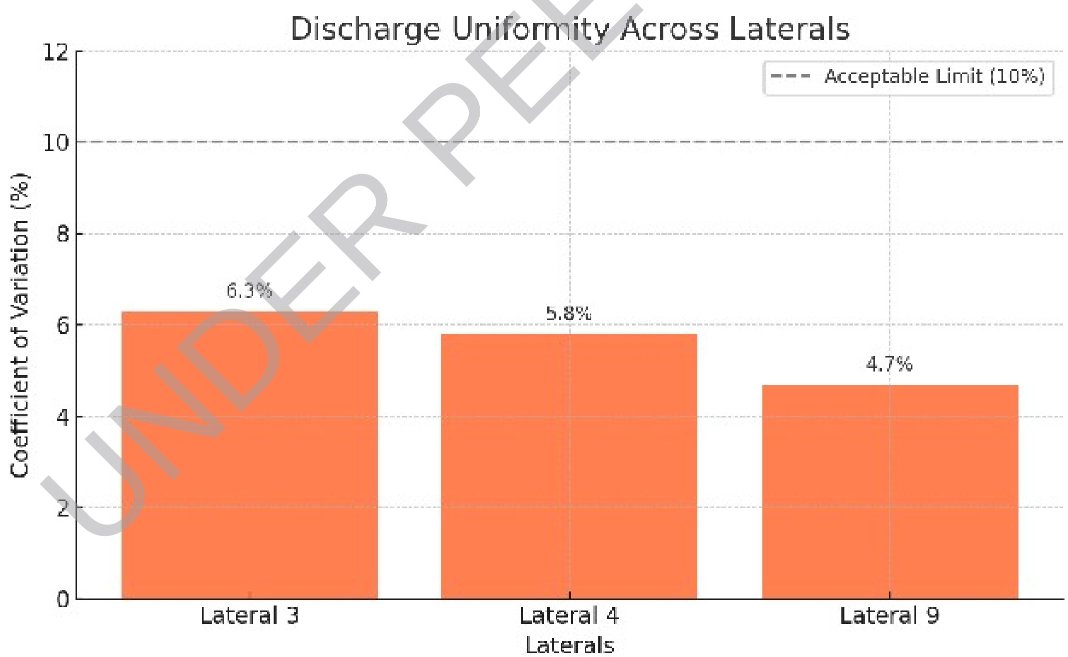

Fig. 2 Emitter discharge uniformity in the selected laterals

4.2 Temporal Stability

Fig.3 shows the temporal variation in emitter discharge over five different days at three time intervals: Morning, Noon, and Afternoon. It demonstrates stable performance with minor fluctuations—supporting your claim of good operational stability. Temporal analysis showed relatively stable performance across the five observation days (Fig. 3). The CV for time-based discharge fluctuations ranged from 4.1% to 7.5%, indicating excellent operational stability. Slight dips during peak afternoon may be attributed to air entrapment or minor temperature-induced pressure changes.

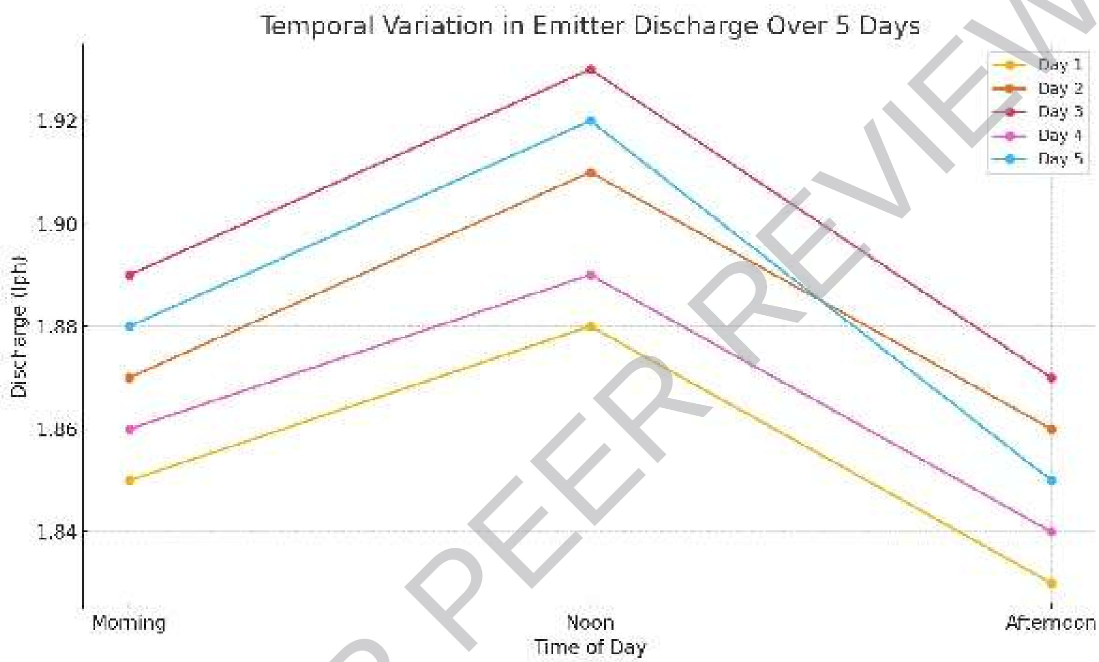

Fig. 3 Temporal variation in emitter discharge over five different days at three time intervals: Morning, Noon, and Afternoon

4.3 Spatial Distribution

Spatial analysis revealed a trend of decreasing discharge with increasing distance from the submain, consistent with theoretical expectations due to head loss along the lateral. For example, average discharge in Lateral 3 decreased from 1.927 lph (Plant 1) to 1.668 lph (Plant 5). Similar patterns were observed in Laterals 4 and 9. While the variation remained within acceptable limits (CV < 10%), the use of pressure-compensating emitters could further enhance distribution uniformity, especially in longer laterals or uneven terrain.

4.4 System Efficiency and Applicability

The integration of solar power with SDI proved to be energy-efficient and field-compatible. The system operated entirely on renewable energy with no fossil fuel dependency. It demonstrated applicability in areas with river water access and sandy soils where surface irrigation is inefficient. This configuration can be particularly useful in regions with limited power supply or where land is adjacent to rivers, lakes, or irrigation canals. The floating solar pump platform enhances mobility and reduces land-use conflict.

5. Conclusions

The experimental evaluation of a boat-based solar-powered subsurface drip irrigation system demonstrated promising results in terms of emitter performance, discharge uniformity, and renewable energy utilization. The observed spatial and temporal discharge variations were minor and fell within acceptable standards. The study validates that combining SDI with floating solar pumping is a viable, scalable, and sustainable solution for agricultural water management in semi-arid regions.

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