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Research Article

Analysis of Discharge in a Subsurface Drip Irrigation System Operated by Boat-Based Solar Energy: A Comprehensive Field Study

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ABSTRACT

Efficient water management in agriculture is increasingly important due to groundwater depletion, climate variability, and rising food demand. Subsurface drip irrigation (SDI) improves water-use efficiency by delivering water directly to the crop root zone, while solar-powered pumps provide a sustainable energy source for irrigation in remote areas. This study evaluates the hydraulic performance of a solar-powered subsurface drip irrigation system using a boat-mounted floating pump installed along the Burhi Gandak River in Samastipur district, Bihar, India.

Field observations were conducted during April–May 2022, with 45 discharge measurements taken from three laterals and five emitter positions at different times of the day. The average emitter discharge was 1.876 L/h with coefficients of variation below 10%, indicating excellent distribution uniformity. A gradual decrease in discharge was observed along the lateral length due to hydraulic head loss, while temporal variations remained minimal.

The results demonstrate that the floating solar-powered SDI system provides reliable and uniform water distribution under field conditions. The system offers a sustainable irrigation solution for riverine and energy-deficient regions by combining renewable solar energy with efficient water delivery technology.

1. INTRODUCTION

Water is undeniably one of the most essential and yet increasingly limited input resources for agricultural productivity, serving as the lifeblood of crop production systems that sustain human civilization. The growing challenges posed by widespread water scarcity, intensifying climate variability characterized by more frequent and severe droughts and floods, and the inexorable pressure of a growing global population demanding more food, feed, fiber, and fuel, all combine to necessitate a fundamental and urgent shift away from conventional, inefficient irrigation practices toward more precise, sustainable, and climate-resilient water management strategies. Traditional irrigation methods that have been practiced for millennia, such as flood irrigation, furrow irrigation, and wild flooding, still dominate the agricultural landscape in many parts of India and other developing countries. These methods are characterized by notoriously poor water use efficiency, typically below forty percent, meaning that more than half of the water diverted for irrigation is lost to evaporation, runoff, deep percolation beyond the root zone, or distributional inequities across the field. Such inefficiencies not only waste a precious and increasingly scarce resource but also contribute to secondary environmental problems such as waterlogging, soil salinization, and the degradation of downstream water quality through agricultural return flows.

In stark contrast to these traditional approaches, micro-irrigation technologies, particularly drip and sprinkler irrigation systems, have demonstrated the potential to dramatically improve water use efficiency, raising it to between eighty and ninety-five percent by delivering water directly to the root zone of crops in precise amounts and at optimal times, with minimal losses to evaporation, runoff, or deep drainage. Among the various forms of drip irrigation, subsurface drip irrigation represents a particularly advanced and efficient variant, in which water is delivered below the soil surface through a network of buried pipes and emitters placed at or near the root zone. This approach offers several distinct advantages over conventional surface drip irrigation. By placing the water delivery points below the soil surface, evaporative losses are virtually eliminated, as the water is applied directly into the soil matrix where it is protected from the drying effects of solar radiation and wind. Weed growth is substantially reduced because the soil surface remains dry, depriving weed seeds of the moisture they need to germinate and establish. The root zone environment is enhanced through more uniform and consistent moisture distribution, promoting healthier root development and more efficient nutrient uptake. The system is also less susceptible to damage from farm operations, as the buried pipes are protected from sunlight, physical disturbance, and vandalism.

Despite these compelling advantages, the widespread adoption of subsurface drip irrigation, particularly in the rural and remote areas of developing countries where it could have the greatest impact, is often constrained by a fundamental challenge: the lack of reliable and affordable energy sources to power the pumps required to pressurize the system and deliver water from its source to the emitters. In many parts of rural India, grid electricity supply is erratic, unreliable, or simply unavailable, forcing farmers to rely on diesel-powered pumps, which are expensive to operate, subject to volatile fuel prices, and contribute significantly to greenhouse gas emissions and local air pollution. The recurring costs of diesel can be prohibitive for small and marginal farmers, limiting their ability to adopt and sustain improved irrigation technologies even when the water-saving benefits are well understood.

The integration of solar photovoltaic technology with irrigation pumping presents an elegant and compelling solution to this energy challenge. Solar-powered irrigation systems harness the abundant and renewable energy of the sun to drive water pumps, offering a clean, quiet, and increasingly cost-effective alternative to both grid electricity and diesel. In a country like India, blessed with high solar insolation throughout most of the year and particularly during the critical summer growing season when irrigation demand peaks, solar energy represents an immense and largely untapped resource for powering agricultural development. The declining costs of solar photovoltaic panels, improvements in pump efficiency, and the availability of government subsidies and supportive policies have all contributed to making solar irrigation an increasingly viable option for farmers across the country.

The present study investigates an innovative integration of these two transformative technologies: a subsurface drip irrigation system powered by a boat-mounted solar pump, installed at the riverbanks of the Burhi Gandak river near Pusa in the Samastipur district of Bihar. This configuration serves multiple purposes simultaneously. It utilizes river water, a surface water source that is often underutilized for irrigation due to the challenges of pumping and conveyance, thereby reducing pressure on increasingly depleted groundwater aquifers. It provides a decentralized, renewable energy source for irrigation, freeing farmers from dependence on an unreliable grid or expensive diesel. The boat-mounted design of the pump adds an additional layer of innovation and practicality, allowing the pumping system to float on the river, moving along the watercourse as needed, and remaining safe from damage during flood events when conventional land-based pumps would be submerged or washed away. This is particularly relevant for the vast riverine areas of Bihar and other parts of the Gangetic plain, where seasonal flooding is a recurring challenge and where land for agriculture is often interspersed with water bodies.

The specific objectives of this research were to conduct an in-depth evaluation of the hydraulic performance of this unique boat-based solar subsurface drip irrigation system, with a particular focus on characterizing the average emitter discharge achieved under real-world field conditions, analyzing the spatial variability in discharge along the length of the laterals to assess distribution uniformity, and examining the temporal variability in discharge across different days and times of day to evaluate operational stability. By providing a rigorous, data-driven assessment of system performance, this study aims to generate valuable insights that can guide future system designs, inform extension recommendations, and support policy decisions related to the promotion of solar-powered micro-irrigation for sustainable and climate-resilient agriculture in water-stressed and energy-deficient regions.

2. LITERATURE REVIEW

The evolution of micro-irrigation technologies over the past century represents a remarkable trajectory of agricultural innovation, from the earliest experimental concepts to the sophisticated, precision-engineered systems available today. The origins of drip irrigation can be traced back to Germany in the late nineteenth century, where researchers first experimented with subsurface clay pipes for irrigation, but it was the development of modern plastic tubing and pressure-compensating emitters in Israel and the United States during the mid-twentieth century that catalyzed the large-scale adoption of this technology in arid and semi-arid regions around the world. These early developments established the fundamental principles of drip irrigation design, including the importance of emitter flow uniformity, the relationship between pressure and discharge, and the need for effective filtration to prevent emitter clogging.

Seminal research by Wu and colleagues in the 1970s and 1980s laid much of the theoretical groundwork for the hydraulic design of micro-irrigation systems. Wu's work on the assessment of hydraulic design in micro-irrigation systems, published in 1997, provided comprehensive frameworks for analyzing pressure distribution, flow variation, and emission uniformity in drip irrigation laterals and manifolds. This research established the fundamental understanding that emitter discharge in a well-designed system should vary minimally along the length of a lateral, with the coefficient of variation serving as a key performance metric. Wu's work also highlighted the importance of considering factors such as pipe friction losses, elevation changes, and emitter manufacturing variability in the design process to achieve acceptable levels of distribution uniformity.

The specific challenges and opportunities of subsurface drip irrigation have been the subject of extensive research, particularly in relation to its performance under conditions of shallow saline groundwater, its effects on soil salinization, and its impacts on crop yield and water productivity. The work of Ayars and colleagues, spanning several decades, has been particularly influential in this area. Their 2001 study comparing the operation of subsurface drip irrigation and furrow irrigation systems in the presence of shallow saline groundwater demonstrated notable improvements in both crop yield and soil health under subsurface drip irrigation. The research showed that by maintaining consistently favorable soil moisture conditions in the root zone while minimizing evaporation and capillary rise of saline groundwater, subsurface drip irrigation could sustain productive agriculture even in areas where traditional irrigation methods would lead to rapid soil degradation. This finding has important implications for the vast areas of India and other countries affected by soil salinity and poor-quality groundwater.

The challenge of maintaining uniform water distribution in drip irrigation systems installed on sloping lands has been addressed by researchers such as Al-Azab and Sirhan in their 2006 study of drip irrigation systems for steep slope land. Their work, conducted in an area with an elevation difference of eight meters between upper and lower terraces, documented significant problems with distribution uniformity resulting from the initial filling and subsequent drainage of pipes after irrigation. The lowest terraces received the highest amounts of water while the upper terraces received the lowest, creating substantial inequities in irrigation application. By redesigning the distribution system, including the length and spacing of laterals on the manifold, the researchers were able to reduce flow variation between terraces from forty percent in the traditional design to just eight percent after the new design. This work highlights the importance of careful hydraulic design adapted to local topographic conditions, a principle that applies equally to the design of systems for riverine areas with varying elevations relative to the water source.

The theoretical understanding of flow deviation in drip irrigation systems was advanced significantly by the work of Zhang and colleagues, published in 2007. Their research analyzed the variation regulation of head loss in laterals under different slope conditions and developed methods for determining the emitter positions with maximum and minimum working pressure. By taking into account both hydraulic variation and terrain slope, they derived formulas for computing flow deviation in individual laterals and in blocks, providing a more accurate representation of actual system performance than previous calculation methods. Their approach, which was subsequently incorporated into technical standards for micro-irrigation projects, allows designers to predict system performance more accurately and to ensure that practical operational targets align with design objectives.

The integration of solar energy with drip irrigation has been explored by several researchers, with studies demonstrating both the technical feasibility and the economic viability of this approach. The work of Persad and colleagues, published in 2011, investigated the feasibility of using solar energy for powering the pumps of a drip irrigation system for food crop production in Trinidad. Their research showed encouraging results for a two-acre plot of land planted with hot peppers, demonstrating that solar-powered drip irrigation could be implemented with a relatively small area of three to five meters required to house the solar panels, and at a cost that was not prohibitive. This study provided early evidence that solar-powered drip irrigation could be a viable option for small to medium-scale farms in tropical and subtropical regions with high solar insolation.

The benefits of subsurface drip irrigation extend beyond water savings to include potential improvements in soil aeration and root zone oxygen status, as demonstrated by the work of Pendergast and colleagues on oxygenation of subsurface drip irrigation water for cotton production in Australia. Their seven-year study, published in 2013, evaluated the effects of aerating irrigation water using a Mazzei air-injector on cotton grown in heavy clay soils. These Vertosols, which are predominant in Australian cotton production, often experience episodes of low oxygen concentration in the root zone following irrigation events, leading to temporal and spatial hypoxia that can significantly reduce crop yields. The study found that oxygenation of subsurface drip irrigation water produced significantly higher yields, averaging two hundred point three grams per square meter compared to one hundred eighty-two point seven grams per square meter for the non-oxygenated control, representing a ten percent increase. The gross production water-use index was also improved by seven percent. The improvements in yield and water-use efficiency were attributed to greater root development and increased light interception by crop canopies, resulting from the amelioration of hypoxia stress through enhanced oxygen delivery to the root zone.

The development of automated and smart irrigation systems has been accelerated by advances in wireless communication, sensor technology, and microcontroller platforms. The work of Olusola and colleagues, published in 2018, described the development of an automated solar-powered irrigation system incorporating wireless communication technology using NRF modules and an Android application for system control. The system was designed to be portable and offered users the flexibility of either manual control for scheduled irrigation or automatic control using wireless sensors to trigger irrigation based on real-time soil moisture conditions. This research demonstrates the potential for integrating modern information and communication technologies with solar-powered irrigation to create highly efficient, responsive, and user-friendly systems that optimize water use based on actual crop needs.

The use of simulation models for the design and evaluation of drip irrigation systems has become increasingly sophisticated, as exemplified by the work of Mansour and Aljughaiman, published in 2020, on the assessment of surface and subsurface drip irrigation systems with different slopes using the HydroCalc simulation model. This model, which is designed for planning and evaluating the hydraulic parameters of irrigation systems, was applied to field trials conducted in Egypt to assess the performance of surface and subsurface drip irrigation under different lateral lengths and slope conditions. The results indicated that for a lateral line length of sixty meters, the friction loss values estimated for subsurface drip irrigation were greater than those for surface drip irrigation, reflecting the additional losses associated with buried installation. The correlation coefficient between predicted and calculated friction loss values exceeded zero point nine, demonstrating the accuracy of the simulation model and its utility for system design and evaluation.

The specific innovation of boat-based solar pumping for riverbed farming was pioneered by Srivastava and colleagues in a project documented in 2020. Their system comprised a wooden boat fitted with a two horsepower pump, either alternating current or direct current, powered by an eighteen hundred watt solar photovoltaic array. The solar system powered both the boat and the pump, which was capable of withdrawing water at a rate of five point seven five liters per second, or approximately twenty cubic meters per hour. This boat-mounted solar pump was specifically designed to provide irrigation to small and marginal farmers using riverbed land for farming, addressing the unique challenges of this niche agricultural system. Since riverbed land is available for farming only during the few months each year when the river recedes after the monsoon, pumps and other equipment mounted on land are at high risk of being flooded and damaged during the subsequent rainy season. The boat-mounted solar pump provides a floating alternative to conventional land-based pumps, remaining safe from flood damage and offering the additional advantage of mobility along the river or water body, allowing farmers to access water at different points as needed.

More recent work by Manfo and Sahin in 2024 has continued to advance the field of solar-powered irrigation, describing the development of an automatic photovoltaic cell-battery powered water irrigation system incorporated with Arduino software for agricultural activities. This research demonstrates the ongoing evolution of solar irrigation technology, incorporating sophisticated control systems, energy storage to enable operation during periods of low solar radiation, and user-friendly interfaces for system management. Collectively, these studies affirm that the integration of solar power with micro-irrigation systems, including subsurface drip irrigation, represents a robust and promising approach to achieving climate-resilient, resource-efficient agriculture that can contribute meaningfully to global food security and environmental sustainability.

3. MATERIALS AND METHODS

3.1 Site Description and Environmental Context

The field study was conducted in a bamboo plantation located on the riverbank, in the riparian area locally known as the dhab area, of the Burhi Gandak river at Pusa, in the Samastipur district of Bihar, India. The site falls under the administrative and research jurisdiction of Dr. Rajendra Prasad Central Agricultural University, which provided the necessary infrastructure and logistical support for the study. The region is characterized by a semi-arid agro-climatic classification, with distinct seasonal variations in temperature, rainfall, and humidity that profoundly influence agricultural practices and irrigation requirements. The soils at the site are predominantly sandy in texture, a common characteristic of riverine areas where alluvial deposition processes have created deep, well-drained profiles with high infiltration rates and low water-holding capacity. The soil pH is alkaline, which poses unique challenges for irrigation design and nutrient management, as alkaline conditions can affect the availability of certain plant nutrients and the performance of irrigation equipment over time.

The climatic context of the study region is defined by a monsoon-influenced subtropical regime. The average annual rainfall is approximately one thousand one hundred twenty-three millimeters, the vast majority of which falls during the southwest monsoon season from June to September. This seasonal concentration of rainfall creates a pronounced dry period during the rest of the year, when irrigation is essential for crop production. Mean daily temperatures range from a minimum of around nineteen degrees Celsius during the cool winter months to a maximum that frequently exceeds thirty-eight degrees Celsius during the peak of summer in May and June. The experimental period for this study fell during the months of April and May in the year 2022, which represent the hottest and driest part of the year, with ambient temperatures averaging between twenty-eight and twenty-nine degrees Celsius and very low rainfall. These conditions are typical of the pre-monsoon summer season and represent a demanding test for any irrigation system, as evaporative demand is at its peak and crop water requirements are highest.

3.2 System Specifications and Components

The irrigation system evaluated in this study was based on the innovative boat-based solar pumping system developed by Srivastava and colleagues, which was adapted and installed for this research at the Burhi Gandak river site. The system comprised several key components, each selected and configured to work together as an integrated unit for extracting river water and delivering it to the subsurface drip irrigation network. The pumping unit consisted of a two horsepower submersible pump, mounted on a specially constructed wooden boat that served as a floating platform. This boat-mounted configuration allowed the pump to float on the river surface, drawing water directly from the river while remaining mobile and protected from flood damage. The pump was powered by an eighteen hundred watt solar photovoltaic array, consisting of multiple solar panels connected in series and parallel to provide the necessary voltage and current for pump operation. The solar array was also mounted on the boat, creating a self-contained, floating power generation and pumping unit that could operate independently of any land-based infrastructure.

Water drawn from the river by the solar pump was first conveyed to a filtration system designed to remove suspended solids and protect the downstream emitters from clogging. The filtration system comprised two stages in series. The first stage was a hydrocyclone filter, also known as a sand separator, with a nominal size of sixty-five millimeters and a nominal pressure rating of four kilograms per square centimeter. This filter uses centrifugal force to separate heavier sand and silt particles from the water, protecting the subsequent components from abrasive damage and reducing the load on the finer filtration stage. The hydrocyclone filter had a rated flow capacity of twenty-five to forty cubic meters per hour, which was more than adequate for the flow rates required by the system. The second stage was a screen filter, also with a nominal size of sixty-five millimeters and a nominal pressure rating of two kilograms per square centimeter, with an aperture size of one hundred twenty mesh.

This screen filter provided fine filtration to remove any remaining suspended particles that could potentially clog the drip emitters.

After filtration, the water entered the pipe distribution network, which was designed to deliver water from the pump to the bamboo plantation with minimal pressure loss and uniform distribution across the field. The mainline consisted of seventy-five millimeter diameter PVC pipe, buried underground to protect it from physical damage and to avoid interference with farm operations. The mainline connected to submains of sixty-three millimeter diameter PVC pipe, which branched off to serve different sections of the plantation. From the submains, laterals of sixteen millimeter diameter PVC pipe were laid out along the rows of bamboo plants, buried at the appropriate depth for subsurface drip irrigation. Inline drip emitters with a nominal discharge rating of four liters per hour were installed at uniform spacing of fifty centimeters along each lateral. These emitters were non-pressure-compensating type, meaning that their discharge rate would vary with the pressure head available at their location along the lateral. The entire layout was designed to simulate practical field conditions of medium-scale bamboo farming, providing a realistic testbed for evaluating system performance.

3.3 Data Collection Methodology

The data collection for this study was designed to capture a comprehensive picture of emitter discharge performance under real-world operating conditions, with sufficient replication to enable robust statistical analysis of spatial and temporal variability. Measurements were focused on three selected laterals, designated as Lateral three, Lateral four, and Lateral nine, which were chosen to represent different positions within the overall system layout and to provide a range of distances from the water source. On each of these laterals, emitter discharge was measured at three specific positions corresponding to the emitters serving Plant one, which was located nearest to the submain connection; Plant three, located at an intermediate position approximately midway along the lateral; and Plant five, located farthest from the submain at the distal end of the lateral. This sampling scheme was designed to capture the expected gradient in pressure and discharge along the length of the lateral due to friction losses.

Discharge measurements were taken on five alternate days over the course of the study period, providing temporal replication to assess day-to-day variability in system performance. On each of these measurement days, readings were taken at three different times of day: morning, noon, and afternoon. This temporal sampling was designed to capture any diurnal variations in system performance that might arise from changes in solar radiation intensity affecting pump output, or from temperature-induced changes in water properties or system pressure. Each individual discharge measurement was made by placing a calibrated one-liter measuring cylinder under the selected emitter to collect the water discharged over a precisely timed interval. The collection time was measured using a digital stopwatch, and measurements were typically taken over periods of three to four minutes, and sometimes up to five minutes, to increase the accuracy of the flow rate calculation by accumulating a larger volume of water and reducing the proportional error in timing. The volume collected was read from the measuring cylinder, and the discharge rate in liters per hour was calculated using the fundamental formula of volume divided by time, with appropriate unit conversions.

3.4 Discharge Calculation and Variability Analysis

The emitter discharge for each measurement was computed using the standard formula: discharge in liters per hour equals the volume collected in liters divided by the time in hours. For each emitter position on each lateral, multiple discharge measurements were obtained across the different days and times of day, allowing for the calculation of summary statistics including the mean discharge, the standard deviation of discharge, and the coefficient of variation, which expresses the standard deviation as a percentage of the mean. The coefficient of variation is a particularly useful metric for assessing the uniformity of emitter performance, as it normalizes the variability by the mean discharge, allowing for meaningful comparisons across emitters with different mean flow rates.

According to the Bureau of Indian Standards IS 13487 of 1992, which specifies the criteria for evaluating the performance of drip irrigation systems, a coefficient of variation below ten percent indicates good distribution uniformity and acceptable system performance. This standard was used as a benchmark for assessing the performance of the system in this study. Spatial variability was assessed by comparing the mean discharge values for emitters at different positions along each lateral, as well as by comparing the performance of different laterals within the system. Temporal variability was assessed by analyzing discharge measurements for the same emitter position across different days and across different times of day within the same day. Statistical tools including calculation of means, standard deviations, coefficients of variation, and graphical visualization of data patterns were employed to characterize system performance and identify any significant deviations or trends.

4. RESULTS AND DISCUSSION

4.1 Overall Emitter Discharge Performance

The comprehensive analysis of the forty-five discharge observations recorded during the study period revealed that all emitters in the system performed at discharge rates reasonably close to their nominal rated discharge of four liters per hour, although the actual field-measured values were consistently lower than this rated value, ranging from a minimum of one point six five zero liters per hour to a maximum of two point one eight seven liters per hour. The overall average discharge across all forty-five measurements was calculated as one point eight seven six liters per hour. This reduction from the nominal rated discharge can be attributed to a combination of factors inherent in the real-world operating conditions of the system. The available pressure head at the emitters under field conditions was lower than the design pressure for which the emitters were rated, due to the combined effects of friction losses in the pipe network, elevation differences between the pump and the field, and the specific characteristics of the solar pumping system which may not maintain constant pressure throughout the day as solar radiation varies. The subsurface installation of the laterals and emitters may also introduce additional flow resistance compared to surface installation, as the surrounding soil can exert pressure on the tubing and potentially affect emitter performance. Minor clogging of some emitters by fine suspended particles that passed through the filtration system, despite the best efforts at filtration, could also contribute to reduced discharge rates. Additionally, the inherent manufacturing variability among emitters, even within the same production batch, means that individual emitters will always exhibit some variation in discharge at a given pressure.

Despite this reduction in absolute discharge rate relative to the nominal rating, the most important finding from a hydraulic performance perspective was the remarkably low variability observed across the entire set of measurements. The overall standard deviation of discharge was small, and the coefficients of variation calculated for different spatial and temporal comparisons consistently fell well below the ten percent threshold specified by the Bureau of Indian Standards as indicative of good distribution uniformity. This demonstrates that while the system may not be delivering water at the design flow rate, it is delivering water with excellent consistency and uniformity across the irrigated area, which is ultimately the more critical factor for achieving uniform crop growth and efficient water use. A system that delivers water uniformly at a somewhat lower rate is far preferable to one that achieves high discharge rates in some areas while starving others, leading to patchy crop development and inefficient use of both water and nutrients.

4.2 Spatial Variation in Emitter Discharge

The spatial analysis of emitter discharge along the length of the selected laterals revealed patterns that are entirely consistent with the fundamental hydraulic principles governing flow in pipes. As water flows along a lateral from the submain connection toward the distal end, friction between the water and the pipe walls gradually dissipates energy, causing a progressive decrease in pressure head along the length of the pipe. Since the discharge rate of non-pressure-compensating emitters is directly related to the pressure head available at their location, this pressure gradient translates into a corresponding gradient in emitter discharge, with emitters nearer to the submain discharging at higher rates and those farther away discharging at lower rates. This expected pattern was clearly evident in the data from all three laterals studied.

On Lateral number three, the average discharge measured at the emitter position nearest to the submain, designated as Plant one, was one point nine two seven liters per hour. At the intermediate position, Plant three, the average discharge decreased to one point eight six nine liters per hour. At the farthest position, Plant five, the average discharge was lowest at one point six six eight liters per hour. This represents a reduction in discharge of approximately thirteen percent over the length of the lateral from the proximal to the distal end. Similar patterns were observed on Lateral four and Lateral nine, confirming the consistency of this hydraulic behavior across different parts of the system. On Lateral four, the average discharge decreased from one point nine three one liters per hour at the proximal position to one point seven five six liters per hour at the intermediate position and one point six five zero liters per hour at the distal position. On Lateral nine, the proximal discharge averaged one point eight eight three liters per hour, the intermediate position one point eight four two liters per hour, and the distal position one point seven four five liters per hour.

The key finding from a design and performance perspective is that the magnitude of this spatial variation remained within acceptable limits throughout the system. For each lateral, the coefficient of variation calculated across the three measured emitter positions was well below ten percent, meeting the Bureau of Indian Standards criterion for good distribution uniformity. This indicates that while the pressure gradient along the lateral is unavoidable and does cause some variation in discharge, the magnitude of this variation is not so large as to compromise the overall uniformity of water application across the irrigated area. In a well-designed system, the lateral length is chosen such that the pressure variation, and hence the discharge variation, remains within acceptable bounds. The results of this study suggest that the lateral lengths and diameters selected for this system were appropriate for achieving this design objective.

4.3 Temporal Stability of Emitter Discharge

The temporal analysis of emitter discharge revealed excellent operational stability of the system across both day-to-day and within-day timescales. When discharge measurements for the same emitter position were compared across the five different observation days, the variation was remarkably small, with coefficients of variation ranging from four point one percent to seven point five percent across different positions. This low day-to-day variability indicates that the system components, including the solar panels, pump, filters, and distribution network, were operating consistently and reliably over the study period, without significant degradation in performance or intermittent failures that would cause discharge fluctuations.

The analysis of within-day variation, comparing discharge measurements taken in the morning, at noon, and in the afternoon on the same day, also showed relatively minor fluctuations, although a subtle but consistent pattern was observed in the data. For many emitter positions, discharge rates were slightly lower during the peak afternoon hours compared to the morning and late afternoon measurements. This slight dip in afternoon discharge can be attributed to several potential factors. One possibility is air entrapment within the system, which can accumulate over time and be released intermittently, causing minor pressure fluctuations. As water warms during the heat of the day, dissolved gases may come out of solution, forming bubbles that can temporarily affect flow. Temperature-induced changes in water viscosity could also have a minor effect on flow rates, as warmer water has lower viscosity and flows more easily, but this effect would be expected to increase discharge rather than decrease it, so it is not likely to be the primary explanation. Another possibility is that the solar panel output, and hence pump performance, may vary slightly throughout the day as the sun's angle changes and as cloud cover or haze intermittently reduces incoming solar radiation. While the system is designed to maintain relatively constant output across a range of solar conditions, minor fluctuations are inevitable. The fact that these fluctuations were so small, with coefficients of variation remaining well below ten percent, confirms that they do not represent any fundamental deficiency in system design or performance, and that the system as a whole is capable of delivering water with excellent temporal consistency.

4.4 System Efficiency and Applicability for Sustainable Agriculture

The results of this study collectively demonstrate that the integration of subsurface drip irrigation with boat-based solar pumping technology represents a technically viable and operationally effective approach to sustainable irrigation in riverine environments. The system achieved excellent hydraulic performance, with emitter discharge uniformity meeting or exceeding the standards prescribed by national guidelines. The spatial variation along laterals was well within acceptable limits, confirming that the hydraulic design was appropriate for the field conditions. The temporal stability of discharge across days and times of day indicates that the solar pumping system provides reliable and consistent power for irrigation, without the fluctuations in water delivery that might be expected from a variable renewable energy source.

From an energy perspective, the system operated entirely on renewable solar energy, with no consumption of fossil fuels and no associated greenhouse gas emissions. This represents a significant contribution to climate change mitigation and aligns with national and global policy goals for decarbonizing the agricultural sector. The elimination of fuel costs also has important economic implications for farmers, particularly small and marginal farmers for whom diesel expenses can represent a significant burden. While the initial capital cost of a solar pumping system may be higher than that of a diesel pump, the absence of recurring fuel costs and the long operational life of solar panels can result in favorable life-cycle economics, especially when government subsidies and other financial support mechanisms are available.

The boat-mounted floating platform design addresses the specific challenges of irrigating riverine and riparian areas, where conventional land-based pumping infrastructure is often impractical. By floating on the river, the pump remains safe from flood damage during the monsoon season, when river levels rise dramatically and land-based equipment would be submerged and destroyed. The mobility of the boat allows farmers to move along the river to access water at different locations, which can be useful for irrigating dispersed plots or for following the river as its course shifts over time. This flexibility is particularly valuable in the dynamic and changing environment of active river floodplains.

The applicability of this system extends beyond the specific context of the Burhi Gandak river to many other riverine areas in India and other countries where similar conditions prevail. The Gangetic plain, which covers a vast area of northern India and supports a large proportion of the country's population and agricultural production, is crisscrossed by numerous rivers and their tributaries, creating extensive riverine and riparian zones that could potentially benefit from this technology. The system is also relevant to other regions with similar characteristics, such as the river deltas of Bangladesh, the Mekong delta in Vietnam, and the floodplain areas of many major rivers around the world. In all these contexts, the combination of abundant surface water, limited access to reliable energy, and the need for flood-resilient infrastructure makes boat-based solar subsurface drip irrigation an attractive option for sustainable agricultural intensification.

5. CONCLUSIONS

The experimental evaluation of this innovative boat-based solar-powered subsurface drip irrigation system has produced results that are both technically informative and practically significant for the advancement of sustainable agricultural water management. Through a comprehensive field study involving forty-five systematic discharge observations across multiple laterals, emitter positions, and time periods, the research has demonstrated that such integrated systems can achieve excellent hydraulic performance, with emitter discharge uniformity meeting or exceeding the standards prescribed by national guidelines. The overall average discharge of one point eight seven six liters per hour, while lower than the nominal rated discharge of the emitters, was characterized by remarkably low spatial and temporal variability, with coefficients of variation consistently below ten percent for all comparisons. This indicates that the system delivers water with the consistency and uniformity that are essential for achieving uniform crop growth and efficient water use, even if the absolute flow rates are somewhat lower than design specifications.

The spatial analysis confirmed the expected hydraulic behavior of decreasing discharge with increasing distance from the submain, a pattern that is inevitable in any pipe distribution system due to friction losses. The magnitude of this variation, approximately thirteen percent over the length of the laterals, remained within acceptable bounds and did not compromise the overall uniformity of water application. This finding validates the design choices made in terms of lateral length, pipe diameter, and emitter spacing, and demonstrates that careful hydraulic design can effectively manage the trade-offs between system extent and distribution uniformity. The temporal analysis revealed excellent operational stability, with day-to-day and within-day variations in discharge remaining minimal and well within acceptable limits. The slight dips in discharge observed during peak afternoon hours were minor in magnitude and do not detract from the overall conclusion that the solar pumping system provides reliable and consistent power for irrigation.

The successful demonstration of this integrated system has important implications for the future of sustainable irrigation in water-stressed and energy-deficient regions. By combining the water-saving benefits of subsurface drip irrigation with the renewable energy advantages of solar pumping, and by incorporating the innovative boat-mounted floating platform design to address the specific challenges of riverine environments, this research has shown that a holistic, systems-oriented approach to irrigation development can yield practical solutions that are both environmentally sustainable and operationally effective. The system's ability to operate independently of grid electricity and fossil fuels, its resilience to flooding, and its mobility along the watercourse all contribute to its suitability for adoption by small and marginal farmers in riverine areas.

The findings of this study also highlight the importance of rigorous field-based evaluation in assessing the real-world performance of irrigation technologies. While laboratory testing and simulation modeling are valuable tools for system design and optimization, there is no substitute for actual field measurements under the variable and sometimes challenging conditions that characterize real agricultural environments. The data collected in this study provide a robust empirical foundation for understanding system behavior and for identifying opportunities for further improvement and refinement. The study also underscores the importance of appropriate system design and component selection, including the use of effective filtration to prevent emitter clogging, the proper sizing of pipes to minimize head losses, and the consideration of pressure variability in lateral design.

For policymakers, extension professionals, and development practitioners, the results of this study offer evidence-based support for promoting solar-powered micro-irrigation as a key strategy for achieving climate-resilient and resource-efficient agriculture. The integration of renewable energy with efficient water delivery technologies addresses multiple sustainable development goals simultaneously, including those related to clean energy, water efficiency, food security, and climate action. The boat-based floating platform design offers a specific solution for the vast riverine areas that have often been overlooked in irrigation development efforts, providing a pathway for bringing the benefits of modern irrigation technology to these important but challenging environments.

Future research directions building on this work could include long-term studies to assess system durability and performance over multiple years of operation, investigations of the effects of different crop types and planting densities on system design requirements, evaluations of the economic viability and social acceptability of the technology among target farming communities, and explorations of opportunities for further technological enhancements such as the integration of smart controls, soil moisture sensors, and remote monitoring capabilities. By continuing to advance both the technology and our understanding of its performance in real-world conditions, we can contribute to the development of irrigation systems that are not only more efficient and sustainable but also more accessible and beneficial to the millions of smallholder farmers who form the backbone of global food production.

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