Research Article

Indian Journal of Extension Education
Vol. 62, No. 2 (April–June), 2026, (59-65)

ISSN 0537-1996 (Print)
ISSN 2454-552X (Online)

Solar-Powered Irrigation and Farm Performance: An Impact Evaluation from Kashmir Valley, India

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HIGHLIGHTS

- Diversified crops with high market value have improved, and overall plant growth has seen considerable progress since adopting solar water pumps.
- Improvements in fruit size, colour, hardness, and consistency were frequently observed by fruit farmers, particularly apple orchardists.
- A considerable reduction in farm expenditures was reported.

ARTICLE INFO

Keywords: Impact, Sustainable irrigation, Agricultural productivity, Solar water pumps, Adoption.

https://doi.org/10.48165/IJEE.2026.62210

Citation: Peer, Q. J. A., Rashid, I., Tabina, Kubrevi, S. S., Shah, I. A., & Para, I. A. (2026). Solar-Powered Irrigation and Farm Performance: An Impact Evaluation from Kashmir Valley, India. *Indian Journal of Extension Education*, *62*(2), 59-65. https://doi.org/10.48165/IJEE.2026.62210

ABSTRACT

The growing demand for energy and the rising costs of traditional irrigation methods have increased the need for sustainable options in agriculture. Solar water pumps are a practical and eco-friendly choice, especially in regions with high solar exposure like Jammu and Kashmir. According to data collected from JAKEDA (2024), a total of 1,309 beneficiaries have used solar water pumps under the PM-KUSUM scheme. The study conducted during 2025, evaluated how adopting solar water pumps affects important agricultural aspects, such as irrigation costs, crop production, crop quality, diversification, and plant growth in three selected districts, namely; Anantnag, Pulwama, and Baramulla (with a large number of functioning solar water pumps). By applying the results of the Wilcoxon signed-rank test to data collected from growers, significant differences between the conditions before and after adoption were recorded. A significant decrease in labor and diesel expenses, along with notable gains in both crop yield and quality, was found. Diversified crops with high market value have improved, and overall plant growth has seen considerable progress since adopting solar water pumps.

INTRODUCTION

Most of India's agriculture depends on regular irrigation; however, farmers face persistent challenges such as unstable power supply, rising labor costs, and increasing diesel prices. These constraints delay timely irrigation and adversely affect crop quality, productivity, and farmers' ability to diversify into higher-value crops. Consequently, sustainable irrigation practices have become increasingly important, particularly in regions such as Jammu and Kashmir, where climatic variability and fragile landscapes demand efficient water management. Effective institutional interventions must prioritise cultural sensitivity, participatory governance, and inter-agency convergence. Strengthening institutional responsiveness alongside local social networks is essential for building resilient, community-driven food systems in tribal regions (Rout et al., 2025).

Since the mid-1980s, groundwater has emerged as the dominant source of irrigation in India. During 2019–20, groundwater-irrigated area expanded from about 6 million hectares in 1950–51 to nearly 48 million hectares, accounting for over two-thirds of the country's

Received 22-01-2026; Accepted 05-03-2026

net irrigated area (MoAFW, 2022). This expansion has contributed significantly to increased cropping intensity, agricultural output, and rural employment. However, it has also raised serious sustainability concerns, including declining groundwater levels, aquifer depletion, and deterioration of water quality due to contamination and salinization

The rapid growth of groundwater irrigation has been closely linked to the electrification of agricultural pump sets, which increased from 5.13 lakh in 1965–66 to 217.99 lakh in 2019–20 (CEA, 2021). Electrification increased access to irrigation, but it also put more strain on groundwater supplies. In order to ensure inclusive and sustainable agricultural development, integrated policies that prioritize resource efficiency, human capacity building, and institutional strengthening are necessary. Evidence from Punjab demonstrates the multifaceted nature of rural livelihoods, shaped by both traditional resources and institutional factors (Yadav et al., 2026).

Solar irrigation has become more well-known as a sustainable solution to these problems. Numerous studies have looked at the factors and obstacles influencing adoption (Kumar et al., 2019) as well as its effects on irrigated area, crop patterns, productivity, and farm income (Meena et al., 2020). Initiatives like Karnataka's "Surya Raitha" program have investigated solar irrigation as a source of revenue (Durga et al., 2021). While applied and policy-oriented studies focus on operational, groundwater use, and management issues related to Solar Irrigation Pumps (SIPs) (Shah et al., 2018; Sahasranaman et al., 2021), comparative analyses of diesel and solar water pumping systems highlight the economic and environmental benefits of solar-based irrigation (Anjum, 2025; Sreedharan et al., 2020).

The significance of digital agricultural interventions is further highlighted by recent research. ICT services that are timely, pertinent, and easy to use are valued by farmers; adoption is influenced by trust and personalization. Policymakers and extension organizations can better understand farmer needs and enhance the design of advisory services by using empirically tested tools, which support evidence-based planning (Upreti et al., 2023; Paliwal et al., 2026).

METHODOLOGY

The Kashmir Valley consists of ten districts. A list of respondents who utilized solar water pumps under the PM-KUSUM program was supplied by the Jammu and Kashmir Energy Development Agency (JAKEDA). A total of 1309 respondents from all ten districts said they used solar pumps. From the current study, three districts–Anantnag, Pulwama, and Baramulla–were specifically selected because they had the highest number of program participants. An analytical and descriptive research design was used. The analytical component concentrated on the effects of the adoption, whereas the descriptive component described the intervention and its aftermath. To incorporate the results from various research channels, both primary and secondary research methods were used. In all districts, there were 1309 recipients. The current study's sample size was calculated using Slovin's formula:

$$n = N/(1+Ne2)$$

where n is the sample size (to be determined), N is the total population, and e is the error tolerance.

Assuming a 5% margin error (e=0.05), the necessary sample size was n= [1309/ {1+1309 (0.05)2}]

n = 306.377, for the current study, a total sample size of 306 was therefore required.

The data was collected in the Kashmir valley in the year 2025, having the maximum number of beneficiaries with Solar Water pumps. The study used a structured questionnaire to collect data, which measured the solar adoption process. The study assessed a range of socio-economic indicators to capture the demographic, economic, and agricultural dimensions of respondents. The key variables included: Age, Family type, Family size, Marital status, Education level, Annual income, Total landholding, Farming experience, Source of irrigation, Access to drinking water and sanitation, Ownership of agricultural implements and Cropping intensity. The study used multi-stage sampling and data processing, and a reliability test was carried which required them to clean the data set by fixing the missing values and resolving the errors. Spreadsheets and statistical software (MS Excel and SPSS) were used to code and analyse the data gathered from the field survey. As explained below, a mix of descriptive and inferential tools were used.

Descriptive statistics, including frequencies, percentages, means, and standard deviations, were used to summarise socio-economic characteristics of respondents. To determine whether there were any significant differences between the two related samples before and after the solar water pump was implemented, the Wilcoxon signed rank test was employed. This non-parametric test was chosen because the data did not have a normal distribution. By comparing the population mean ranks of paired observations, the test ascertains whether they differ. Data were analysed using descriptive and inferential statistics. To test whether the SWP usage significantly alters farm expenses and production outcomes, the Chi-square test was applied.

RESULTS

Impact of solar water pumps on agricultural productivity parameters

People who had installed solar water pumps were asked to report on the state of certain indicators (crop yield, crop quality, crop diversification, plant development, and labour and diesel costs) both before and after the installation. A three-point directional scale with the options of increase, decrease, and no change to measure each indicator was used. The answers were coded and put into pairs of before-and-after datasets for each agricultural parameter. Directional changes were transformed into ordinal differences, allowing for a meaningful comparison of conditions before and after solar pump installation. The Wilcoxon Signed Ranks Test was then performed to determine whether the observed shifts were statistically significant.

Impact of solar water pumps on crop yield

The findings in Table 1 analysed the impact of solar water pump installation on crop yield through a before-and-after comparison. The Wilcoxon Signed Ranks Test revealed a strong and statistically significant increase in crop yield following the adoption

Table 1. Wilcoxon Signed Ranks Test – Crop Yield (Before vs After Solar Water Pump Installation)

Comparison	Category	N	Mean Rank	Sum of Ranks
Crop Yield (After–Before)	Negative Ranks	0[a]	0.00	0.00
	Positive Ranks	268[b]	134.50	36,046.00
	Ties	38[c]	-	-
	Total	306		
a: Negative Ranks: Crop yield after installation < crop yield before installation				
b: Positive Ranks: Crop yield after installation > crop yield before installation				
c: Ties: Crop yield after installation = crop yield before installation				
Z-value		–15.231		
Asymptotic Significance (2-tailed)(p-value)		0.000		

of solar water pumps. There were 268 positive ranks and no negative ranks, which shows that all but 38 respondents said their crop yield improved after installation. There were also 38 cases where there was no change.

The Z-value (–15.231) and the very significant p-value ($p < .001$) showed that the increase in crop yield was not just random chance. This strong positive shift suggested that access to reliable and timely irrigation enabled by solar water pumps substantially enhanced crop productivity. Farmers were probably able to water their crops at important growth stages thanks to better access to water, which led to higher overall yields.

Impact of solar water pumps on crop quality

Table 2 shows the results of changes in crop quality after installing a solar water pump. The findings indicated a strong and statistically significant improvement in crop quality after the intervention. 271 people said that the quality of their crops got better, while none said it got worse and 35 said it stayed the same.

The Wilcoxon Signed Ranks Test yielded a Z-value of –15.310 (Table 2) and a p-value of less than .001, validating the significance of this enhancement. The results suggested that consistent and sufficient irrigation made possible by solar pumps led to healthier crops, better grain or produce formation, and higher overall quality. Better water management may have made plants less stressed and more uniform, which could have led to better outputs.

Impact of solar water pumps on crop diversification

Table 3 provides a summary of how the use of solar water pumps affects crop diversification. Diversification, in contrast to yield and quality, increased moderately but statistically significantly. 143 respondents said that diversification had increased, 7 said it had decreased, and 156 said it had not changed.

The Wilcoxon test result ($Z = -11.104$, $p <.001$) verified that the overall change was statistically significant in spite of the ties (Table 3). This implied that some farmers were able to diversify into other or water-intensive crops thanks to access to solar-powered irrigation, though other factors like market access, risk tolerance, and land availability may also play a role. The findings showed that, despite their slow adoption, solar water pumps offer chances for diversification.

Table 2. Wilcoxon Signed Ranks Test – Crop Quality (Before vs After Solar Water Pump Installation)

Comparison	Category	N	Mean Rank	Sum of Ranks
Crop Quality (After – Before)	Negative Ranks	0[a]	0.00	0.00
	Positive Ranks	271[b]	136.00	36856.00
	Ties	35[c]	-	-
	Total	306		
a: Negative Ranks: Crop quality after installation < crop quality before installation				
b: Positive Ranks: Crop quality after installation > crop quality before installation				
c: Ties: Crop quality after installation = crop quality before installation				
Z-value		–15.310		
Asymptotic Significance (2-tailed)(p-value)		0.000		

Table 3. Wilcoxon Signed Ranks Test – Crop Diversification (Before vs After Solar Water Pump Installation)

Comparison	Category	N	Mean Rank	Sum of Ranks
Crop Diversification (After – Before)	Negative Ranks	7[a]	75.50	528.50
	Positive Ranks	143[b]	75.50	10796.50
	Ties	156[c]	-	-
	Total	306		
a: Negative Ranks: Crop diversification after installation < crop diversification before installation				
b: Positive Ranks: Crop diversification after installation > crop diversification before installation				
c: Ties: Crop diversification after installation = crop diversification before installation				
Z-value		–11.104		
Asymptotic Significance (2-tailed)(p-value)		0.000		

Table 4. Wilcoxon Signed Rank Test – Plant Development (Before vs After SWP Installation)

Comparison	Category	N	Mean Rank	Sum of Ranks
Plant Development (After – Before)	Negative Ranks	0[a]	0.00	0.00
	Positive Ranks	270 [b]	135.50	36585.00
	Ties	36[c]	-	-
	Total	306		
a: Negative Ranks: Plant development after installation < plant development before installation				
b: Positive Ranks: Plant development after installation > plant development before installation				
c: Ties: Plant development after installation = plant development before installation				
Z-value		-15.294		
Asymptotic Significance (2-tailed) (p-value)		0.000		

Table 5. Wilcoxon Signed Ranks Test – Labour and Diesel Costs (Before vs After SWP Installation)

Comparison	Category	N	Mean Rank	Sum of Ranks
Labour and Diesel Costs (After – Before)	Negative Ranks	280 [a]	140.50	39340.00
	Positive Ranks	0 [b]	0.00	0.00
	Ties	26 [c]	-	-
	Total	306		
a: Negative Ranks: Labour and diesel costs < Labour and diesel costs before installation				
b: Positive Ranks: Labour and diesel costs after installation > Labour and diesel costs before installation				
c: Ties: Labour and diesel costs after installation = Labour and diesel costs before installation				
Z-value		-16.074		
Asymptotic Significance (2-tailed) (p-value)		0.000		

Impact of solar water pumps on plant development

The findings shown in Table 4 investigate how plant development is impacted by the installation of solar water pumps. Plant development improved significantly and statistically after solar water pumps were installed, according to the Wilcoxon Test. 36 respondents indicated no change, while 270 of the 306 respondents reported a positive shift in plant development, as evidenced by 270 positive ranks and no negative ranks.

The observed improvement in plant development was confirmed to be statistically significant and not the result of random variation by the Z-value (–15.294) and the highly significant p-value (p <.001) (Table 4). This outcome demonstrates how well solar water pumps promote plant growth, probably by offering a steady and dependable water supply that promotes healthy plant development, particularly during crucial growth stages.

Impact of solar water pumps on labour and diesel costs

The comparison of the labour and diesel costs associated with irrigation before and after the intervention is shown in Table 5. This factor revealed a significant reduction after the installation of solar water pumps, unlike the productivity measures. Out of the total, 280 farmers reported a reduction in the cost, 26 did not experience any changes, and no farmer faced any increase.

The result from the Wilcoxon Signed Ranks test gave a Z-statistic of -16.074 with p<0.001, indicating a highly significant decrease in operational costs (Table 5). This was attributed to the elimination or reduction in the use of diesel fuel and the minimized human labor needed to run solar-powered water pump systems. The significance of solar water pumps and their impact on harnessing solar power was exhibited in their ability to make water pump operations more cost-effective and less dependent on conventional forms of power.

Economic and production-related outcomes of solar water pump adoption in the study area

Based on Table 6, the information indicates that out of the 306 respondents, 69.3% noticed a considerable reduction in farm expenditures, whereas 27.5% noticed a slight reduction in farm expenditures following the installation of SWPs. Irrigation sessions per week improved for 94.8% of the respondents. Crop performance for the large number of respondents improved, where 61.1% noticed

Table 6. Impact of solar water pump usage-economic and production-related outcomes of solar water pump.

Response Category	Percentage
Impact on monthly farm expense	
No change	3.3
Reduced slightly	27.5
Reduced significantly	69.3
Total	100.0
X^2	148.62
p	0.000
Frequency of irrigation increased after SWP	
No	5.2
Yes	94.8
Total	100.0
X^2	241.75
p	0.000
Impact of SWP on crop	
No impact	4.6
Improved slightly	34.3
Improved Significantly	61.1
Total	100.0
X^2	132.48
p	0.000

Table 6 contd...

Response Category	Percentage
Impact on soil moisture	
Decreased	18.6
No change	10.1
Increased	71.2
Total	100.0
X^2	156.90
p	0.000
Impact on availability of irrigation	
Decreased	3.6
No change	13.7
Increased	82.7
Total	100.0
X^2	186.43
p	0.000
Has SWP lead to cultivate additional crops	
No	31.0
Yes	69.0
Total	100.0
X^2	56.78
p	0.000
Has SWP reduced dependency on rainfall	
No	5.9
Yes	94.1
Total	100.0
X^2	249.67
p	0.000
Impact on annual income	
No impact	3.9
Improved slightly	32.7
Improved Significantly	63.4
Total	100.0
X^2	138.92
p	0.000
Do you feel financially secure after adopting SWP	
No	7.2
Yes	92.8
Total	100.0
X^2	232.41
p	0.000
Did installation of SWP influence your decision to invest more in agriculture	
No	12.4
Yes	87.6
Total	100.0
X^2	180.56
p	0.000

considerable improvement, whereas 34.3% noticed slight improvement with chi-square values of 148.62, 241.75, 132.48, respectively and p value of 0.000. Conditions in the soil moisture were favourable for 71.2% of the farmers, with irrigation availability increased for 82.7%. Moreover, an increased percentage of farmers at 69% could grow supplemental crops, while 94.1% of the farmers could depend less on rainfall with chi-square values of 156.90, 186.43, 56.78 and 249.67, respectively and p value of 0.000.

Adoption of SWP practices was also important in increasing financial well-being, with 63.4% of farmers experiencing a significant increase in yearly income, while 92.8% of respondents felt financially secure. Moreover, 87.6% of farmers found that other farmers have been encouraged to invest more in agriculture, which shows that irrigation services have encouraged farmers to invest in agri-business with chi-square of 138.92 and 232.41, respectively and p-value of 0.000.

DISCUSSION

The high improvement in agricultural output, as indicated by most of the respondents, was a key finding. Most of the farmers depended on either rainfall or seasonal water sources, which would often dry up during the peak seasons for irrigation but later depended on solar water pump technologies. During critical stages of plant phenology, water stress would, therefore, be experienced, eventually hampering crop performance. With the aid of solar water pump technologies, farmers could, therefore, be able to enjoy an uninterrupted and reliable water supply source for the whole planting season. It is, however, widely accepted that water availability, through its ability to regulate soil moisture, promote nutrient uptake, and relieve physiological stress, remains one of the most critical determinants of agricultural productivity (FAO, 2016). This finds support from the statements offered by the respondents, who indicated that the continuous water supply increased agricultural output. According to a number of studies, including those by Burney et al. (2010), Hossain et al. (2014), Campana et al. (2015), and Ali et al. (2016), solar irrigation allows farmers to switch from shortfall irrigation to a secured water supply, which greatly boosts crop yields and cropping intensity.

The respondents also reported improvements in plant development and crop quality. Improvements in fruit size, color, hardness, and consistency were frequently observed by fruit farmers, particularly apple orchardists. This is consistent with well-established horticultural research showing that fruit quality characteristics including cell expansion, sugar accumulation, and color development are much improved when ideal moisture conditions are maintained during flowering and fruit-set stages. Timely and even irrigation improved marketable quality for growers of vegetables and paddy by reducing deformities and physiological abnormalities. These results verify that solar irrigation raises the market value of products in addition to increasing output volume. Reliable irrigation with solar pumps increases crop quality by boosting plant vigor and uniformity. The findings are in line with those of Hossain et al. (2014), Campana et al. (2015) and Ali et al. (2016). Recent research supports that maintaining optimal moisture during flowering and early fruit-set enhances fruit quality traits. Controlled irrigation and moderate water stress at key developmental stages improve sugar accumulation, size, and coloration in apples (Tao et al., 2023; Ananthakrishnan et al., 2025).

Additionally, a moderate but considerable increase in crop diversification was shown by the data. The positive trend is consistent with empirical findings that irrigation security encourages farmers to diversify into high-value crops, horticulture, and multi-cropping systems, even though the degree of diversification was less noticeable (than improvements in yield or plant development)

(Kumar et al., 2022). However, market access, land availability, agronomic knowledge, and farmers' risk preferences all have an impact on diversity in addition to irrigation; these factors may account for the increase in diversification, albeit not to the same degree as other factors. Therefore, different farmer diversification trends are consistent with global results that diversity is not entirely driven by irrigation technology alone. Amede (2014) and Hossain et al. (2014) reported similar results.

The sharp decline in labour and diesel prices was one of the biggest effects of solar water pump adoption. The decrease in these operating costs was statistically significant and practically significant. Previous research by Rana et al. (2021), Guno and Agaton (2022), Jovanoviæ et al. (2023), and Upadhyay et al. (2024) demonstrates that solar irrigation systems significantly lower operational costs, enhancing net farm revenue and long-term economic outcomes. The substantial cost savings also enhanced financial stability for small and marginal farmers, who are disproportionately affected by rising fuel prices. The study supports the findings of IRENA (2020), which said that farmers are encouraged to increase cultivated areas, diversify crops, and use modern inputs when irrigation reliability is increased.

CONCLUSION

The Wilcoxon Signed Rank Test results show that the installation of solar water pumps led to significant improvements in key agricultural parameters. Large negative z-scores with p-values of 0.000 for labour and diesel costs, agricultural output, productivity, diversification, and overall growth confirm highly significant differences between pre- and post-adoption conditions. Unfavourable ranks for labour and diesel expenses indicate substantial reductions in operational costs, while positive ranks for agricultural output, crop quality, and plant growth reflect notable gains in production. Positive diversification ranks further suggest that access to low-cost and reliable irrigation encouraged crop diversification. Overall, the findings confirm that solar water pumps enhance agricultural performance by reducing costs and improving productivity, making solar irrigation an economically viable technology for farmers.

DECLARATIONS

Ethics approval and informed consent: Informed consent was sought from the respondents and their organisations regarding the study during the course of the data collection.

Conflict of interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that during the preparation of this work, they thoroughly reviewed, revised, and edited the content as needed. The authors take full responsibility for the final content of this publication.

Acknowledgements: The authors express sincere gratitude to the Indian Council of Social Science Research (ICSSR) vide file No.: 32/2024-25/SES/GEN/RP/ICSSR for providing the financial support and academic encouragement necessary for undertaking this research project. We deeply appreciate the support of Jammu and Kashmir Energy Development Agency (JAKEDA) and their invaluable cooperation and supplying the essential data that significantly contributed to the progress of this study. The authors extend their appreciation to the Division of Agriculture Extension and Communication, Faculty of Agriculture, SKUAST-Kashmir for providing crucial research-related documents, guidance and support that strengthened the quality and depth of this work. Their assistance has been instrumental in the smooth execution and completion of the project.

Data availability: The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. Due to ethical considerations and farmer privacy concerns, individual-level data cannot be made publicly available. Aggregated data and analysis codes are available upon request for research purposes subject to appropriate data use agreements.

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