Center for Management Science Research
ISSN: 3006-5291 3006-5283 Volume 4, Issue 2, 2026

FUELING THE FUTURE OF RICE PRODUCTION: ECONOMIC INSIGHTS INTO SOLAR VS. DIESEL TUBE WELLS IN PUNJAB, PAKISTAN

Rahman Illahi[*1], Prof. Dr. Asghar Ali[2], Wisha Raza[3], Sanjina Naeem[4], Dr. Raza Ullah[5]

[*1,3]*M.Sc. (Hons.) Agricultural Economics from University of Agriculture, Faisalabad*
Department of Agricultural Economics, Faculty of Social Sciences, University of Agriculture, Faisalabad
[2]*Chairman, Institute of Agricultural Economics, University of Agriculture Faisalabad*
Department of Agricultural Economics, Faculty of Social Sciences, University of Agriculture, Faisalabad
[4]*Ph.D in Agricultural Economics from University of Agriculture, Faisalabad*
Department of Agricultural Economics, Faculty of Social Sciences, University of Agriculture, Faisalabad
[5]*Associate professor, Institute of Agricultural Economics, University of Agriculture Faisalabad*
Department of Agricultural Economics, Faculty of Social Sciences, University of Agriculture, Faisalabad

[*1]rahmibaloch32@gmail.com, [2]asghar.ali@uaf.edu.pk, [3]ch.wisha07@gmail.com, [4]sanjinanaeem55@gmail.com, [5]raza.khalil@uaf.edu.pk

DOI: https://doi.org/10.5281/zenodo.18627413

Keywords
Solar tubewells. BCR. Irrigation.

Article History
Received: 13 December 2025
Accepted: 27 January 2026
Published: 13 February 2026

Corresponding Author: *
Rahman Illahi

Abstract

The rising diesel prices, along with the possibility of free solar energy, are modifying the water pumping for crops in Punjab's rice belt. This study investigates the economic benefits, drivers and constraints of solar water pumping for tube wells in the rice–wheat system. The analysis uses data from 120 farmers: 60 who are pumping water with diesel and 60 who have installed solar photovoltaic water pumping systems in the districts of Gujranwala, Hafizabad and Sialkot. Statistical descriptors used to compare the costs and profitability. They were used by researchers to check which of the things matter while the adoption of solar ones. Perceived constraints of using solar tube wells can be ascertained by Likert-scale analysis. Solar irrigation brought about a saving of 37% in variable costs as the fuel cost is eliminated, the study reveals. Thus, the total cost of rice production of the solar water pump users was PKR 122,913 per acre, whereas it was PKR 165,022 of diesel users. The net income of the diesel users was PKR 27,491 per acre. The net income of the solar water pump users was PKR 67,635 per acre almost 2.5 times the net income of diesel users. The adoption of solar tube wells increased the benefit–cost ratio from 1.16 to 1.55. According to logistic regression model, as with Smallholders gain considerably from the economic advantages of tube wells based on PV. Nonetheless, constraints in finances and information are limiting factors for the adoption of these tubewells. Subsidy schemes and targeted financing are required to further promote the expansion of solar irrigation. In addition, the sustainable extension of solar irrigation in the rice sector of Pakistan should be strengthened.

INTRODUCTION

Rice, Pakistan's second-largest crop, is vital for nutrition, economic growth, and agro-based industries, contributing 3.0% to agricultural value added and 0.6% to GDP (GOP, 2024). Punjab dominates rice production due to favorable climatic conditions, with 2.19 million hectares under cultivation in 2022–23, compared to 0.60 million hectares in Sindh, 0.06 million in Khyber Pakhtunkhwa, and 0.13 million in Baluchistan (MNSFR, 2024). As a semi-aquatic crop grown under standing water, rice requires intensive irrigation, consuming about 30–45% of global freshwater resources (Humphreys et al., 2024). Irrigation fuel represents a major cost component and, if fully paid by farmers, can raise total production costs by nearly 36% (Perret et al., 2018). Pakistan ranks as the world's 10th largest rice producer, with an annual output of about 8.9 million tons (GOP, 2024). Compared to other cereals, rice is more energy-intensive due to heavy tillage, high irrigation demand, and greater mid-season and post-harvest operations (Ashfaq et al., 2021).

Reliable irrigation is the need of the time for modern agriculture to increase productivity, ensure stable income of farmers and adapt to climate change. The cost of energy for tubewell operation is very high for smallholders which makes call for adoption of renewable energy for economic and environmental sustainability. (Hussain et al., 2023). According to some studies, the availability of surface water is less by 38 % in Pakistan (2024) which increases the usage of groundwater for irrigation (Ullah et al., 2023). Farmers heavily depend on tube wells, particularly in Punjab (995,456 units), followed by Sindh (71,454), Khyber Pakhtunkhwa (42,970), and Balochistan (39,567), with about 58% being diesel-powered systems of 16–20 hp, resulting in high fossil fuel use (Asfahan et al., 2022). During this period, energy imports of Pakistan have risen to about 11 million tonnes during the first half of FY 2024 (Zulfiqar et al. 2024). The irrigation which uses most amount of energy in agriculture mainly for diesel pumps (Siddiqi and Wescoat, 2013) faces a big challenge from rising fuel prices and shortages. To increase productivity and meet the rising demand for food supply, Pakistan should use different sustainable sources of water and energy (Ullah et al., 2023).

Solar energy is a clean and abundant resource that can meet global energy needs without harming human health or the environment (Ali and Shah, 2018). Pakistan, covering 796,096 km², receives 185–290 sunny days a year with 8–8.5 hours of daily sunshine and an average solar irradiance of 200–250 W/m², offering a potential of 2.9 million MW (Mirza *et al.*, 2003; Solangi *et al.*, 2019). Using photovoltaic power in agriculture helps conserve energy, reduce grid dependence, and support rural development (Raza *et al.*, 2022). Photovoltaic power offers a cost-effective alternative to diesel irrigation, providing farmers in remote areas with affordable water and improving their socio-economic conditions (Shouman *et al.*, 2016). Solar-powered irrigation systems also conserve resources by reducing energy use, labor costs, and water consumption, particularly benefiting off-grid rural regions(Raza *et al.*, 2022). With the increase in diesel prices, increase in electricity tariffs and environmental concerns, therefore conventional tube wells for irrigation has become relatively expensive and thus more unviable option (Razzaq et al., 2023). Solar tube wells are a more viable alternative than diesel and electric tube wells for irrigation purpose that further give a higher return smaller payback period better net present value and overall a more cost-effective alternative (Sadiqa *et al.*, 2021; Bukhari *et al.*, 2023).

Pakistan's dependence on diesel powered tube wells, rising fuel prices, and dwindling surface water supplies are making rice irrigation more and more unsustainable. This research has been conducted to take a look at the rice farmers in Punjab which face rising irrigation costs and declining water availability, with most still relying on diesel-powered tube wells. While solar-powered systems offer a sustainable and cost effective alternative, their adoption remains low due to economic, technical, and social barriers incomes (Anjum *et al.*, 2025; Bukhari *et al.*, 2023). By analyzing their relative profitability, cost structures, and adoption factors, this study fills that knowledge gap and offers data to devise policies that support sustainable irrigation and raise farmer. The study aimed to:

- Conduct a financial analysis of solarization in rice-wheat zone of Punjab, Pakistan.
- Identify the factors contributing to the promotion of solar tube wells in the study area
- Recognize the constraints in the adoption and use of solar powered tubewells.
- Suggest policy recommendations for co

ncerned stakeholders

2. Materials and Methods

Study Area

The study was orchestrated in the influential rice–wheat zone of Punjab, selecting the key rice producing districts of Gujranwala, Hafizabad and Sialkot because of their central role in rice production. The aforementioned districts were also chosen for study because they differ in the adoption of irrigation technologies. The three districts together accounted for an estimated share of 45% in the total rice output of Pakistan and area under rice–wheat cropping system stood at almost 48% according to Crop Reporting Service (Government of the Punjab, 2024–25). This study area faces hot summers and mild winters because of its sub-tropical climate. The majority of the farming in the region takes place under rice–wheat cropping rotation. Due to unreliable canal water supplies, use of both diesel and solar tube well-based irrigation is quite widespread and both these technologies function as mains.

Sampling Design

The sampling strategy used in the study was multi-stage purposive. Three major rice-producing districts i.e. The researchers purposely selected Gujranwala, Hafizabad, and Sialkot to conduct the research on the basis of the existence of both diesel and solar tube wells. The choice of tehsils and villages was thus made on the concentration of farmers having these systems and growing rice crops. In total, 120 farmers were randomly chosen of which 91 originate from Gujranwala, 17 from Hafizabad and 12 from Sialkot, equally divided between diesel and solar users for comparison.

Data Collection

A structured questionnaire was applied for data collection through a personal interview. Before fully implementing the questionnaire, a pilot test was completed to ensure clarity and relevance of questions. The interview schedule has questions pertaining to the demographic profile, input costs, crop production, type of irrigation presently in use, choice of irrigation, and farmers' perceptions of challenges and technology adoption. It also included questions on institutional support, extension services, and access to digital information.

Analytical methods

Using descriptive statistics like mean, percentage and standard deviation, the socioeconomic characteristics of the respondents have been summarized and cost structure of diesel and solar irrigation systems have been assessed. Variables analyzed included age, education, farming experience, landholding size, rice area, district distribution, primary occupation, cropping pattern, and access to extension services and digital media with software like spss and excel.

Profitability Analysis

The financial feasibility of irrigation systems (diesel versus solar) was assessed using standard farm level indicators like Gross margin (GM), Net income (NI) and Benefit-cost ratio (BCR). The gross margin was calculated as total revenue minus variable cost. – These reputed measures are reflective of the production efficiency and financial soundness of any resource use. GM therefore signifies the profitability from the usual day-to-day activities. The net income is defined as total revenue less total cost. NI, thus, indicates the overall profit after discounting all costs. Profitability was calculated as the division of total revenue by total cost. The BCR denotes the return per rupee spent. Values of BCR more than one give profits and vice versa.

Binary Logistic Regression

We applied a logistic regression model to evaluate the factors responsible for adopting solar tube wells. The adoption of solar irrigation was examined by Khan et al., (2025) and Sunny et al., (2022) using a similar method of analysis. The coded dependent variable took the following form; 1 means solar tube well users, 0 means diesel users, and the logistic regression model is of the following form.

$$\text{Log}(P / (1 - P)) = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 4X4 + \beta 5X5 + \beta 6X6 + \beta 7X7 + \beta 8X8$$

Where P represents the probability of adopting a solar tube well, β0 is the constant, and βi (i = 1 to 8) are the coefficients of the independent variables. Each coefficient indicates the change in log-odds of adoption for a one-unit increase in the respective variable, holding others constant. The independent variables included: X1 = Age (years), X2 = Education (years of schooling), X3 = Farming experience (years), X4 = Access to extension services (1 = Yes, 0 = No), X5 = Operational landholding (acres), X6 = Peer influence (1 = Yes, 0 = No), X7 = Internet/social media access (1 = Yes, 0 = No), and X8 = Main occupation (1 = Farming, 0 = Non-farming). The model assesses the influence of socioeconomic and informational factors on the adoption of solar irrigation in Punjab's rice-wheat cropping zone.

Constraint Analysis

For better comprehension, the respondents' data was collected through a Likert-scale to know about the barriers faced during the adoption and use of solar tube well. The respondents were asked to rank each of the constraints using a scale of 1–5 (1= Strongly Agree to 5= Strongly Disagree). A low mean value response was considered a severe constraint. To say it more simply, every responses was coded (Strongly Agree=1, Agree=2, Neutral=3, Disagree = 4, strongly Disagree=5) and mean was calculated. The average indicates the barrier severity. Results were visually represented through bar charts to facilitate comparison.

3. Results and Discussions

The research work uses the data collected from 120 rice growers in rice-wheat cropping system of Punjab. It compares profitability indicators and cost structures of tube wells worked on diesel power and solar power. Analyses of constraints were used to support profitability indicators highlighting limiting factors for solar irrigation. Binary logistic regression has been utilized to analyze the impact of socioeconomic and informational factors on the adoption decisions made by farmers.

Socioeconomic Characteristics of the Farmers

Analysis of socio-economic profile of rice farmers. Table 1 gives descriptive statistics of the rice farmers from Punjab under study. The average age of the sample was 47(SD 9.62) years old indicating that the respondent was middle-aged and experienced enough in agricultural production. The subjects' reported farming experience was also in line with their age as they were found to have been in agricultural work for the past 20 years (SD 8.49). The respondents are therefore mature and experienced enough to cope with existing and new farming practices.

Table 1. Profile of Sampled Rice Farmers

Variables	Mean + St. Dev or %
Age	47.06 S.d 9.62
Education(years)	5.98 S.d 4.80
Farming Experience(years)	20.02 S.d 8.49
Land Holding (Acres)	9 S.d 14.69
Rice Area (Acres)	12 S.d 10.40
District	Gujranwala 75.8 %, Hafizabad 14.2 %, Sialkot 10.0 %
Main Occupation	Farming 88.3 %, Business 10.0 %, Job 1.7 %
Cropping Pattern	Rice–Wheat 79.2 %, Rice–Vegetable 10.0 %, Others 10.8 %
Extension Services	Yes 55 %, No 45 %
Access to internet/Social media	Yes 62.5 %, No 37.5 %

Farmers had an average of 5.98 (SD 4.80) years of schooling; thus they had completed primary schooling or somewhat more. The relatively low formal education amongst farmers demonstrates that they have reasonable levels of literacy. It can be expected that farmers have a basic understanding of agricultural information and can interact reasonably with extension agents, technology providers, and the like. The average farm size was found to be 9 acres (SD 14.69) acres, while the average rice area of a farmer was found to be 12 acrs (SD10.40). The standard deviations of farmers' land ownership as well as rice-specific cultivation are very high indicating heterogeneous farmers. The sample includes both smallholder and mid-level farmers.Most respondents were from Gujranwala District (75.8%) while others belong to Hafizabad (14.2%) and Sialkot (10.0%). It is because most rice farmers were in these districts. About 88.3 percent of respondents indicated farming as their main occupation, while the remaining mentioned they were either in business (10%) or jobs (1.7%). This indicates that the sample consists mostly of full-time farmers. Seventy-nine point two per cent (79.2%) of the farmers were in a traditional rice-wheat cropping system, whereas the rest produce other crops on an experimental or commercial basis in rice-vegetable or mixed cropping systems. About 55% of respondents had access to extension services, while 45% lacked such access, reflecting an uneven institutional outreach. However, 62.5% of the population have uptakes of the internet and social media meaning that they are increasingly become go to platforms for information.

Comparative Economic Performance of Diesel and Solar Tube Well Users

This section compares the performance of rice farmers of diesel and solar tube wells in Punjab. Table 2 shows the production costs and returns of both groups. The report shows that the largest gap was in the irrigation cost as diesel users spent an average of PKR 40,450 per acre. This was zero in the case of solar users thus it shows the main cost benefit of solar irrigation. The remaining input costs like land preparation, nursery, fertilizers, and sprays were found to be similar amongst groups. All in all, the total variable costs incurred by the diesel users stood at PKR 113,022 while that of the solar users stood at PKR 70,913meaning that the diesel users were incurring 37% costs higher and hence, the solar systems indeed represented a more economic and cost-efficient option.

Both of the groups incurred fixed costs of PKR 52,000 per acre for land rent and permanent hired labor. As a result, the total cost of production was PKR 165,022 for the diesel user as against PKR 122,913 for the solar user. Yields achieved were almost similar at 39.75 maunds per acre for diesel and 39.48 maunds for solar. Despite this similarity, the lower production cost of solar irrigation translated into a significant profit margin. On average, the net income of diesel users was PKR 27,209 per acre against PKR 67,635 for solar users, which is almost 2.5 times higher. This advantage is further reflected in the Benefit–Cost Ratio (BCR), which stood at 1.16 for diesel users and 1.55 for solar users, underscoring the superior economic viability of solar-powered tube wells.

Table 2. Comparative Profitability and Cost Structure of Rice Farmers Using Diesel vs. Solar Tube Wells

Metric	Diesel Users (PKR/acre)	Solar Users (PKR/acre)
Nursery preparation cost	5,334	4,317
Land preparation	14,745	14,029
Transplanting cost	12,183	12,183
Irrigation cost	40,450	0
Fertilizers subtotal	22,596	22,863
Spray subtotal	7,714	7,586
Harvest cost	10,000	9,935
Total variable cost (VC)	113,022	70,913
Total fixed cost (FC)	52,000	52,000
Total cost (TC = VC + FC)	165,022	122,913
Yield per acre (maunds)	39.75	39.48
Price per maund (PKR)	4,836	4,829
Total revenue (TR)	192,231	190,648
Gross margin (TR – VC)	79,209	119,735
Net income (TR – TC)	27,209	67,635
Benefit–Cost Ratio (TR / TC)	1.16	1.55

Factors effecting adoption decision for solar tubewells

A binary logistic regression analysis was conducted on the adoption of solar tube wells by rice farmers. The adoption of the solar tube well was considered as a dichotomous variable (0 and 1) in which, 1 was assigned for solar users and 0 for diesel users. According to several fit indices (Nagelkerke R^2= 0.546; –2 Log Likelihood = 103.079), the model results were satisfactory. Education showed a positive and significant effect (Wald = 8.349, p = 0.004), indicating that educated farmers are more likely to adopt solar technology due to better awareness and understanding. The strongest predictor of solar tube well adoption was peer influence which was statistically significant (Wald = 12.058, p = 0.001) indicating that farmers adopt solar tube well when their neighbors adopt. The internet and social media were important determinants that also had a positive and significant effect (Wald = 7.037, p = 0.008), highlighting the growing role of digital information in promoting technology adoption.

Operational landholding had a negative and significant effect (Wald = 4.692, p = 0.030), indicating that larger farmers were less likely to adopt solar tube wells due to greater water needs and the limited discharge capacity of solar systems. These technical constraints make solar irrigation less practical for extensive farms. Similar findings were reported in Tamil Nadu, where a NABARD study (Narayanamoorthy, 2024) found that larger farm size and higher cropping intensity reduced adoption likelihood. Other variables were not statistically significant at the 5% level but provided useful insights. Off-farm occupation showed moderate significance (p = 0.080), implying that diversified income sources may support investment in solar systems. Access to extension services, though positive, was not significant (Wald = 2.442, p = 0.118), pointing to limited effectiveness of current institutional outreach. Age and farming experience had negative but insignificant effects (p > 0.36 and 0.61), indicating no strong relationship with adoption decisions.

Table 3. Logistic Regression Results for Solar Tube Well Adoption

Variable	β (Log odds)	Wald Score	Significance
Age (Years)	-0.04	0.809	0.369
Education (Years)	0.179	8.349	0.004
Farming Experience (years)	-0.028	0.251	0.617
Access to Extension services (1)	0.969	2.442	0.118
Operational Land (Acres)	-0.051	4.692	0.03
Influence from peers/ neighbours (1)	1.907	12.058	0.001
Access to Internet/ social media (1)	1.475	7.037	0.008
Main occupation (1)	-1.806	3.068	0.08
Constant	1.27	0.411	0.522

Significance level 1 percent, 5 percent, 10 percent
Dependent variable: solar tubewell adoption
-2LogLikelihood = 103.079
Cox & Snell R^2 = 0.410
Negelkerke R^2 = 0.546

Constraints in adoption of solar tubewells

The barriers to adoption identified by sixty diesel farmers, rated on a 5 point Likert scale are shown in figure 1. The least barrier reported with mean values of 3.97 was the lack of extension support and spare part. One may assume that informal market and social network do partially relax this barrier. Moderate constraints included limited awareness and absence of role model farmers (mean = 3.57), while concerns about technical skills, equipment quality, and price fluctuations (means = 3.42, 3.35 respectively) reflect uncertainties about system maintenance and cost stability.

There were several significant constraints, among them were no access to formal credit and loans (mean=3.23), inadequate water flow for high water demanding crops (mean=3.03), reduced efficiency on cloudy days (mean=2.82). Some other economic constraints were also quite serious with high maintenance costs (mean = 2.92), expensive spare parts (mean = 2.95), fear of equipment failure (mean = 2.75), and lack of government subsidies (mean = 2.73) perceived as major roadblocks. The main obstacle to installation was high initial installation costs have (mean=2.02) (mean = 2.02), underscoring the challenge of adopting solar systems without financial or institutional support. Overall, adoption decisions are shaped by intertwined technical, informational, and financial constraints, with cost-related barriers being the most influential.

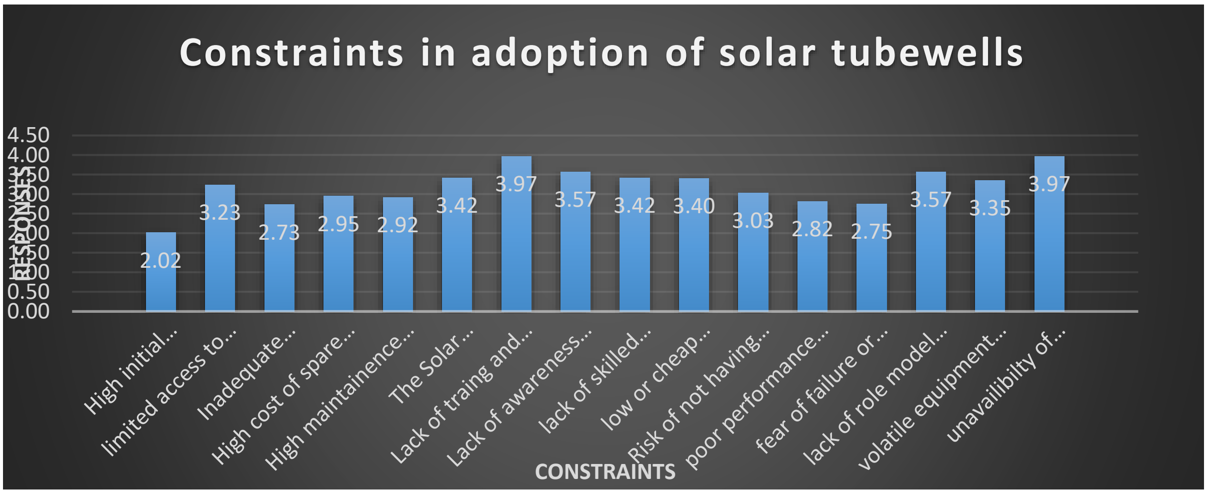

Figure 1. Constraint Analysis of Utilization of Solar Tubewells

Constraint in the Utilization of Solar Tubewells

The constraints of farmers using solar tube well is shown in figure 2. The item's statement was measured on a five-point Likert scale ranging from strongly agree to strongly disagree. The lower mean score denotes that the majority of the farmers strongly agreed to it and hence the constraint was very severe. On the contrary, higher means show the respondents disagree with the item and hence it is less severe constraint.The least severe issues were dust accumulation on solar panels (mean = 3.98) and availability of local technicians (mean = 3.95), suggesting that panel maintenance has become a routine practice and local technical skills are increasingly available. Similarly, poor after-sale service (mean = 3.83) and limited access to repair facilities (mean = 3.78) were viewed as minor concerns, reflecting improved service networks and greater farmer competence in handling basic maintenance.

As mentioned by the farmers, a moderate level challenge is inadequate water discharge (mean = 3.50) and no battery storage for night time irrigation (mean = 3.35) during critical crop growth stage. Other operational concerns, such as frequent equipment breakdowns (mean = 3.08), reduced sunlight during rainy periods (mean = 2.80), and frequent maintenance needs (mean = 2.78), reflect the system's vulnerability to environmental variability. The most critical constraints were financial and technical risks: equipment theft (mean = 1.85) was the most severe issue, followed by inverter and controller failures (mean = 2.43), high spare part costs (mean = 2.47), and maintenance expenses (mean = 2.62). These issues collectively underscore the financial strain and sustainability challenges of solar irrigation, particularly for small-scale farmers.

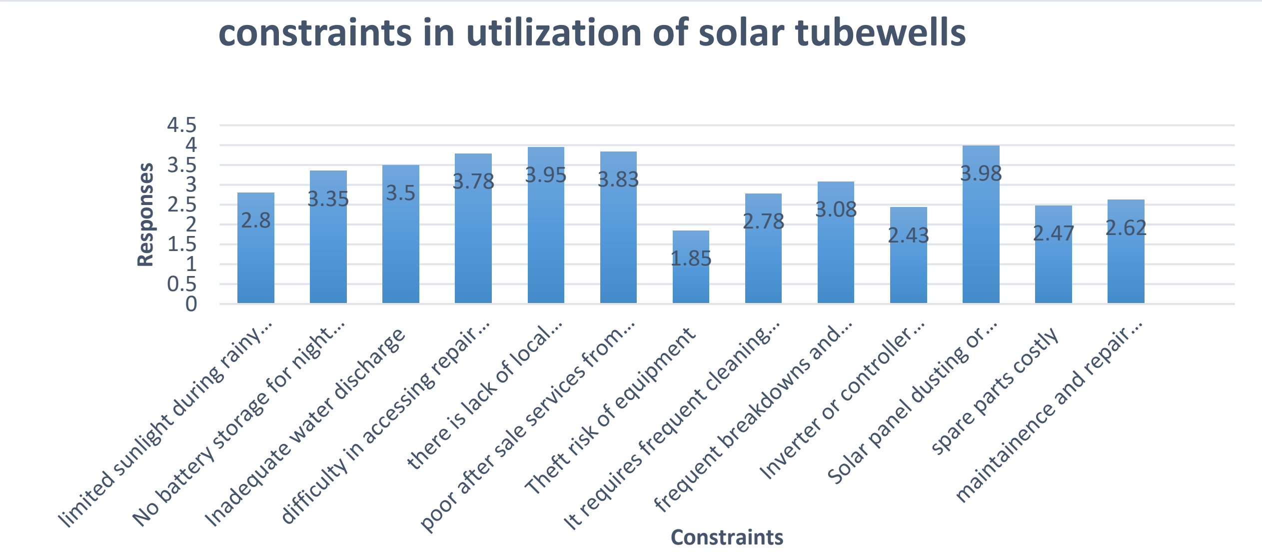

Figure 2 Constraints in utilization of solar tubewells

4. Conclusions and Policy Recommendations

Pakistan's rice sector is central to food security, rural employment, and economic stability but faces challenges from high input costs, environmental degradation, and energy insecurity. This study compared the economic viability of solar and diesel tube wells in Punjab, focusing on profitability, costs, and adoption drivers. Results show that solar irrigation offers a superior economic alternative. Solar users eliminated fuel costs, reducing total variable costs by 37% (Rs. 70913/acre vs. Rs. 113022/acre for diesel) and achieving net returns of Rs. 67635/acre, more than double diesel users' Rs. 27209/acre. Benefit–cost ratios further highlight the advantage: 1.55 for solar versus 1.164 for diesel. Logistic regression confirmed that education, digital access, and peer influence significantly enhance adoption, while older age and larger landholdings negatively affect uptake.

Key adoption barriers include high initial costs, limited credit access, equipment reliability concerns, and insufficient government support. Operational risks such as theft, spare part availability, and variable performance under cloudy conditions further limit adoption. Policy interventions are essential, including subsidies, low-interest or installment-based financing, strengthened extension services, on-field demonstrations, and digital awareness campaigns. Ensuring quality maintenance and local technician support, along with measures to mitigate weather and security risks, can enhance trust in solar systems. Cross-sector collaboration, long-term research, and pilot programs are recommended to scale solar irrigation sustainably, improve profitability, reduce fossil fuel dependence, and foster climate-resilient rice production in Punjab.

5. References

Ali, R. and M. ali. Shah. 2018. Solar powered irrigation system for agriculture based on moisture content in the field and saving energy and water with optimum designing. Asian J. Eng. Sci. Technol. 8:1–9.

Afzal, A., & Bell, M. 2023. Precision agriculture: Making agriculture sustainable. In *Precision agriculture* (pp. 187-210). Academic Press.

Anjum, T. and I. Tuhin. 2025. S. A Comparative Analysis of Solar and Diesel-Powered Irrigation Systems in Bangladesh. *J. Eng. Manag. Inf. Technol*, 3, 223-230.

Ashfaq, M., U. Mubashar, M. S. Haider, M. Ali, A. Ali and M. Sajjad. 2021. Grain discoloration: an emerging threat to rice crop in Pakistan. JAPS: Journal of Animal & Plant Sciences, 27:3.

Asfahan, H.M., M. Sultan, F. Ahmad, F. Majeed, M.S. Ahamed, M. Aziz, R.R. Shamshiri, U. Sajjad, M.U. Khan and M. Farooq. 2022. Agrovoltaic and smart irrigation: Pakistan perspective. In: Irrigation and Drainage-Recent Advances, IntechOpen.

Bukhari, M. D., H.F. Khan, M. S. Hameed, M. Yasir, M. Safdar, U. Ahmad and W.A. Khawaja. 2023. Feasibility and comparative analysis of solar power tube well with existing conventional systems and its utilization in irrigation of the agricultural lands. PalArch's Journal of Archaeology of Egypt/Egyptology. 20:1070-1081.

Bakhsh, A., M. Ashfaq, A. Ali, M. Hussain, G. Rasool, Z. Haider and R.H. Faraz. 2015. Economic evaluation of different irrigation systems for wheat production in Rechna doab, Pakistan. Pakistan Journal of Agriculture Sciences. 52:821-828.

Best, R., & Nepal, R. (2022). Saving and subsidies for solar panel adoption in Nepal. *Applied Economics*, *54*(59), 6768-6783.

Connor, M., Tuan, L. A., DeGuia, A. H., & Wehmeyer, H. (2021). Sustainable rice production in the Mekong River Delta: Factors influencing farmers' adoption of the integrated technology package "One Must Do, Five Reductions"(1M5R). *Outlook on Agriculture*, *50*(1), 90-104.

GOP. 2024. Agriculture, Government of Pakistan:Economic Survey of Pakistan.

Government of the Punjab. (2024). *Kharif and Rabi Estimates in Punjab 2024–25*. Crop Reporting Service, Agriculture Department, Government of the Punjab, Lahore.

Gul, A., Rehman, A., Chandio, A. A., Ankrah Twumasi, M., & Wu, X. (2025). Factors influencing the adoption of solar energy tube-wells technology on rice production in Sindh Pakistan: a novel investigation. *Local Environment*, 1-22.

Hoang, A. T., & Nguyen, X. P. (2021). Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process. *Journal of cleaner production*, *305*, 127161.

Humphreys, E., S.S. Kukal, E.W. Christen,G.S. Hira, S. Balwinder, Y. Sudhir and R. Sharma. 2024. Halting the groundwater decline in north-west India-which crop technologies will be winners? Advances in Agronomy, 109: 155-217.

Hussain, F., S.J. Maeng, M.J.M. Cheema, M.N. Anjum, A. Afzal, M. Azam, R.S. Wu, R.S. Noor, M. Umair and T. Iqbal. 2023. Solar Irrigation Potential, Key Issues and Challenges in Pakistan. Water (Switzerland). 15:1–22.

Mirza, U.K., M.M. Maroto-Valer and N. Ahmad. 2003. Status and outlook of solar energy use in Pakistan. Renewable and Sustainable Energy Reviews. 7:501-514.

Mishra, T., Rabha, A., Kumar, U., Arunachalam, K., & Sridhar, V. (2020). Assessment of solar power potential in a hill state of India using remote sensing and Geographic Information System. *Remote Sensing Applications: Society and Environment*, *19*, 100370.

Mallareddy, M., Thirumalaikumar, R., Balasubramanian, P., Naseeruddin, R., Nithya, N., Mariadoss, A., ... & Vijayakumar, S. (2023). Maximizing water use efficiency in rice farming: A comprehensive review of innovative irrigation management

MNSFR, 2024. Ministry of National Food Security and Research (Economic Wing) Government of Pakistan. "Crops Area AND Production by 2022-23.pdf (mnfsr.gov.pk)".

Narayanamoorthy, A. (2024). *Economic and Other Impacts of Solar-Powered Irrigation Pumps: An Empirical Study from Tamil Nadu*. NABARD Research Study No. 49. National Bank for Agriculture and Rural Development, Mumbai.

Perret, S., P. Saringkarn, D. Jourdain and M.S. Babel. 2018. Energy use and efficiency in selected rice-based cropping systems of the Middle-Indo Gangetic Plains in India. Energy Reports. 4:554–564.

Raza, F., M. Tamoor, S. Miran, W. Arif, T. Kiren, W. Amjad, M.I. Hussain and G.H. Lee. 2022. The Socio-Economic Impact of Using Photovoltaic (PV) Energy for High-Efficiency Irrigation Systems: A Case Study. Energies. 15:1–21.

Raza, W., T. Sadaf, A. Rouf, R. Illahi and Z. Zafar. 2025. Impact of Mechanically Transplanted (MTR) technology on rice productivity and farmers livelihood in Punjab, Pakistan. Econ. Impact. 7:119–127.

Razzaq, A., H. Liu, M. Xiao, K. Mehmood, M.A. Shahzad and Y. Zhou. 2023. Analyzing past and future trends in Pakistan's groundwater irrigation development: Implications for environmental sustainability and food security. Environmental Science and Pollution Research. 30:348-354.

Sadiqa, A., A. Gulagi, D. Bogdanov, U. Caldera and C. Breyer.2021. Renewable energy in Pakistan: Paving the way towards a fully renewables-based energy system across the power, heat, transport and desalination sectors by 2050. Iet Renewable Power Generation. 16:177-197.

Siddiqi, A. and J.L. Wescoat. 2013. Energy use in large-scale irrigated agriculture in the Punjab province of Pakistan. Water Int. 38:571–586.

Shouman, E.R., E.T. El Shenawy and M.A. Badr. 2016. Economics analysis of diesel and solar water pumping with case study water pumping for irrigation in Egypt. Int. J. Appl. Eng. Res. 11:950–954.

Siddiqi, A. and J.L. Wescoat. 2013. Energy use in large-scale irrigated agriculture in the Punjab province of Pakistan. Water Int. 38:571–586.

Solangi, Y.A., Q. Tan, N.H. Mirjat, G.D. Valasai, M.W.A. Khan and M. Ikram. 2019. An integrated Delphi-AHP and fuzzy TOPSIS approach toward ranking and selection of renewable energy resources in Pakistan. Processes. 7:90-118.

Tauseef, A. and I. Uddin. 2024. Novel Insights on Sustainable Nanoparticles in Crop Protection: Current Status and Future Prospectives. In *Sustainable Nanomaterials: Synthesis and Environmental Applications* (pp. 249-270). Singapore: Springer Nature Singapore.

Ullah, I., N. Khan, Y. Dai and A. Hamza. 2023. Does solar-powered irrigation system usage increase the technical efficiency of crop production? new insights from rural areas. Energies. 16:1–16.

technologies. *Water*, *15*(10), 1802.

Paudel, G. P., Khanal, A. R., Krupnik, T. J., & McDonald, A. J. (2023). Smart precision agriculture but resource constrained farmers: Is service provision a potential solution? Farmer's willingness to pay for laser-land leveling services in Nepal. *Smart Agricultural Technology*, *3*, 100084.

Supe, H., Abhishek, A., & Avtar, R. (2024). Assessment of the solar energy–agriculture–water nexus in the expanding solar energy industry of India: An initiative for sustainable resource management. *Heliyon*, *10*(1).

Sanogo, S., & Ba, A. (2023). Data related to performance evaluation of an installed on-grid photovoltaic system at Bamako. *Data in Brief*, *50*, 109514.

Shahbaz, P., Ul Haq, S., Abbas, A., Batool, Z., Alotaibi, B. A., & Nayak, R. K. (2022). Adoption of climate smart agricultural practices through women involvement in decision making process: Exploring the role of empowerment and innovativeness. *Agriculture*, *12*(8), 1161.

Tasnim, Z., Saha, S. M., Hossain, M. E., & Khan, M. A. (2023). Perception of and adaptation to climate change: the case of wheat farmers in northwest Bangladesh. *Environmental Science and Pollution Research*, *30*(12), 32839-32853.

Yadav, I. S., & Rao, M. S. (2024). Agricultural credit and productivity of crops in India: field evidence from small and marginal farmers across social groups. *Journal of Agribusiness in Developing and Emerging Economies*, *14*(3), 435-454.

Zulfiqar, M., A. Farooq, Z. Usmani, Ubaid Ur Rehman Zia, S. Ullah and Z. Bin Babar. 2024. Pakistan's electric vehicle market: challenges , opportunities , and future pathways †. Eng. Proc. 15:1–10.