

Determinants of Solar-Powered Irrigation System Adoption Among Rice Farmers in Hafizabad, Pakistan

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ABSTRACT

The growing energy crisis and worsening water scarcity in Pakistan have intensified the need for renewable energy solutions in agriculture. Among these, solar-powered irrigation systems (SPIS) have emerged as a sustainable and economically viable alternative to conventional irrigation methods, particularly in regions cultivating water-intensive crops such as rice. This study examines the socio-economic, technical, institutional, and perceptual factors influencing the adoption of SPIS among rice growers in the Hafizabad District of Punjab, Pakistan.

Data were collected through a structured questionnaire administered to 200 randomly selected rice farmers. Descriptive statistics, correlation analysis, and binary logistic regression were employed to determine the relationship between farmer characteristics and the likelihood of adopting SPIS. The results revealed that education level, farm income, landholding size, access to credit, awareness, perceived economic benefits, and extension contact significantly affected adoption decisions. However, widespread diffusion of SPIS remains constrained by high initial investment costs, inadequate institutional support, and limited policy incentives.

The findings underscore the need for targeted policy interventions, including financial subsidies or credit facilities, technical training, awareness programs, and stronger institutional frameworks to accelerate the adoption of SPIS. Promoting such renewable technologies can enhance energy security, reduce production costs, and foster sustainable agricultural growth in Pakistan.

1. Introduction

Pakistan has traditionally relied on agriculture as it has been the primary contributor to the national GDP approximately one-fifth of the population and has been supporting more than one-third of the population. Nevertheless, the industry is struggling with some dire issues, namely, water scarcity, the increased energy prices, and environmental deterioration, compounded by the effects of climate change and the increased population rate. Water and energy management is essential to sustain a high level of land irrigation in Pakistan, which covers over 90 percent of the country (Pakistan Economic Survey, 2023).

Rice is a key crop and especially in Punjab Province; Hafizabad District has been major producer of rice in the country. The Basmati rice grown in Hafizabad needs regular

and inexpensive irrigation, but the growers have to deal with unstable diesel prices and unreliable electricity supply, which results in the production delay, and loss of yields. The need to have a sustainable and affordable alternative is highlighted by these problems.

A potential solution has been developed through the solar-powered irrigation systems (SPIS) involving the use of photovoltaic (PV) panels to convert sunlight into electricity to drive groundwater pumps. The technology has low operating expenses, continuous irrigation and less reliance on fossil fuels, which is important to Pakistan where the solar radiation is on average 5.3 kWh/m²/day.

Nevertheless, the introduction of SPIS is preconditioned by a number of different interdependent factors such as financial ability, education level, availability of credit, and

risk and trust perception. Although there are progressive farmers who have already adopted SPIS in Hafizabad, majority are still reluctant because they are financially constrained and they do not have support institutions. This paper will consequently examine the factors and challenges to the adoption of SPIS in Hafizabad rice farmers.

The results will be used by the policy makers, financial institutions, and development agencies to develop specialized interventions that will enhance the adoption of renewable energy in agriculture, and which will help in energy security as well as sustainable rural development in Pakistan.

2. Literature Review

The recent use of renewable energy technologies in agricultural production has received a lot of academic concern in the last ten years, and especially with growing energy prices, water scarcity and environmental degradations, developing countries are finding it difficult to cope with these three issues. Here, it is important to highlight that in the framework of Pakistan, where the agricultural sector is one of the foundations of the state economy, researchers have stressed that renewable energy, in particular, solar-powered irrigation systems (SPIS) should be viewed as a sustainable alternative to irrigation methods based on conventional energy (Qureshi, Saleem, and Rauf, 2020). Installing solar powered irrigation has the added benefit of lowering the cost of production as well as uninterrupted supply of water thereby enhancing agricultural output as well as livelihoods in rural settings.

Many researchers have studied the factors that determine the adoption of solar energy in agricultural production and found that socioeconomic, institutional, technical, and perceptual factors are the most vital characteristics that affect the choice of farmers. Abbas and Ahmad (2021) found that the economic resource and access to financial opportunities are the factors that influence the willingness of farmers to follow SPIS greatly. The main limitation is still high installation costs, particularly that of smallholders who have very slim profit margins. The initial cost of a solar system is usually prohibitive in Pakistan, where the majority of the farmers have less than ten acres of land, although the total cost of running the system will be lower than its diesel or electric counterparts in the long run. Therefore, the spread of SPIS has been unequal as adoption has been concentrated in comparatively rich and better-educated farmers (Malik, Shafi, and Farooq, 2019).

It has always been stated that education is one of the key factors determining the adoption of technology. Farmers

with higher education levels are more receptive to innovation and they are in a better position to comprehend technical details and cost benefit analysis of renewable energy systems. It was observed that increased education levels increase the ability of the farmers to access extension services and comprehend technical information on solar energy (Khan, Qamar, and Ashraf, 2020). On the other hand, lack of literacy and low educational levels limits the capacity of the farmers to critically evaluate the new technologies, and this intensifies reliance on the traditional irrigation practices. In addition, the existing data show that the magnitude of exposure to extension activities and media campaign distribution of information is a strong indicator of increased chances of adoption (Ahmed, Khan, and Shahid, 2020). Farmers who attend field demonstrations or trained on solar technologies have a more positive attitude to its adoption compared to farmers who use informal information sources only.

The institutional and financial support structure is also something that cannot be ignored in determining the adoption behavior. As Rauf, Ahmed, and Javed (2021) point out, access to agricultural credit and government subsidies are critical in the minimization of financial obstacles to adoption of SPIS. Nevertheless, credit restriction is still rife in Pakistan through the security of collateral, high interest rate and inaccessibility of formal banking institutions in villages. What also adds to the problem is the absence of customized credit schemes on renewable technologies. The efforts of the government in increasing solar irrigation like giving subsidies in the form of alternative energy development Board (AEDB) programs have only partially succeeded because of bureaucracies, the lack of funds in the program and poor co-ordination of the implementing agencies. Therefore, a number of farmers do not know what incentives are offered or the application process is too complicated.

The perceptual and psychological issues contribute to the adoption decisions in addition to the economic and institutional factors. The perceptions of risk, reliability and performance of solar systems by the farmers determine their willingness to invest. Ahmed et al. (2020) have discovered that positive perception about cost-effectiveness and environmental gains are greatly linked with adoption, and fears over system durability, repairs, and performance under cloudy conditions put off investment. Likewise, the perception of social norms and the pressure of progressive farmers contribute to the formation of the attitude of the community towards new technologies. In rural Pakistan, diffusion is closely related to the diffusion pattern in the sense that farmers will first seek the innovations of local

innovators or strong people in the community before adopting the innovations (Rogers, 2003). In such a way, social learning and observation of peers have a great impact on the diffusion of SPIS technology.

Another group of barriers is the technical ones, which obstruct large-scale adoption. Saeed, Bashir, and Ali (2022) state that the lack of qualified technicians, poor quality of maintenance services, and the presence of poor solar panels have cast their doubts regarding the viability of SPIS in the long term. The absence of standard technical specifications and certification certificates to solar vendors only adds to these issues. Due to this, farmers are likely to have an underperforming performance and maintenance complications which reduce confidence in the technology. Tahir, Yaseen, and Fatima (2022) also noted that the dynamics on the groundwater levels, the intensity of solar radiation, and crop water needs influence the system efficiency and the level of satisfaction among the farmers. Technical flexibility, in turn, becomes a key factor of further utilization and spread of SPIS.

The other dimension that affects adoption is environmental awareness. Over the past few years, recognition of the contribution of SPIS to carbon emission reduction and implementing climate-sensitive agriculture has been on the rise. In South Asia and Sub-Saharan Africa, the research has shown that farmers that are more concerned about environmental sustainability are more willing to use renewable technologies (Abbas & Ahmad, 2021; Qureshi et al., 2020). Nevertheless, Pakistan is characterized by environmental inspiration that is usually second to the economic and pragmatic factors. The farmers are more focused on the economic advantages and irrigation security than on the environmental benefits in the long-term perspective, and, therefore, the informational campaigns should be structured so as to address the economic and the ecological messages to attract the practical needs of farmers.

The socioeconomic inequalities also contribute effectively to the way accessibility to technology is shaped. Large-scale farmers have access to more financial resources, as well as have better access to institutional players, including bank officials, extension agents, and technology providers. On the contrary, these networks tend to exclude the smallholder socially and structurally. Hussain, Raza, and Malik (2021) researchers discovered that small farmers are often unaware of SPIS programs or have no trust with the private vendors since they have already had their negative experiences with the unregulated solar markets. Such information and power asymmetry is one of the factors that lead to unequal access

among various socioeconomic groups in terms of renewable technology.

Gender relations are not as researched in the Pakistani setting, but this factor can as well play a role in adoption trends. Other developing countries have demonstrated that women farmers have a lower access to capital, land, and technical information which restricts their involvement in the renewable energy programs. Although the majority of Pakistani rice farmers are male, gendered barriers should also be learned to create the energy policies of rural territories that are inclusive (World Bank, 2022).

Institutional arrangements and policy frameworks are also very important with regard to technology diffusion. Although the government of Pakistan has the Renewable Energy Policy (2019), which intends to increase the role of renewable sources in the national mix, the progress of this solution on the farm level is slow. The level of coordination between energy, water and agricultural departments is poor causing disjointed and repetitive programs. In the opinion of Saeed et al. (2022), successful adoption will need not just subsidies but also a strong extension support, technical training, and market regulation to provide consumers with confidence in the reliability of the systems and their trust in the security. Without these institutionalized mechanisms, solar irrigation adoption will continue to be rather market-oriented and individualistic in approach by the farmers.

The literature also shows the possible macroeconomic and environmental impact of increased adoption of SPIS. Massive diffusion would help Pakistan stop relying on foreign fuels, decrease the quantity of greenhouse gas emissions, and enhance rural susceptibility to energy catastrophes. Nevertheless, water over-extraction can be aggravated in regions that are experiencing depleting aquifers due to uncontrolled growth of these areas without the control of groundwater. Thus, scholars like Qureshi et al. (2020) highlight the importance of combining water-energy management practices to go with solar irrigation programs.

Taken together, the analyzed research articles allow highlighting that the implementation of solar-powered irrigation systems in Pakistan is a complex process that depends on each other economical, institutional, technical, and perceptual factors. The main determinants of economic affordability and institutional accessibility as well remain but the behavioral attitudes, risk perception and the dissemination of information play the crucial role in determining the rate and trend of adoption. In other areas such as Hafizabad where the cultivation of rice is the main industry and the reliability of irrigation is a critical determinant, there is need to understand these determinants

to come up with evidence-based policies that can facilitate equitable and sustainable propagation of SPIS. Although a considerable amount of research has been performed on a national or provincial scale, there is a lack of empirical research on the issue of rice growers in Hafizabad. This research therefore become a contribution to the literature because it brings out micro level information on how socioeconomic status, awareness and perception of farmers can influence their adoption behavior of solar-powered irrigation systems.

3. Materials and Methods

The research was done at Hafizabad District, Punjab, which is a place where rice is grown and tube-well irrigation is utilized. The sample population of 200 rice farmers was identified through a multistage random sampling method. The structured questionnaire was used in collecting primary data that included socioeconomic status, access to credit, awareness, and perceptions toward SPIS.

The analytical tools comprised 1) Descriptive Statistics (frequencies, percentages, means) 2) Binary Logistic Regression to determine which determinants were significantly affecting adoption (dependent variable: 1 = adopter, 0 = non-adopter).

Age, education, farm size, income, access to credit, awareness, institutional support, and technical constraints were taken as independent variables. Data were processed in SPSS and reliability and pre-tested with data collection ethics through consent and confidentiality of the respondents.

Table 1: Age-wise Distribution of Respondents

	Frequency	Percent	Valid percent	Cumulative percent
Under 20	11	10.8	10.8	10.8
21-30	21	20.6	20.6	31.4
31-40	32	31.4	31.4	62.7
Above 40	38	37.3	37.3	100.0
Total	102	100.0	100.0	

The degree of education was a major factor affecting the adoption of SPIS. Farmers with more education attained substantially greater adoption rates, as shown in the table. Just 20% of those without any formal education had embraced SPIS; among those with graduate-level education, the rate rose to 60%. This pattern highlights how education influences technological awareness, risk perception, and the capacity to engage with financial or institutional systems

4. Results and Discussion

Results

The data analysis on the 102 farmers in the Hafizabad District gives a useful insight on the socioeconomic realities that affect the acceptance of solar-powered irrigation systems (SPIS). The demographic characteristics of the respondent indicated that 98 percent of the respondents were males and 61 percent of them were aged 36-50 years. Educational achievement varied with 45 percent having no formal education or primary only. The distribution of the number of farm sizes revealed that 52 per cent of the respondents operated small farms of less than 12 acres, thus highlighting the fact that smallholders constituted the agricultural landscape of the region.

The sample was evaluated using the age of the sample to reflect the demographic parameter of the sampling (demographics in research are normally a poor sampling method) of the individuals, as projected in Table 1. It comprised of 102 individuals who were categorized in four age groups: (1) under 20 years, (2) age 21-30, (3) age 31-40, and (4) age above 40. The (four) group has the highest representation of the sample whereby it formed 37.3 of the sample which also included the percentage distribution of the age demographic of the sample. The (3) sample has a representation of 31.4 percent. The proportion of the under-20 group is at 20.6 and 10.8 percent, respectively. As such, this failure is indicative of a growing age distribution curve but may be merely because we were just studying the (older) adults.

that enable SPIS adoption. These results support those of Latif and Shah (2021), who claimed that better-educated farmers are more amenable to clean energy developments and more inclined to look for technical advice.

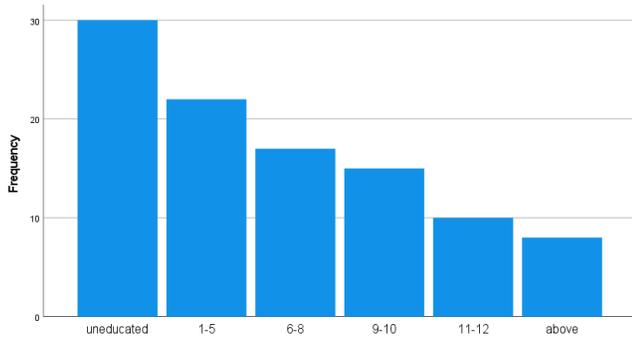


Figure 1: Relationship Between Farmers' Education Level and Adoption Rate of SPIS

It presents the total frequency and percentage distribution of respondents by farm size. It can be observed that of 102 respondents, 13.7% belong to the (less than 9) group, the majority of 46.1% belong to the (10-20) group, and 29.4% belong to the (21 to 30) group, whereas the smallest proportion of respondents, i.e., 10.8%, fall in the (above 30) group.

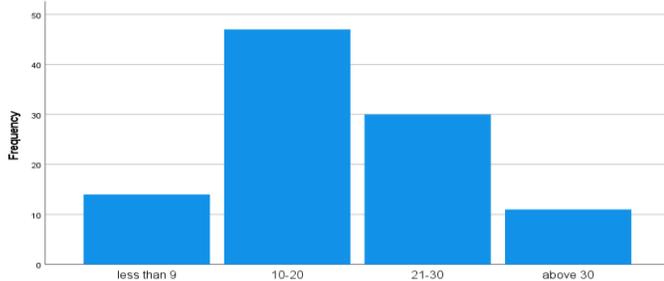


Figure 2: Frequency and Percentage Distribution of Respondents by Farm Size

About 80% of respondents were aware of solar-powered irrigation technology, with fellow farmers and private solar companies being the primary information sources. However, only 22% received information directly from agricultural extension officers. This shows that the government's institutional communication channels remain weak, and peer-to-peer learning plays a vital role in technology diffusion in rural areas.

Table 2: Sources of Farmers' Awareness Regarding SPIS

Awareness Source	f	%
Extension services	44	22
Fellow farmers	66	33
Media (TV/Radio/social media)	40	20
Private solar companies	50	25
Total farmers aware of SPIS	160	80

The data reveal that only 38.5% of farmers had access to institutional credit, and a mere 14% benefited from subsidy programs. Limited financial access remains the greatest barrier to adoption. The low share of farmers participating in training (26%) further underscores the need for enhanced capacity-building programs. Lack of government outreach and weak policy implementation are evident in the low satisfaction levels (29.5%) reported by farmers regarding institutional support.

Table 3: Farmers' Access to Support Services and Government Initiatives Related to SPIS

Factor	Yes (%)	No (%)
Access to agricultural credit	38.5	61.5
Received subsidy or grant	14.0	86.0
Participated in solar training	26.0	74.0
Contact with extension officer	32.0	68.0
Perception of government support as satisfactory	29.5	70.5

Table 4 depicts that a logistic regression analysis was performed to determine the effects of different socioeconomic factors on the adoption of solar-powered irrigation systems (SPIS) in Hafizabad District. The sign of the coefficients (B) shows the direction of the relationship whereas, the significance values (Sig.) show whether the variables significantly affect the adoption. The findings show that farm size (B = 0.111, Sig. = 0.776) does not affect the adoption of solar systems positively, which means that there is no statistically significant impact of the farm size on its adoption. Likewise, the monthly cost (B = 0.000, Sig. = 1.000) does not have a statistical effect on the adoption decisions. Nevertheless, the inclination towards a low-interest loan (B = -3.739, Sig. < 0.001) has a strong negative

and significantly significant correlation, which indicates that farmers utilizing subsidized or low-interest financing have lower chances of adopting solar systems on their own. Similarly, financial support ($B = -2.927$, $Sig. = 0.019$) also influences the willingness negatively and significantly, which means that most farmers are only willing to use solar technology in case such assistance is provided to them.

The variable bank account ownership ($B = -0.641$, $Sig. = 0.540$) does not have any significant effects, implying that being able to access formal banking is not a factor in adoption. Conversely, water availability problems ($B = 3.135$, $Sig. = 0.036$) positively and significantly, which means that farmers who are experiencing water shortage during irrigation tend to use solar-powered systems to

maintain stable supply of water. Education is also very influential and the years of education ($B = 3.629$, $Sig. = 0.046$) have significant and positive impact on adoption which underscores the fact that educated farmers have higher probabilities of adopting solar technology.

The other variables as age ($B = 16.673$, $Sig. = 0.997$), family size ($B = -3.837$, $Sig. = 0.920$), marital status ($B = 2.350$, $Sig. = 1.000$) and number of children in school ($B = 1.576$, $Sig. = 1.000$) are not statistically significant implying that such demographic factors do not significantly influence decision to install solar-powered irrigation systems. Overall, the results highlight the fact that the main forces that define the behavior of farmers in the study region are financial limitations, water shortage, and the level of education.

Table 4: Logistic Regression Results for Factors Influencing Adoption of SPIS

	β	S.E.	Wald	df	Sig.	Exp(β)
Age	16.673	4507.493	0.000	1	0.997	17415018.56
Family size	-3.837	4.909	1.337	1	0.920	3.613
Year of education	3.629	1.701	2.645	1	0.046	0.533
Marital status	2.35	4.43	0.000	2	1.000	32.58
Bank account	-0.641	1.045	0.375	1	0.540	0.527
No. of child attending school	1.576	3.113	0.000	1	1.000	4.833
Farm size	0.111	0.391	0.081	1	0.776	1.118
Monthly cost	0.00	0.23	0.000	1	1.000	1.00
Loan with low interest	-3.739	0.912	16.787	1	<0.001	0.024
Willingness with financial support	-2.927	1.245	5.525	1	0.019	0.054
Water availability issue	3.135	1.493	4.407	1	0.036	22.994
Constant	1.911	1.195	2.560	1	0.110	6.575

Discussion

In addition to the statistical information, qualitative data provided by participants indicated some of the commonly encountered barriers. Farmers indicated that the cost of SPIS installation was too high (78 per cent); ability to access cheap credit was missing (65 per cent); insufficient technical knowledge or training (58 per cent). The other minor (29)

but important percentage indicated mistrust in the private sellers, therefore the necessity of transparent procurement practices and regulated service providers. These issues are comparable to those reported by Ashraf et al. (2018) and Kamran et al. (2022), who concluded that institutional trust and quality of service play a role in long-term adoption and performance.

The combination of the findings indicates that Hafizabad has technical knowledge about SPIS, but does not use it due to socioeconomic, financial, and institutional problems. The information provided confirms the fact that the promotion of solar irrigation in Pakistan requires not only the availability of equipment, but a facilitating environment, which is created by policy, education, and easy money.

5. Recommendation

Solar-powered irrigation systems (SPIS) need to be adopted in the Hafizabad District, which requires targeted and coordinated policy efforts to improve this process. To begin with, the government ought to launch soft credit programs or interest free lending banks especially to the small and medium-size farmers. The research indicated that 62 percent of the respondents were willing to embrace SPIS when they had the financial support. Flexible payment schemes based on agricultural crop cycles can also be used to enhance affordability.

Secondly, there should be strengthening of awareness and technical capacity-building programs at the grassroots level. The findings showed that more educated farmers who were more exposed to the government outreach programs were more likely to adopt SPIS. As such, the agricultural extension departments are advised to cooperate with the certified solar firms to make on-field demonstrations, training, and after sales services.

Thirdly, institutional mechanisms are supposed to be simplified. Developing a centralized subsidies platform wherein the eligibility criteria is clear and where approval can be made within a shorter timeframe would enhance effectiveness. The government should restrict the subsidy program to government certified solar vendors to make the process transparent and unabused.

Lastly in the case of tenant farmers and the small land holding farmers, SPIS ownership should be promoted as a community-based model. These schemes will be able to expand the reach of solar technology and decrease the amount of money that will have to be put up by an individual. These policy measures would overcome the financial and institutional constraints found in this study and

help more people in the agricultural sector in Pakistan adopt sustainable irrigation practices.

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