DETERMINANTS OF SOLAR WATER PUMPING SYSTEM ADOPTION AMONG FARMERS: A FACTOR ANALYSIS APPROACH

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ABSTRACT

Renewable energy technologies have become increasingly important in agriculture, especially in the regions experiencing energy insecurity and groundwater shortages. This study examines the key factors influencing the adoption of solar water pumping systems (SWPS) among farmers in West Bengal, India, a state with high solar potential. A total of 150 farmers has been interviewed to collect data on their adoption of SWPS. Factor analysis was employed using IBM SPSS software for the analysis. In the study, three main factors were identified as contributing to adoption behavior: institutional support, economic benefits, and technical benefits, which together explained over 62.483 percent variance in adoption behavior. Integrated policies are needed that combine financial incentives, capacity building, and technical support to encourage equitable and widespread adoption of solar irrigation. This study offers valuable insights to policymakers, development agencies, and stakeholders working to enhance energy access, promote climate-resilient agriculture, and accelerate the transition to green energy.

Keywords: Solar water pumping system; Technology adoption; Institutional support; Sustainable agriculture; West Bengal.

JEL codes: Q01; Q56; O14; O13

INTRODUCTION

India, as an agrarian economy, finds itself in a double bind, as it must promote sustainable agricultural practices amid dwindling groundwater resources and increasing energy demand. Given that over 80% of extracted freshwater is used in agriculture, which accounts for 30–40% of electricity usage, innovation in the use of water and energy is crucial (Goel et al., 2022; Verma et al., 2018). Solar water pumping systems (SWPS) have evolved as an efficient alternative to grid-powered or diesel-based irrigation, providing a localized, renewable source for groundwater extraction (Fathima M.S. et al., 2023; Sathish Kumar et al., 2024). The move towards solar-powered agriculture worldwide is being driven by factors such as environmental concerns, rising fuel costs, and government subsidies (Bouaguel & Alsulimani, 2022; HADOUGA, 2023). There are schemes at the centre and state levels supporting SWPS adoption in India, providing 60% subsidies (Manimaran, 2025). Programs like the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme plan to install 2 million standalone solar pumps, aiming to make farmers self-reliant in terms of energy. There are also differences in adoption rates across the country, even though mobilized by policies due to socio-economic and infrastructural disparities (Varbanov et al., 2021; Yasmeen et al., 2023). In the high and largely smallholder-dominated farming state of West Bengal, with erratic electricity supply, the potential of SWPS is high. There are 2,200 to 2,800 sunshine hours in a year, and therefore, solar irrigation is technically viable (Kumar M et al., 2024). Adoption in the Sundarbans and other remote areas has transformed irrigation, particularly through the use of solar-powered drip systems (Das et al., 2024; Goel et al., 2022). Nevertheless, the overall uptake is low due to the upfront cost, limited awareness, and fragmented landholdings (Agrawal & Jain, 2019; Bwalya et al., 2023; Yadav et al., 2023). Factors influencing adoption are multifaceted. Some of the economic contributions include low operating costs, flexible credit schemes, and selling excess energy (Kar et al., 2024; Zhou & Abdullah, 2017). At the same time, non-economic factors such as awareness, education, trust in technology, and extension services are also extremely important (Asif et al., 2022; Sommerfeld & Buys, 2014). The policy implemented by governments in states such as Gujarat, combined with institutional trust, led to strong adoption of the Suryashakti Kisan Yojana (SKY) program (V. Kumar et al., 2020; Varshney et al., 2024). These can inform similar interventions in

West Bengal. Considering the important role of SWPS in sustainable rural electrification and climate-resilient agriculture, this research seeks to outline the determinants of the adoption of SWPS among farmers in West Bengal. It will utilize a multi-dimensional framework to analyze economic, social, environmental, and policy-related factors. The results will guide policymakers and stakeholders in charting effective solar irrigation strategies with an eye to achieving equitable access and sustained uptake in the agroecological zones of West Bengal.

REVIEW OF LITERATURE

The shift to sustainable economy and sustainable agricultural practices has fueled international interest in renewable energy-based features, including irrigation technologies, especially the solar water pumping system (SWPS) (Gatto et al., 2025) (Bala et al., 2025; Gatto & Nuta, 2024; Geng et al., 2025; A. C. Nuta, 2024; NuȚă, 2025). These systems are gaining ground as critical tools for reducing dependency on fossil fuels, mitigating greenhouse gas emissions, and enhancing irrigation reliability among smallholder farmers. In the Indian context, particularly in West Bengal, the factors influencing the adoption of SWPSs are complex and multidimensional, encompassing socio-economic, environmental, technical, and institutional aspects. India's adoption trends exhibit significant geographic disparities. A full-scale evaluation (P. Kumar et al., 2024) emphasized that, despite policy efforts, widespread adoption has been achieved in only a few states, such as Gujarat, primarily due to sustained subsidies and technical support. Several studies outline the leading role of awareness and education. Knowledge dissemination and extension services have a direct bearing on the adoption rate (Sommerfeld & Buys, 2014). Similarly, digital literacy and training can significantly improve system usability among rural farmers (Yadav et al., 2023). In West Bengal, the situation is nuanced. The state receives over 2,500 hours of annual sunlight, suggesting favorable climatic conditions for solar irrigation (Sarkar & Modak, 2024; Sathish Kumar et al., 2024). Nevertheless, to replicate Gujarat's model, substantial policy changes are required (Powell et al., 2021). Economic factors play a significant role in the adoption of solar water pumping systems. The high costs associated with initial investment and concern about affordability continue to be significant barriers for small landholding farmers (Powell et al., 2021; Zhou & Abdullah, 2017) (Cao et al., 2024; A. C. Nuta, 2025). There are also substantial challenges associated with the lack of financing, which limits access to credit for farmers (Atulkar, 2022). In contrast, environmental benefits serve as strong incentives that act as a powerful motivator, especially in areas facing water scarcity challenges. SWPS can contribute to groundwater sustainability when combined with effective water management practices (Datta, 2019; Shah et al., 2018). There is also a need for integrating solar pumping into broader water governance frameworks to avoid over-extraction (P. Kumar et al., 2024). Technical aspects such as system reliability and access to support services are crucial. Issues like design mismatches and limited maintenance infrastructure often deter adoption (Manimaran, 2025), and user satisfaction with system performance significantly affects continued use (Bouaguel & Alsulimani, 2022). Government initiatives such as PM-KUSUM have been instrumental. The scheme offers a subsidy of up to 60%; however, its uptake in West Bengal remains low due to bureaucratic delays and a lack of localized policy support (Anjanappa et al., 2023; Schuller, 2024). Aligning central schemes with regional implementation frameworks could bolster success (Kumar M et al., 2024). Social capital and community engagement also play a significant role. Trust in local institutions and peer influence are crucial enablers (Irfan et al., 2021), as is participatory design in successful SWPS projects (Asif et al., 2022). Emerging technologies are poised to enhance adoption potential (Abban et al., 2025) (F. Nuta et al., 2024; Tiwari et al., 2025). Integration of IoT for real-time monitoring (Sunny et al., 2023), and AI-enhanced irrigation schedules using local meteorological data (Ercan Oğuztürk et al., 2025; Kim & AlZubi, 2024), offer promising advancements. The adoption of SWPS in West Bengal is contingent upon harmonizing economic feasibility, institutional support, farmer training, and local engagement. Effective implementation will depend on policy customization, robust service delivery, and sustained awareness programs tailored to regional needs.

METHODOLOGY

Data

The aim of this study is to identify the factors that are responsible for the adoption of SWPS among farmers in West Bengal. Several factors contribute to SWPS's adoption worldwide. Identifying the factors behind the adoption of SWPS in a region-by-region manner will help policymakers make informed decisions. In several areas of West Bengal, 150 farmers have been interviewed to identify which of them have adopted SWPS. In various regions of West Bengal, approximately 1,500 farmers were identified as potential participants in this study through a preliminary analysis conducted earlier. Simple random sample techniques were employed to collect the data, and then the sample size was fixed based on the statistical test with a 95% confidence level. A reliability test was conducted, which reduced the total of 24 variables into a subset of variables suitable for applying the factor analysis technique. This factor analysis was conducted using IBM SPSS software. To extract the factor from the six variables that remained after the reliability test, Principal Component Analysis (PCA) with Varimax Rotation was performed. The factor with eigenvalues greater than one was retained based on the scree plot and explained variance.

METHODS

Factor analysis

Factors influencing farmers in West Bengal were identified by conducting factor analysis. Similar to multiple analysis, variables are represented as linear combinations of underlying factors in this factor analysis. The percentage of variance each variable shares is called commonality. Several common factors contribute to the covariance between variables, while a unique factor is responsible for the covariance between each variable. There is no overt observation of these factors. A factor model based on standardized variables would look as follows (Atulkar, 2022; M. et al., 2025).

$$Xi = Ai1F1 + Ai2F2 + Ai3F3 + \dots + Aim\ Fm + Vi\ Ui \quad \dots\dots\dots\dots (1)$$

Where

Xi = i^{th} standardized variable

Aij = standardized multiple regression coefficient of variable i on common factor j

F= common factor

Vi= standardized regression coefficient of variable on unique factor i

Ui= the unique factor for variable i

m= number of common factors

Factors that are unique are not related to one another or to factors that are common. If there are common factors among the observed variables, then a linear combination of these variables can help describe them.

$$Fi = Wi1X1 + Wi2X2 + Wi3X3 + \dots + Wik\ Xk \quad \dots\dots\dots\dots (2)$$

Where

Fi = estimate of i^{th} factor

Wi = weight or factor score coefficient

k = number of variables

RESULTS AND DISCUSSION

Socioeconomic characteristics of solar farmers in West Bengal

Factors responsible for the adoption of solar water pumping systems in West Bengal were identified using factor analysis. The data is derived from 150 farmers who adopted solar water pumping systems. Table 1 shows a summary of the socio-economic profile of farmers.

According to Table 1, the majority of solar farmers are between the ages of 36 and 50. As far as education is concerned, most of the farmers have completed secondary and higher secondary education. Most of the farmers earn between ₹1,00,001 and ₹5,00,000 per year. Farmland ownership in the study area ranges from 2.01 to 4.00 hectares. The adoption of solar water pumping systems was strongly correlated with education, age, income, and land ownership among farmers.

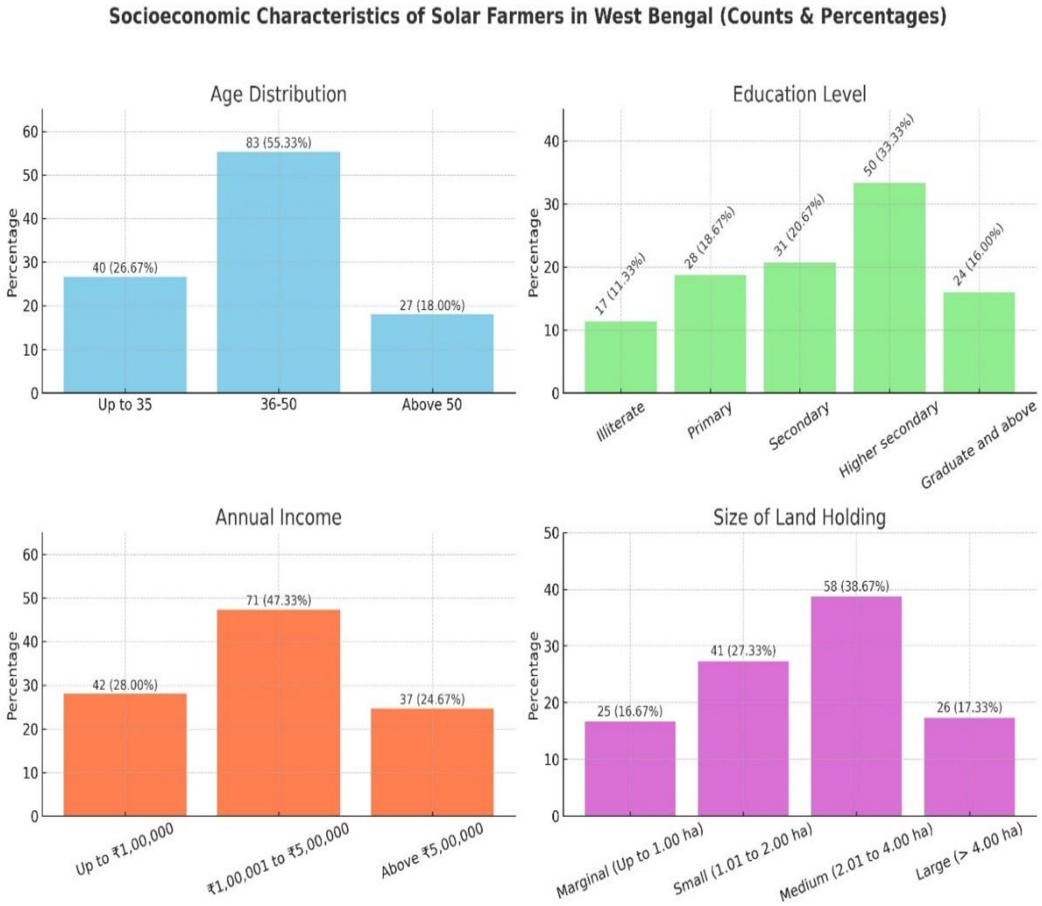

Fig. 1. Socioeconomic characteristics of solar farmers in West Bengal (n=150)

Result of factor analysis

A variable considered in this study is listed in Table 1 to provide clarity to the readers.

Table 2 Variables under consideration for this study

S. No	Variables
1	Banks and cooperatives offer credit facilities for the installation of solar pumps.
2	Farmers perceive solar pumps as a financially sustainable solution.
3	Solar pumping is suitable for shallow and medium-depth water tables.
4	Farmers who attended training sessions are more likely to adopt solar pumps.
5	Adoption of solar pumps contributes to sustainable agriculture.
6	Technological improvements have increased the efficiency of solar pumps.
7	Local agriculture departments and NGOs provide training and awareness.
8	In areas with erratic electricity, solar pumps ensure timely irrigation.
9	Peer influence plays a significant role in the adoption of technology.
10	Solar pumps reduce dependency on fossil fuels for irrigation.
11	Solar pumps are easy to operate and require less technical knowledge.
12	Irrigation efficiency improves with continuous water availability.
13	Solar pumps reduce the recurring cost of diesel or electricity for irrigation.
14	Availability of after-sales service influences adoption decisions.
15	Awareness programs have increased knowledge about the benefits of solar pumps.
16	Use of solar energy is perceived as environmentally friendly.
17	Assistance with installation and maintenance encourages adoption.
18	The system works reliably even with fluctuating sunlight conditions.
19	Long-term savings on fuel and repairs offset the high initial investment.
20	Solar pumps provide a reliable water source during critical stages of crop growth.
21	Government schemes and subsidies make solar pumps affordable.
22	Farmers are aware of the benefits of renewable energy in mitigating climate change.
23	Success stories in nearby villages increase confidence in solar technology.
24	Government subsidies improve the economic viability of solar pumps.

As a result of the reliability test, 24 variables were reduced to 6 variables in order to identify a smaller number of identifiable groups. Before conducting a factor analysis of the data collected from farmers, a reliability test was performed to verify the validity of the data collected by the researchers.

Table 2. KMO and Bartlett's Test of Influencing Factors

Kaiser- Meyer-Olkin Measure of Sampling Adequacy		.551
Bartlett's Test of Sphericity	Approx. Chi-Square	34.509
	Df	15
	Sig.	0.003

As shown in Table 2, the KMO value of 0.551 indicates that the sample size and factor analysis used in this study were appropriate. A significance value of 0.003 indicated that Bartlett's test rejected the hypothesis. There is a correlation between the means of the variables and factors, which makes it appropriate to perform a factor analysis.

Table 3 Influencing factors to adopt the solar water pumping system communalities

Description	Initial	Extraction
Availability of after-sales service influences adoption decisions.	1.000	.572
Banks and cooperatives offer credit facilities for the installation of solar pumps.	1.000	.598
Solar pumps reduce the recurring cost of diesel or electricity for irrigation.	1.000	.693
Farmers perceive solar pumps as a financially sustainable solution.	1.000	.479
Solar pumps are easy to operate and require less technical knowledge.	1.000	.738
Government schemes and subsidies make solar pumps affordable.	1.000	.669

In the presence of multiple variables with low communalities (less than 0.5) it has been found that disproportionately more factors are identified when these variables are combined together. Interestingly, no variables had a communality score of less than 0.5 in Table 3. Therefore, even in the most ideal circumstances, these variables could be identified.

As a rule of thumb, factor eigenvalues are calculated by adding up the squared loadings of each factor. The strength of eigenvalues is often used as a means of selecting the number of factors to be extracted from an analysis, a standard method for determining the optimal number of factors. When the value of the eigenvalue (I) is greater than or equal to 1, significant results can be obtained. To extract factors, the varimax rotation method has been employed.

Table 4: An eigenvalue-based factor analysis to extract the principal components

Total Variance Explained

	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1.509	25.158	25.158	1.509	25.158	25.158	1.347	22.443	22.443
2	1.185	19.745	44.902	1.185	19.745	44.902	1.244	20.734	43.177
3	1.055	17.580	62.483	1.055	17.580	62.483	1.158	19.306	62.483
4	.827	13.777	76.259						
5	.740	12.332	88.592						
6	.684	11.408	100.00						

Extraction Method: Principal Component Analysis.

Table 4 presents the results of the factor analysis, based on the eigenvalues derived from the eigenvalue matrix. The percentage of variance explained refers to the extent to which a specific variable accounts for variance in relation to all variables. To describe a phenomenon effectively, all its aspects must be taken into consideration. Figure 1 shows the scree plot diagram of factors with eigenvalues exceeding one.

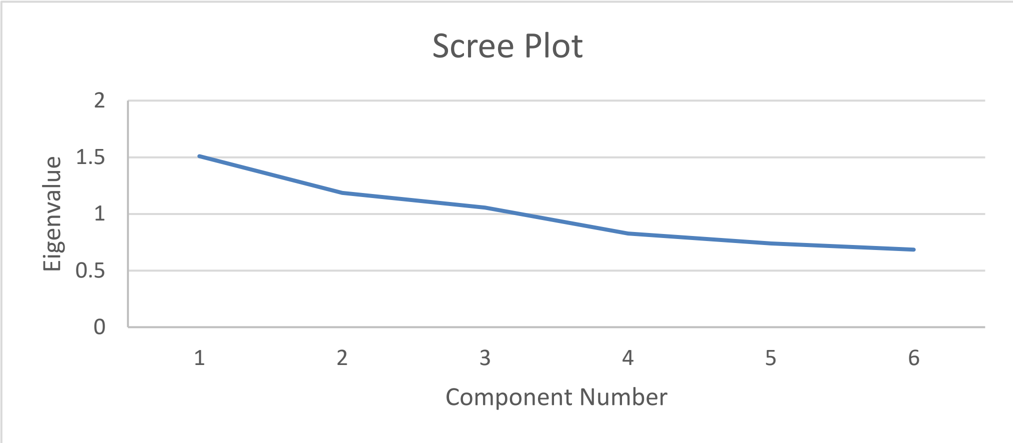

Fig.2. Scree Plot

As a result of factor analysis of the data, three factors explained 62.483% of the variance found in the attitudes of farmers who adopted solar water pumping systems in West Bengal. Factors are included in the number of factors extracted if the Eigenvalue exceeds one.

An explanation of the correlation between variables and factors can be found in factor matrices. Factor loading indicates the correlation between variables and factors. If a coefficient has an absolute value of more than one, there is a close relationship between the factor and the variables. The factors were described based on the coefficients of the factor matrix.

Table 5 Rotated component matrix

Description	**1**	**2**	**3**	**Factors**
Government schemes and subsidies make solar pumps affordable.	**.791**			**Institutional Support**
Banks and cooperatives offer credit facilities for solar pump installation.	**.716**			
Solar pumps reduce the recurring cost of diesel or electricity for irrigation.		**.829**		**Economic Benefits**
Farmers perceive solar pumps as a financially sustainable solution.		**.524**		
Solar pumps are easy to operate and require less technical knowledge.			**.826**	**Technical Benefits**
Availability of after-sales service influences adoption decisions.			**.654**	

Extraction Method: Principal Component Analysis., Rotation Method: Varimax with Kaiser Normalization., a. Rotation converged in 3 iterations

Considering Table 5, it is evident that the first factor has been loaded onto two variables: government schemes and subsidies that make solar pumps affordable (0.791) and Banks and cooperatives offer credit facilities for solar pump installation (0.716). These two variables are grouped under one factor titled "**Institutional Support".** The first factor accounts for 22.443% of the variance in explaining the adoption of solar water pumping systems by farmers in West Bengal. A second factor included two variables: Solar pumps reduce the recurring cost of diesel or electricity for irrigation (0.829), and Farmers perceive solar pumps as a financially sustainable solution (0.524). These two variables were grouped under the category of "Economic Benefits." Consequently, this second factor accounted for 20.734% of the variance in factors contributing to the adoption of solar water pumping systems by farmers in West Bengal. A third factor included two variables: Solar pumps are easy to operate and require less technical knowledge (0.826), and the availability of after-sales service influences adoption decisions (0.654). These two variables were grouped under the category of "Technical Benefits." Consequently, this third factor accounted for 19.306% of the variance in factors contributing to the adoption of solar water pumping systems by farmers in West Bengal. A study found that Institutional Support contributed the most to the adoption of solar water pumping systems, accounting for a 22.443 percent variance, followed by Economic Benefits, which accounted for a 20.734 percent variance, and Technical Benefits, which accounted for a 19.306 percent variance. A significant factor contributing to the adoption of solar water pumping systems was institutional support, as it was the primary reason farmers adopted these systems, driven by subsidies and the PM-KUSUM scheme. Banks and financial institutions played a key role in supporting farmers by offering low-interest loans for the adoption of solar water pumping systems. In terms of economic benefits, these systems were perceived as highly beneficial due to their relatively low installation and maintenance costs, coupled with the flexibility of loan repayment. Compared to diesel and electric pumps, solar pumps have a significantly higher cost-effectiveness over the long run than diesel and electric pumps used by farmers. Technically, the PM-KUSUM scheme facilitates ease of operation and after-sales service, further encouraging adoption. A similar finding reported in Gujarat (Sathish Kumar et al., 2024) found that institutional support, economic benefits, and technical conveyance supported the adoption of solar water pumping systems by farmers in West Bengal.

SUMMARY AND CONCLUSIONS

Solar water pumping systems become popular among farmers in West Bengal, a region with increasing potential for solar-powered irrigation. The analysis identified three important factors in choosing solar-powered irrigation: institutional support, economic and technical benefits. Regarding institutional support, it was found that this included government subsidies (notably the PM-KUSUM) as well as loans and credit facilities from banks and cooperatives, which had the greatest impact on adoption decisions. The reduction of recurring costs and the long-term financial sustainability of solar systems are also crucial factors that have significantly contributed to the success of solar systems. Additionally, some related features, as the simplicity, user-friendly operation, and availability of after-sales service also contributed to the success of adopting the systems. The financial, institutional, and technical dimensions must be aligned to enhance the widespread and sustainable adoption of solar irrigation. These results are consistent with earlier studies in states such as Gujarat and can be used to inform policies and interventions tailored to the region.

CHALLENGES AND POLICY RECOMMENDATIONS

However, several challenges are still beaking the adoption of SWPS in West Bengal. High upfront costs continue to deter many small and marginal farmers, even with the availability of subsidies. Awareness about the benefits of solar irrigation remains limited, especially in remote and underserved areas. Fragmented landholdings also reduce the feasibility of individual installations, while delays in subsidy disbursements and limited institutional coordination limit the implementation. Moreover, scarce technical support and unreliable maintenance services affect farmers' confidence. In this sense, policy measures must include the development of region-specific financial models such as low-interest loans or group-based ownership structures. Strengthening local institutions and decentralizing the implementation process through Panchayati Raj institutions can improve outreach and efficiency. Capacity-building programs and services, should focus on both training and increased awareness about its potential. Additionally, a strong network for after-sales services must be developed to ensure the maintenance support. Ultimately, better alignment between central schemes, such as PM-KUSUM, and state-level operational strategies is a request for enhancing uptake and impact.

FUTURE RESEARCH DIRECTIONS

Future research should deepen and broaden the understanding of solar water pumping system adoption through comparative studies across different agro-climatic zones in India, assessing how socio-economic and institutional variables vary regionally.

Longitudinal research can evaluate the long-term socio-economic and environmental impacts of solar water pumping system adoption, including effects on groundwater sustainability, income diversification, and resilience to climate variability. Behavioral studies focusing on technology diffusion, and peer influence provide insights into the informal mechanisms that drive adoption. Moreover, detailed cost-benefit and life-cycle assessments are needed to evaluate the financial feasibility of solar pumps under various ownership and financing models. Ultimately, integrating solar water pumping systems with emerging digital technologies, such as IoT-based monitoring systems and AI-driven irrigation scheduling tools, can set the direction for innovative, efficient, and climate-resilient farming systems.

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Conceptualization, Sathish Murugan, Ganeshkumar D Rede, Prity Kumari, and Alina Cristina Nuta; Formal analysis, Ganeshkumar D Rede, Teena Baskaran; Methodology, Sathish Murugan, Teena Baskaran, Prity Kumari and Alina Cristina Nuta; Writing – original draft, Sathish Murugan, Ganeshkumar D Rede, Teena Baskaran, Prity Kumari, and Alina Cristina Nuta; Writing – review & editing, Sathish Murugan, Ganeshkumar D Rede, Teena Baskaran, Prity Kumari and Alina Cristina Nuta

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