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Impact of Solar-Powered Irrigation on Farm Economics in Haryana: A Comparative Analysis

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Abstract

The adoption of irrigation systems that use renewable energy sources has become a topical policy measure in India due to the constantly growing energy prices, unstable water supply, loss of groundwater reserves, and the growing need to establish climatic-resistant agricultural systems. The national programme schemes like PM-KUSUM have led to Solar Irrigation Pumps (SIPs), which are expected to reduce fossil fuel dependency, reduce production expenses, and increase the stability of irrigation, but organized micro-level studies of their economic effects are relatively rare, especially in states with a larger agrarian economy, like Haryana. This paper questions how solar-powered irrigation affects farm economics by contrasting between the beneficiary and non-beneficiary farmers in Haryana with greater focus being given to the cost of production of crop, crop productivity, cropping intensity, and income of the farmers. Primarily based on cross-sectional data using primary data collected on 240 farm households of 120 SIP beneficiaries and 120 non-beneficiaries, the sample of the analysis includes the major agricultural regions of the state. An explicit questionnaire was also used to obtain sufficient data on the socio-economic attributes, method of crop production, irrigation and the use of inputs, production incurred, production, and farm proceeds. To summarize the sample characteristics, descriptive statistics were employed and independent t tests were used to compare differences in the major indicators of the economy of the two groups. The findings prove that the introduction of solar irrigation significantly reduces irrigation spending and the overall cost of cultivation since it eliminates the frequent diesel and electricity spending. There is increased crop productivity and increased cropping intensity that is observed as a result of assured and timely irrigation as well as analysis also reveals statistically significant improvement in net farm income as a result of cost savings and increased crop production. Regardless of these good results, high costs of investments at the start-up level, limited access to institutional credit and inadequate maintenance and technical support facilities still hinder wider reach especially amongst small and marginal farmers.

Key words: Farm economics, Solar irrigation pumps, Agricultural productivity, Farm profitability, Cost of cultivation, Sustainable agriculture

In India, agricultural irrigation has been greatly dependent on the traditional sources of energy like diesel and grid electricity, which is subsidized and which significantly increases the costs of production, the emission of greenhouse gas, and fiscal pressures on utilities [1]. To counter these issues, solar-powered irrigation pumps (SIPs) have been proposed as an effective renewable energy, which allows farmers to supply power to irrigation without repeated debt on fuel-related expenses or grid electricity and reduce reliance on fossil fuels [2]. The significant reduction in costs of photovoltaics (PV) modules and favourable government programs have increased the adoption of SIPs in India in the last decade [3]. This strategic concern over solar irrigation in India increased with the introduction of the Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan (PM-KUSUM) in 2019. It is in this flagship scheme that millions of standalone solar pumps are expected to be installed as well as grid-connected pumps solarized in order to improve energy and water securities among farmers, lower operational costs, and reduce carbon emissions. Under the elements of Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan (PM-KUSUM), the farmers are provided with capital subsidies and financing opportunities to install solar pumps or change their current electric pumps to solar and as a result, renewable energy is closely tied with the requirements of agriculture.

The existing empirical evidence suggests that SIP adoption can significantly change the economics of farms. In Rajasthan, composing a difference-in-differences analysis showed that adopters of solar pumps had reduced both electricity and diesel consumption, more intensified cropping, and better profits in the farms by up to 41.5 percent [4]. These results present the capability of solar-powered irrigation pumps (SIPs) in enhancing the capacity of farmers with regard to income security and food production because of assured irrigation during unstable energy supply conditions. Supporting literature on economic viability also indicates that the long-term

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life-cycle costs of solar pumps can be lower than the diesel and grid systems mainly when the initial investment is higher [5].

Other than the economic variables, the solar irrigation technology is directly related to the food-energy-water nexus. Although SIPs are considered to decrease the utility of traditional fuels and decrease greenhouse gases, this policy can also result in the development of groundwater since it becomes less expensive to drill pumps, which means that water management strategies will need to be designed to be combined [4]. Therefore, the sustainability of SIP implementation is grounded on proper regulation and co-ordination with groundwater conservation activities.

Large-scale usage of SIPs among the Indian farmers is subject to a number of inhibiting factors in spite of their potential. Some of the factors that discourage the small and marginal farmers to purchase solar pumps include high initial capital outlays, complicated procedures in applying subsidies, minimal after-sales services, and lack of awareness [6]. In addition, disparities in application of state subsidies and extension systems have led to geographically disproportionate adoption levels with certain geographical areas falling behind in their adoption.

Haryana is a major agrarian state with high irrigation demands and where traditional subsidies on energy still have a major share. The inclusion of SIPs in the state is a valuable setting to analyze the impact of solar irrigation on the economics of farming particularly the cost structure, productivity and the stability of income in the household. Despite the vast potential shown in research conducted in other states, it is still premature to have regular comparative studies comparing the results of the beneficiary and non-beneficiary farmers with the help of careful statistical methods.

The paper fills this gap, and carries out a comparative analysis of farm production costs, productivity, and income about SIP beneficiaries and non-beneficiaries in Haryana. The results of the findings are expected to produce the evidence that can be used to design the policies, work out the implementation of renewable agricultural programs like PM-KUSUM, and create the plan to develop sustainable irrigation and rural developments.

MATERIALS AND METHODS

The present study was conducted in the state of Haryana, India, which is one of the leading agrarian states in the country, with agriculture being the primary source of livelihood for a majority of its population. To capture the diversity in agricultural practices, cropping patterns, and agro-ecological conditions, three districts Jind, Sirsa, and Yamunanagar were purposively selected. These districts represent different agro-climatic zones of the state and were chosen based on the maximum installation of Solar Irrigation Pumps (SIPs), ensuring that the study areas reflected active adoption of solar-based irrigation technologies. The districts vary in soil type, rainfall, and cropping intensity, providing a representative sample of Haryana's heterogeneous agricultural landscape. A district-wise map illustrating the study area was prepared to provide a visual representation of the selected sites.

Sample design and respondents

The study employed a stratified purposive sampling design. A total of 240 farmers were surveyed, with 80 respondents drawn from each district. Within each district, farmers were stratified into two categories: SIP beneficiaries (40 respondents) and non-beneficiaries (40 respondents), resulting in 120 SIP users and 120 non-users. This stratification ensured a balanced comparative framework for assessing the economic impact of SIP adoption. Farmers were included based on the following criteria: ownership or tenancy of at least one acre of agricultural land, cultivation of at least one of the selected crops, and willingness to participate in the study. Farmers who had recently switched irrigation methods or had incomplete records were excluded to maintain data reliability.

Crops considered

The study focused on five major crops widely cultivated in Haryana: Wheat, Rice, Cotton, Bajra, and Sarso (Mustard). These crops were selected to represent both food and cash crops, covering Rabi and Kharif seasons, and to assess the differential impact of SIP adoption across crop types. Information on seasonal cropping patterns, acreage, and productivity for each crop was collected to contextualize the economic analysis.

Data collection

Primary data were collected through a structured questionnaire, designed to capture detailed information on irrigation practices, cost of cultivation, crop production, gross income, and net income on a per-acre basis, facilitating meaningful comparisons across farm sizes and districts. The questionnaire was pre-tested on a small sample to ensure clarity, reliability, and relevance, and necessary adjustments were made based on feedback. Data collection was conducted through face-to-face interviews during the post-harvest period of the 2022–23 agricultural seasons. Secondary data from district agricultural offices, government reports, and published literature were used to cross-validate primary data and to provide context on crop yields, input costs, and SIP adoption trends.

Variables of analysis

The key variables considered in this study included:

- Irrigation Cost (₹/acre)
- Cost of Cultivation (₹/acre)
- Crop Production (Yield) (quintals/acre)
- Gross Income (₹/acre)
- Net Income (₹/acre)

Net income was calculated as gross income minus total cultivation and irrigation costs, including labor, seeds, fertilizers, and maintenance of irrigation infrastructure.

Hypotheses

To empirically evaluate the economic impact of SIP adoption, the following null and alternative hypotheses were formulated:

1. H_{01}: There is no significant difference in the irrigation cost between SIP and Non-SIP farmers.
   H_{11}: There is a significant difference in the irrigation cost between SIP and Non-SIP farmers.
2. H_{02}: There is no significant difference in the cost of cultivation between SIP and Non-SIP farmers.
   H_{12}: There is a significant difference in the cost of cultivation between SIP and Non-SIP farmers.
3. H_{03}: There is no significant difference in crop production (yield) between SIP and Non-SIP farmers.
   H_{13}: There is a significant difference in crop production (yield) between SIP and Non-SIP farmers.
4. H_{04}: There is no significant difference in gross income between SIP and Non-SIP farmers.
   H_{14}: There is a significant difference in gross income between SIP and Non-SIP farmers.

5. H_{05}: There is no significant difference in net income between SIP and Non-SIP farmers.
   H_{15}: There is a significant difference in net income between SIP and Non-SIP farmers.

These hypotheses were tested crop-wise, allowing a detailed assessment of the comparative advantage of solar-powered irrigation pump (SIP) adoption for each major crop.

Analytical framework and statistical tools

Data analysis was conducted using descriptive and inferential statistics. Descriptive statistics, including mean, variance, and standard deviation, were calculated to summarize the distribution of key variables. For inferential analysis, the Independent Sample t-test (two-sample assuming unequal variances) was applied to compare the mean values of SIP beneficiaries and non-beneficiaries across irrigation cost, cost of cultivation, yield, gross income, and net income at a 5% level of significance. Prior to hypothesis testing, normality and homogeneity of variance assumptions were checked to ensure the appropriateness of the t-test. All analyses were performed using SPSS.

RESULTS AND DISCUSSION

Impact of solar irrigation pumps on agriculture

This section presents the empirical results and discussion on the impact of Solar Irrigation Pumps (SIPs) on agricultural performance in Haryana. The analysis is based on crop-wise comparative t-tests between beneficiary (Solar Irrigation Pump) and non-beneficiary farmers for five major crops wheat, mustard, cotton, rice, and bajra. The key indicators examined include irrigation cost, cost of cultivation, crop production, gross revenue, and net revenue per acre.

Impact of solar irrigation pumps on wheat cultivation

Statistical results

To assess the economic and agronomic impact of Solar Irrigation Pumps (SIP) adoption on wheat cultivation, a two-sample t-test assuming unequal variances was conducted. The results (Table 1) indicate statistically significant differences across all variables.

Table 1 Comparative t-test results for wheat crop (SIP vs. Non-SIP Farmers)

Variable	SIP Mean	Non-SIP mean	t-Statistic	p-value (two-tail)	Significance	Direction of difference
Irrigation cost (₹/acre)	354.79	4752.21	-74.45	2.74E-102	Significant	SIP < Non-SIP
Cost of cultivation (₹/acre)	14,205.98	18,219.73	-18.70	3.43E-48	Significant	SIP < Non-SIP
Crop production (qtl/acre)	24.94	22.38	4.94	2.32E-06	Significant	SIP > Non-SIP
Gross revenue (₹/acre)	55,135.04	49,145.30	8.40	1.09E-14	Significant	SIP > Non-SIP
Net revenue (₹/acre)	40,929.06	30,925.57	13.61	1.31E-30	Significant	SIP > Non-SIP

Source: Author's computation from field survey data (n = 33 for each group)

SIP users incur a drastically lower irrigation cost (₹354.79/acre) compared to non-SIP farmers (₹4,752.21/acre). The total cost of cultivation is also significantly lower among SIP users (₹14,205.98 vs. ₹18,219.73 per acre). In terms of productivity, SIP users achieve higher yields (24.94 qtl/acre) than non-users (22.38 qtl/acre). Consequently, gross and net revenues are substantially higher among SIP farmers, with net income increasing by nearly ₹10,000 per acre. The results demonstrate that solar irrigation significantly reduces production costs and enhances farm profitability in wheat cultivation. The near-elimination of irrigation energy costs constitutes the major source of savings. Reliable water availability also improves crop growth and grain filling, leading to higher yields and revenues. These findings corroborate earlier studies highlighting the cost-efficiency and productivity gains associated with solar irrigation adoption [7-8].

Impact of solar irrigation on mustard (Sarso) cultivation

Statistical results

The comparative analysis in (Table 2), for mustard reveals similar patterns. Irrigation costs for SIP users are significantly lower (₹320.91/acre) than for non-SIP farmers (₹1,455.76/acre). SIP adoption reduces the total cost of cultivation by about ₹938 per acre. Productivity improves markedly, with yields rising from 899 kg/acre to 1,046 kg/acre. Gross and net revenues also show significant increases, with net income rising by approximately 23 per cent.

Table 2 Comparative t-test results for mustard (Sarso) Crop (SIP vs. Non-SIP Farmers)

Variable	SIP Mean	Non-SIP mean	t-Statistic	p-value (two-tail)	Significance (0.01 level)	Direction of difference
Irrigation cost (₹/acre)	320.91	1,455.76	-63.39	8.79×10^{-59}	Significant	SIP < Non-SIP
Cost of cultivation (₹/acre)	9,474.24	10,412.12	-3.06	0.0033	Significant	SIP < Non-SIP
Crop production (kg/acre)	1,045.76	899.39	16.45	6.74×10^{-23}	Significant	SIP > Non-SIP
Gross revenue (₹/acre)	59,085.30	50,815.76	16.45	6.74×10^{-23}	Significant	SIP > Non-SIP
Net revenue (₹/acre)	49,611.06	40,403.64	16.33	2.30×10^{-23}	Significant	SIP > Non-SIP

Source: Author's computation from field survey data (n = 33 for each group)

The findings indicate that SIP adoption enhances both cost efficiency and crop performance in mustard cultivation. Timely irrigation during flowering and pod-filling stages improves yields, while lower operational costs strengthen profitability. These results support previous evidence on renewable-energy-based irrigation improving farm income and livelihood security [9-10].

Impact of solar irrigation on cotton cultivation
Statistical results

For cotton, SIP users incur irrigation costs of only ₹318.89 per acre compared to ₹3,091.43 for non-users. The total cost of cultivation declines by more than ₹3,000 per acre. The (Table 3) shows that Yield increases by nearly 17 per cent, leading to higher gross revenue and a striking rise in net income from ₹41,903.71 to ₹56,470.74 per acre.

Solar irrigation proves economically transformative for cotton farmers. The combined effects of reduced energy expenditure and improved yields generate a 35 per cent increase in net profitability. These results confirm that Solar Irrigation Pumps (SIP) adoption can justify its capital cost, particularly when supported by subsidy schemes such as Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan (PM-KUSUM). The evidence aligns with earlier studies on decentralized solar irrigation in cotton-growing regions [11].

Table 3 Comparative t-test results for cotton crop (SIP vs. Non-SIP Farmers)

Variable	SIP Mean	Non-SIP mean	t-Statistic	p-value (two-tail)	Significance (0.01 level)	Direction of difference
Irrigation cost (₹/acre)	318.89	3,091.43	-46.94	9.03×10^{-42}	Significant	SIP < Non-SIP
Cost of cultivation (₹/acre)	22,356.30	25,525.71	-5.28	4.24×10^{-6}	Significant	SIP < Non-SIP
Crop production (qtls/acre)	11.91	10.19	4.90	8.22×10^{-6}	Significant	SIP > Non-SIP
Gross revenue (₹/acre)	78,827.04	67,429.43	4.90	8.22×10^{-6}	Significant	SIP > Non-SIP
Net revenue (₹/acre)	56,470.74	41,903.71	5.96	1.97×10^{-7}	Significant	SIP > Non-SIP

Source: Field survey data (n = 27 SIP users, n = 35 non-SIP users)

Impact of solar irrigation on rice cultivation

Statistical results

Rice cultivation exhibits the largest gains from SIP adoption. Irrigation costs decline sharply from ₹6,302.22 to ₹394.51 per acre, while cultivation costs fall by over ₹6,000 per acre. Yield increases by approximately 17 per cent, resulting in significantly higher gross and net revenues. Net income rises by nearly 45 per cent among SIP users. The results are summarized in (Table 4).

Table 4 Comparative t-test results for rice crop (SIP vs. Non-SIP Farmers)

Variable	SIP Mean	Non-SIP mean	t-Statistic	p-value (two-tail)	Significance (0.01 level)	Direction of difference
Irrigation cost (₹/acre)	394.51	6,302.22	-52.77	2.01×10^{-41}	Significant	SIP < Non-SIP
Cost of cultivation (₹/acre)	21,562.20	27,606.67	-22.46	2.86×10^{-37}	Significant	SIP < Non-SIP
Crop production (kg/acre)	2,609.27	2,225.78	14.44	3.23×10^{-23}	Significant	SIP > Non-SIP
Gross revenue (₹/acre)	78,278.05	66,773.33	14.44	3.23×10^{-23}	Significant	SIP > Non-SIP
Net revenue (₹/acre)	56,715.85	39,166.67	22.46	4.85×10^{-36}	Significant	SIP > Non-SIP

Source: Author’s computation from field survey data (n = 82 for SIP, n = 45 for non-SIP)

The strong impact observed in rice reflects the water-intensive nature of the crop. Reliable irrigation during critical growth stages such as tillering and panicle initiation reduces crop stress and enhances productivity. Economically, SIP adoption substantially strengthens income stability and resilience for rice farmers. These results strongly validate government initiatives promoting solar irrigation for high-water-demand crops [12-13].

Impact of solar irrigation on bajra (pearl millet) cultivation

Statistical results

In Bajra cultivation, SIP users incur irrigation costs of ₹310.71 per acre compared to ₹1,396.43 for non-users. Total cultivation costs decline by about ₹1,420 per acre. Yield increases by nearly 16 per cent, while net revenue rises from ₹22,451.79 to ₹28,183.93 per acre, reflecting a 25 per cent increase in profitability. (Table 5) summarizes the results.

Table 5 Comparative t-test results for bajra crop (SIP vs. Non-SIP Farmers)

Variable	SIP Mean	Non-SIP mean	t-Statistic	p-value (two-tail)	Significance (0.01 level)	Direction of difference
Irrigation cost (₹/acre)	310.71	1,396.43	-19.76	1.44×10^{-20}	Significant	SIP < Non-SIP
Cost of cultivation (₹/acre)	6,066.07	7,485.71	-3.78	0.000394	Significant	SIP < Non-SIP
Crop production (kg/acre)	1,270.00	1,097.50	9.45	4.94×10^{-13}	Significant	SIP > Non-SIP
Gross revenue (₹/acre)	34,250.00	29,937.50	9.45	4.94×10^{-13}	Significant	SIP > Non-SIP
Net revenue (₹/acre)	28,183.93	22,451.79	10.09	4.98×10^{-14}	Significant	SIP > Non-SIP

Source: Author’s computation from field survey data (n = 28 for each group)

The results indicate that SIP adoption is particularly beneficial in semi-arid Bajra-growing regions. Improved irrigation reliability enhances crop establishment and flowering, leading to higher yields and income. The findings confirm the suitability of solar irrigation as a sustainable solution for dry land cereal production [9].

Comparative synthesis across crops

Across all five crops, a consistent pattern emerges:

- Irrigation costs decline sharply for SIP users, ranging from ₹1,085 to ₹5,908 per acre.
- Total cultivation costs fall significantly; reflecting energy cost savings and improved resource efficiency.
- Crop yields increase by 11–17 percent, indicating agronomic benefits from timely and reliable irrigation.

- Gross and net revenues raise substantially, with net income gains ranging from 23 to 45 per cent.

The magnitude of impact is particularly pronounced in water-intensive crops such as rice and wheat, underscoring the importance of solar irrigation in high-irrigation-demand systems.

This inquiry provides rich empirical description of the economic implications of Solar Irrigation Pumps (SIPs), which is achieved through the comparison of beneficiary agrarian interests and non-beneficiary agrarian interests in Haryana. The salient findings distilled out of the analysis are listed below:

To begin with, there is an immediate reduction in the cost of irrigation and aggregate costs on crop-productions by beneficiary farmers due to the adoption of solar-powered irrigation systems. The die off of diesel and grid-based electricity expenditure has significantly reduced variable costs of inputs, thus increasing cost efficiency in the operations in agriculture.

Second, the beneficiary farmers are characterized by greater level of crop productivity as compared to non-beneficiaries. Due to availability and constant supply of irrigation water through the solar pumps, it has been easy to water crops in good time, manage them well and also use better cropping methods and all these have led to improved labor yields.

Thirdly, the research indicates that the income of farmers grew significantly at the beneficiaries of SIP. The accompanying decrease in energy consumption and the increase in the level of crop production have been translated into a rise in net farm returns, and this emphasizes the centrality of the solar irrigation in enhancing economic performances at the farm level.

Fourthly, assured irrigation and reduced uncertainty in operations allow beneficiary farmers to have a higher pattern of cropping intensity and diversification. This shows how the adoption of SIP has impacted positively on farm planning and risk management.

Fifth, the outcome shows that the satisfaction level of beneficiary farmers with operational cost saving, ease of use and reliability of the solar pumps is high. However, there are issues connected with maintenance services, technical assistance, and startup cost.

Lastly, the comparison study shows that although solar irrigation has a significant positive effect on the economics of the farms, not all farms have the advantage of solar irrigation. Small and marginal farmers are still facing limits with regard to the availability of capital, level of awareness and access to institutions hence they are not able to bear full fruits of the gains.

All in all, the results are supported by the fact that solar-powered irrigation is an economically efficient and productivity-theoretical technology that has large potential to foster sustainable agricultural development in Haryana.

Suggestions

Given the above findings, solar irrigation programmes are promoted with the following policy and operational recommendations in order to make them more effective and sustainable.

To begin with, the subsidy measures like PM-KUSUM need to be increased in terms of coverage and outreach with special attention being shifted towards small and marginal farmers. Complexities unavoidable in the application processes should be simplified and subsidies should be disbursed to a large extent to enhance significantly the level of adoption and equity in access.

Secondly, institutional credit facilities and novel financing arrangements also need to be strengthened. Low-cost loans, repayment options, and subsidies dependent on credit may be used to overcome the impediment of high initial investment in the installation of SIP.

Thirdly, it is necessary to establish a special system of maintenance and after sales services that will provide continuous functionality of solar pumps. By training up local technicians and strengthening extension services and developing district-level service centres, timelines will be supported and confidence to the farmers will be achieved.

Fourthly, there should be harmonious integration of SIP promotion with ground water management strategies. There is a need to introduce water-saving technologies like drip irrigation, sprinkler irrigation and an awareness program on sustainable use of water to ensure the avoidance of over extraction of groundwater.

Fifth, capacity building and awareness programmes frequent training of farmers on efficient way of operating and maintaining the solar irrigation machine, and on the long term economic and environmental advantages of solar irrigations should be conducted.

Lastly, there is a need to enhance coordination between renewable energy officials, government agencies managing agriculture, and rural financial institutions in order to have successful implementation, monitoring, and scaling-up of solar irrigation projects under the wider scope of climate resilient agricultural policies.

CONCLUSION

This paper provides the empirical evidence of the use of Solar Irrigation Pumps (SIPs) on the economic aspect in Haryana by conducting comparison of beneficiary and non-beneficiary farmers. Against the backdrop of increasing electricity prices and growing demands on the groundwater supply the results highlight the importance of solar driven irrigation to improve the farm level economic outputs in a business world. The findings confirm that adopting SIP will lead to big savings in the cost of irrigation and the overall cost of cultivating because it eliminates the constant spending on the grid electricity and diesel. Assured and reliable irrigation allows the beneficiary farmers the ability to provide timely watering, standardized crop-management techniques and produce increased crop-productively and a high cropping density. These benefits can be interpreted into statistically significant growth in farm incomes and therefore add to the economic stability of agricultural families. At the same time, the research notes that several factors, such as high start-up raised capital, institutional credit availability, and poor maintenance and technical suppliers, are major limitations that limit its scale among the small and marginal population. The results also demonstrate the need to combine solar irrigation with sustainable management of groundwater to prevent accidental environmental effects. On the whole, the research paper finds out that solar-powered irrigation is a relatively inexpensive and development-promoting intervention in advancing climate-resilient and low-carbon agriculture in Haryana. Solar irrigation will be crucial in supporting sustainable agricultural development and rural income improvement through proper policy support through the PM- KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyaan) programmes.

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