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Does Solar-Powered Irrigation System Usage Increase the Technical Efficiency of Crop Production? New Insights from Rural Areas

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Abstract: Fossil fuel and electricity-powered irrigation techniques boost the water availability expense and increase greenhouse gas emissions. Especially in developing countries, solar-powered irrigation is becoming more popular as a response to the growing energy and environmental issues associated with agriculture systems. The existing study used data from 1080 wheat farmers in Balochistan, Pakistan, to investigate the impact of solar-powered irrigation system (SPIS) usage on the technical efficiency (TE) of wheat production. The TE of wheat production is estimated using a stochastic frontier production function, and the potential self-selectivity bias is addressed using an endogenous switching regression model. The findings indicated that 13.7% of the wheat cultivators assessed used SPISs to produce their crops. Using an endogenous switching regression model shows that SPIS usage increases the TE of wheat growers by 6.657%, after controlling for self-selection bias. While using SPISs, wheat farmers with large farms and farming familiarity had stronger positive effects on TE. The results highlight the need for more investigation and research into evidence-based good practice for SPIS solutions at the site level to ensure that the rollout of modern equipment not only drives the energy sector forward but also contributes significantly to our level playing field and sustainable environment.

Keywords: solar energy; technical efficiency; crop production

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1. Introduction

Improving agricultural production requires attention to technical efficiency (TE). Simultaneously, one of the main factors affecting the efficiency of agricultural technology is the promotion, acceptance, and effective use of solar irrigation systems (SPISs). The world is suffering from an energy crisis, with countries increasing their use of coal, oil, and gas to power their economies despite decades of calls to reduce reliance on non-renewable energy sources [1]. The impact of the widespread use of fossil fuels has exacerbated the carbon emissions problem and created a global society with increasingly centralized food and energy systems, making them particularly sensitive to disturbances. The world is currently dealing with a series of waves (heat waves, the millennium drought, the impoverishing impact of COVID-19) that have severely affected agriculture systems and triggered possibly serious food crises. These interconnected challenges have caused worldwide food and power price increases, putting farming and irrigation in jeopardy and making energy-efficient technologies usage essential [1–3]. Pump irrigation is vital to the survival of the predominantly agricultural societies of South Asia and Pakistan. Farmers in these areas rely heavily on groundwater to irrigate their crops. Research shows that South Asia is the world's largest consumer of groundwater, withdrawing nearly 210 cubic kilometers a year. Groundwater abstraction is largely dependent on energy supply; thus, the irrigation and energy sector are inextricably linked, a relationship known as the energy–irrigation relationship [4,5]. This linkage has major implications for agricultural production, family income, and the reduction of poverty. The energy–irrigation–poverty link is multifaceted and needs systematic examination to fully understand it, particularly in the background of Pakistan's farming industry.

Energy is a necessary resource for supplying high-efficiency irrigation systems and the usage of tube well irrigation, which may be costly and typically relies on petroleum and coal, leading to greenhouse gas emissions and aggravating environmental deterioration. Pakistan is the world's third biggest consumer of subterranean water for agricultural irrigation, with around 73% of its total land area irrigated either directly or indirectly utilizing 60 billion m^3 of groundwater extraction [6,7]. There are over 1.2 million tube wells, of which 16% are powered by electricity and the rest by diesel, according to one estimate [8]. Around 85% of the 1.2 million tube wells are located in Punjab, with the remaining 15 percent located in Sindh (6.4%), Khyber-Pakhtunkhwa (3.8%), and Balochistan (4.8%). Farmers prefer petroleum tube wells over electric tube wells due to their lower installation and operating costs. The modest depth and higher quality of groundwater in Punjab have facilitated the rapid expansion of privately owned tube wells [9]. Approximately 3000 sunny hours per year with 5 to 7 kWh/m^2 of solar irradiation can be utilized in solar-powered irrigation systems, according to estimates [10,11]. Pakistan has high solar irradiation, with a total installed power of 1083 MW, but there has been slow progress in adopting this technology [12].

According to the specific statistics, Pakistan has a solar photovoltaic (PV) power potential of 1200 kWh/kWp to 2100 kWh/kWp per year, which can be tapped into thanks to the country's overall annual average of worldwide horizontal irradiation (1300 to 2300 kWh/m^2). Solar energy has great potential in Pakistan because of the country's enormous land area and high solar radiation. According to the National Renewable Energy Laboratory (NREL), Pakistan has a solar energy potential of approximately 5500 TWh/year, which exceeds the country's current electricity consumption by more than five times [13]. Pakistan has a high solar energy potential for both on-grid and off-grid applications, according to Shah et al. [11]. The research indicates that Pakistan can produce more than 10,000 GWh of solar-generated energy, which is equivalent to over 50% of Pakistan's current energy consumption. Furthermore, the study found that solar energy can provide a dependable source of electricity for remote and off-grid areas, which can help to enhance access to electricity in these areas [14]. According to the World Bank, Pakistan's present electricity consumption can be met by utilizing only 0.071% of its land for solar photovoltaic energy, as the average yearly solar insolation potential is 5.30 kWh/m^2, which can generate 175,800 GWh [15,16]. Pakistan has invested much in solar energy for agriculture, homes, and businesses [17].

In an agricultural economy like Pakistan, a qualified energy supply is critical to fostering stronger growth in the agricultural sector and improving employment and income opportunities for the vast rural population. Historically, thermal and hydroelectric power has been Pakistan's main energy base. However, Pakistan is currently experiencing severe power outages due to large power supply gaps and excessive growth in energy demand from the expanding industrial and agricultural sectors [18–20]. Because energy is the single most critical condition for the country's economic growth, the rising disparity between energy demand and capacity has severely hampered Pakistan's economic advancement. This disparity has led to higher power prices, denying most poor people in Pakistan the availability of inexpensive and sufficient energy [20–23]. The rise in energy prices, along with frequent power shedding, has had a significant impact on Pakistan's agriculture industry and other economic sectors. More than 60.3% of Pakistan's 180 million people belong to rural regions and rely heavily on farming and associated industries for a living [24]. In

Pakistan, the agricultural industry accounts for around 19.3% of the national gross domestic product (GDP) and employs almost 2/3 of the residents. It accounts for 50% of total exports and occupies 42% of the labor force [4,25]. The agricultural sector's substantial contribution to the economy of Pakistan is owing to climatic circumstances that allow its growers to efficiently cultivate numerous sorts of crops of the top internationally traded quality when compared to the remainder of the globe.

Maize, rice, and wheat are the three principal grain crops farmed in Pakistan [26–28]. The country is self-adequate in crop (wheat) and produces roughly 24.28 million tons of wheat annually, most of which is eaten domestically. Nonetheless, rice is farmed for local consumption and export system, and basmati rice has a significant comparative advantage in global markets. Wheat, rice, and maize are the three most significant crops, occupying 4.8% of all cultivated land and contributing 3.5% of all agricultural production. Annually, 1.3 million tons are produced on an estimated 0.9 million hectares of land [4]. It is crucial to remember that growing these grains demands a lot of water since they need to be regularly watered to employ contemporary inputs such as fertilizer and insecticides. As was already said, farmers in Pakistan frequently utilize traditional energy sources such as electricity to irrigate their land. For Pakistan to have secure food supplies and to reduce poverty, these three crops must be harvested well. The association between irrigation system and energy in this setting is crucial and embraces the importance for the sectors' inclusive success. An insufficient and inconsistent energy supply can harm the possibilities of the agriculture industry overall and families in rural areas.

Pakistan has recently experienced severe energy shortages, leading to frequent power outages and rising electricity prices, negatively impacting farmers using pumped irrigation. Due to a severe lack of energy and insufficient water, farmers are finding it challenging to accomplish the application of the input, which has implications for the country's food production and security. However, due to regular shortages and rising electricity bills, the farmers are utilizing alternative energy sources to pump water. Many farmers in the country have historically utilized electrically powered systems, but due to regular shortages and instability of the power supply, many farmers are converting to pumps powered by different energy sources including diesel, solar, and biogas. Crop growers are forced to satisfy the rising requirement for irrigating various crops at various periods during the growing season which has led to a move from traditional electrically powered pump sets to pumps driven via different bases of energy [29]. While they provide growers with more choices to irrigate their crops, the alternative-energy-driven pump system is more affordable and practical than electricity-powered pumps.

As traditional sources of energy (such as diesel and electricity) gradually become costly and limited, there is a lot of opportunity for employing energy from renewable sources for irrigation systems via pumping in Pakistan [4,30,31]. In the water pumping sector, biogas, windmill pumps, and solar energy photovoltaic (PV) can be utilized in part place of fuel and power [32]. In distant areas of Pakistan where grid energy is either unavailable or insufficient, solar energy pumping is anticipated to provide an adequate alternative for delivering water to fulfill agriculture and drinking needs. Photovoltaic systems are being used to irrigate farms throughout the world, including Pakistan [33–35]. Given that Pakistan utilizes groundwater heavily for agriculture, has a high number of distant communities without access to the grid, and receives around 300 days of the sunshine year [34,36–39], this country offers tremendous potential for renewable-energy-based water pumping technology. Nevertheless, the widespread adoption of these eco-friendly water pumping methods will depend on both their economic and ecological feasibility [4,40]. The adoption and use of water-pumping machinery in rural areas of Pakistan would primarily rely on the amount of knowledge as well as other demographic and socioeconomic characteristics of the participating farmers, in addition to their economic and ecological feasibility. The main purpose of existing research is to pinpoint solar-powered irrigation systems usage and its impact on the technical efficiency of crop production in rural areas of Pakistan.

The rest of the article is separated into the following parts. Explaining the study area is Section 2. The methodology is shown in Section 3. The empirical results are described in Section 4. Section 5 presents the discussion. The research's conclusion, suggestions, and limitations are covered in Section 6.

2. Study Area

Balochistan, the largest province in Pakistan in terms of landmass, covering a whopping 44% of the country's total land area, holds great potential for agricultural development. With a land size of 347,190 square kilometers, this region offers numerous suitable locations for the cultivation of cash crops. However, despite its vast potential, Balochistan's agriculture sector faces significant challenges that hinder its growth and productivity [41,42]. One of the major obstacles faced by the agricultural industry in Balochistan is the scarcity of water, which has a detrimental effect on agricultural activities. Additionally, the lack of energy resources, particularly electricity, further exacerbates the problems faced by farmers in the province. This dire situation has led to a concerning statistic: over 81% of farmers in Balochistan express deep concerns regarding these challenges. In light of these issues, it is crucial to explore alternative and sustainable solutions to address the agricultural woes of Balochistan [43]. One such solution gaining significance worldwide, particularly in developing countries, is the utilization of solar energy systems. Solar power holds immense potential in providing a reliable and renewable energy source for agricultural operations.

3. Methodology

3.1. Data Collection

The current study was carried out in Pakistan's Balochistan province from September 2022 to February 2023. To obtain the data needed for the current investigation, firstly, 1080 questionnaires were delivered to wheat growers. Direct meetings with respondents were conducted utilizing a multistage random sample approach to gather basic information. To better understand the initial platform of SPIS adoption by crop producers in Balochistan, study data were composed in 4 districts (Ziarat, Loralai, Qilla Saifullah, and Harnai), based on their proportion of agricultural production. In the second step, 10 tehsils were selected from 4 districts to complete the planned questionnaire, and in the third stage, 20 union councils (UCs) were nominated from the 10 selected tehsils. In the fourth stage, 40 nominated villages were randomly tracked from 20 UCs and finally key information was obtained from 1080 respondents in designated villages (Figure 1). The questionnaire for this study is separated into several portions. The primary unit of the prepared questionnaire covered the socioeconomic and demographic data of the particular samples. The rest of the feedback form was planned to collect SPIS data from respondents. Questionnaires were used to obtain existing data from wheat growers. Due to the questionnaire's complexity, we conducted detailed interviews. The questionnaire was pre-tested to eliminate uncertainties. This questionnaire contained detailed information on farmers' socio-economic factors, SPISs, and other study-relevant variables. Stata 14 was used to edit and code the data to verify the accuracy, authenticity, homogeneity, coherence, and completeness.

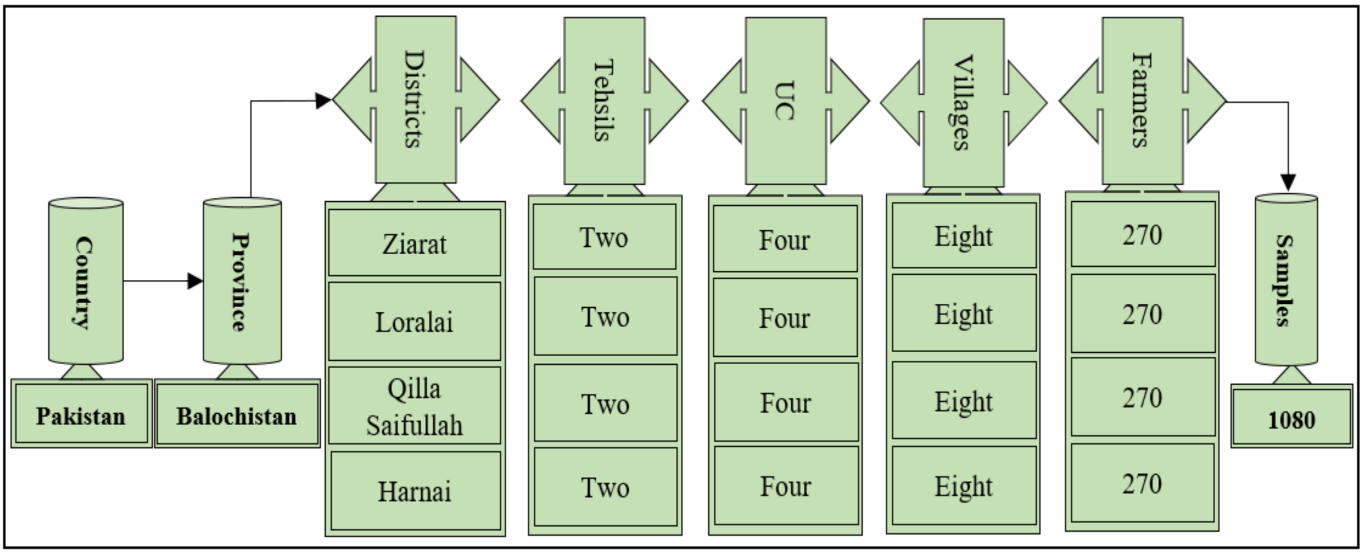

Figure 1. Distribution of sample [44,45].

3.2. Empirical Methods

The evaluation of the existing study was carried out in three phases. First, the TE of wheat production was calculated using an SFPF model. Second, an ESR model was utilized to study the factors influencing growers' decision to acquire irrigation systems from SPISs, and the impact of this technology and other attributes on wheat yield TE and irrigation heterogeneity. In addition, the validity of instrumental variables (IV) was also confirmed at this stage. Finally, robustness testing and heterogeneity analysis were performed.

3.2.1. The SFPF Model

The TE was calculated by using the SFPF model instead of employment data envelopment analysis, which cannot consider random elements such as extreme weather occurrences. The SFPF model was developed as follows:

$$Q_i = Q(X_i;\alpha)\exp(v_i - u_i) \tag{1}$$

where i represents the i-th growers; Q_i signifies the crop output; X_i represents a collection of wheat production inputs like labor, technology, pesticides, and fertilizers; α represents the coefficients to be assessed; v_i signifies the random error factor; and u_i represents the non-negative efficiency factor. The TE of farmers in wheat yield may be calculated according to the following formula:

$$Eff_i = \frac{Q_i}{Q(X_i;\alpha).\exp(v_i)} \times 100\% = \exp(-u_i) \times 100\% \tag{2}$$

where Eff_i represents the TE of the i-th farmer. However, the TE of the farmers is 0 to 100 percent.

3.2.2. The ESR Model

It should be noted that growers' decisions to use SPISs to irrigate their wheat crops may be self-selecting, leading to possible self-selection bias. To resolve self-selection bias, the ESR model consisting of one treatment equation and two outcome equations was widely utilized in past studies [46–49]. In existing research, the stochastic utility framework was to examine growers' decisions to attain irrigation for the wheat crop from the SPISs. We hypothesized that D_i* represents the difference in utility between wheat crops irrigated by SPISs and those that were not. If D_i* > 0, farmers will accept SPISs to irrigate wheat crops, when D_i* ≤ 0, farmers will not accept SPISs to irrigate wheat crops. Consequently, growers' decision to get irrigation for wheat crops through SPISs is modeled as:

$$D_i^* = T_t\beta + \omega_i, D_i = \begin{cases} 1 \text{ if } D_i^* > 0 \\ 0 \; else \; D_i^* \leq 0 \end{cases} \tag{3}$$

where D_i is a dummy variable that is 1 if the wheat grower receives irrigation via SPISs and 0 otherwise; T_i is factoring impacting the growers' decision to use SPISs for crop irrigation; β are coefficients to be calculated; and ω_i is the random error term with 0 means. As well as irrigation from SPISs, there are additional aspects that influence TE. Consequently, two outcome equations were established:

$$Eff_{1i} = Z_i\delta_1 + v_{1i} \text{ if } D_i = 1 \tag{4}$$

$$Eff_{0i} = Z_i\delta_0 + v_{0i} \text{ if } D_i = 0 \tag{5}$$

where 1 represents wheat growers who utilize SPISs to get irrigation crop production and 0 those who do not; the TE in production of wheat by growers using SPISs for irrigation and those not using it is shown by the values Eff_{1i} and Eff_{0i}, respectively; Z_i shows an exogenous variable impacting TE, δ_1 and δ_0 are to be estimated coefficients, and v_{1i} and v_{0i} are random error terms with 0 means.

Assuming the existence of self-selective partiality, the estimated average TE in the actual and fictitious scenarios among growers using SPIS to irrigate their crops are:

$$E(Eff_{1i} \,|D_i = 1) = Z_i\delta_i + \sigma_{\omega v1}\,\lambda_{1i} \tag{6}$$

$$E(Eff_{0i} \,|D_i = 1) = Z_i\delta_0 + \sigma_{\omega v0}\,\lambda_{1i} \tag{7}$$

where $\sigma_{\omega v1}$ is the covariance of ω_i and v_{1i}; $\sigma_{\omega v0}$ is the covariance of ω_i and v_{0i}; and λ_{1i} = $\phi(Ti\beta)/\Phi(Ti\beta)$ represents the inverse Mills ratio. However, φ(•) specifies the standard normal probability density, and Φ(•) represents the cumulative distribution function of the standard normal distribution. The average treatment effect in the treated (ATT), also known as the difference between the predicted average TE of wheat output in the actual and in the actual and counterfactual conditions among growers who use SPISs to irrigate their wheat crops, is determined as:

$$\text{ATT} = E(Eff_{1i}|\,D_i = 1) - E(Eff_{0i}|D_i = 1) = Z_i(\delta_1 - \delta_0) + \lambda_{1i}\,(\sigma_{\omega v1} - \sigma_{\omega v0}) \tag{8}$$

Let σ_ω, σ_{v1}, and σ_{v0} represent the standard deviations of ω_i, v_{1i}, and v_{0i}, respectively. Consequently, $\varrho_{\omega v1} = \sigma_{\omega v1}/(\sigma_{\omega\sigma v1})$ signifies the correlation coefficient between ω_i and v_{1i}, and $\varrho_{\omega v0} = \sigma_{\omega v0}/(\sigma_{\omega\sigma v0})$ signifies the correlation coefficient between ω_i and v_{0i}. The presence of self-selectivity bias is shown by substantial $\varrho_{\omega\upsilon 1}$ and $\varrho_{\omega\upsilon 0}$. To calculate the ESR model, at least one IV is needed. The IV should be represented in T_i but not in Z_i. In addition, it should be associated with the decision of farmers to get irrigation through SPISs, but not with TE until obtained by the SPIS. To estimate the ESR model, the existing study uses the full info maximum likelihood technique [49,50].

4. Empirical Results

4.1. Descriptive Statistics of the Model Variables

According to the descriptive data for imperative variables in Table 1, 13.7% of respondents in the study area used SPISs. About 90% of the sample household heads are male, the average age of the respondents is about 57 years old, and the education level is about 7 years. Only 29% of the growers have tube wells; the remaining 70% have to borrow water for irrigation, signifying that Pakistan has a thriving groundwater market. According to statistics on load shedding, in rural areas, load shedding often lasts for more than 10 h a day, greatly limiting the number of activities using modern inputs and negatively affecting agricultural yields. Based on the study outcomes, an estimated 48% of growers are living in poverty. Regarding the significance of multiple energy sources used by growers in the research area, it is worth noting that the preferred energy source for many farmers is electricity, followed by biogas, diesel, and SPISs. The average area of cultivated land per household is 1.9 hectares, and the output of wheat is 1995 kg/ha.

Table 1. Summary of variables' descriptive statistics.

Variables	Explanation of Variables	Mean (S.D.)
SPIS	1 = if farmer uses SPIS, 0 = No	0.137 (0.49)
Wheat yield	Wheat yield (kg/ha)	1995.5 (290.5)
Gender	1 = If the household head is male, 0 = No	0.828 (0.377)
Age	Farmers' age (years)	57.00 (9.680)
Education	Farmers' education (years)	6.622 (3.281)
Poverty	1 = if the farmer is below the poverty line; 0 = No	0.481 (0551)
Tube well	1 = if farmer has a tube well; 0 = No	0.292 (0.660)
Electricity	1 = if the farmers' energy source is electricity; 0 = No	0.633 (0.521)
Load shedding	Load shedding during a day (hours)	10.57 (7.53)
Diesel	1 = if the farmers' energy source is diesel; 0 = No	0.38 (0.63)
Farm size	The area under production (ha)	1.944 (10.95)
Labor	Labor (1000 h/ha)	0.442 (0.410)
Direct seeding	1 = if grower adopt direct seeding; 0 = No	0.470 (0.498)
Hybrid	1 = if grower adopt hybrid variety; 0 = No	0.486 (0.499)
Agri-Extension	1 = if extension services available; 0 = No	0.270 (0.383)
Organic	Organic fertilizer (kg/ha)	0.637 (3.880)
Chemical	Chemical fertilizer (kg/ha)	0.520 (0.349)
Pesticide	Pesticide (kg/ha)	16.43 (18.40)

The primary differences between growers who receive irrigation for crop production using SPISs and those who do not are shown in Table 2. It demonstrates that there are variations in a wide range of factors between these two groups of wheat growers. Farmers that use irrigation from SPISs for crop production produce wheat at much greater yields while using fewer herbicides, more agricultural machinery, and less human labor than farmers who do not use irrigation from SPISs. Yet, there are no appreciable variations between the two categories of farmers' use of chemical and organic fertilizers. Farmers who receive SPIS irrigation are mostly younger, well-educated, and have more wheat farms in terms of individual and plantation attributes. These large differences may indicate a self-selection bias.

Table 2. Differences between farmers' use and non-use of SPISs.

Variables Name	SPIS Users (n = 300)		SPIS Non-Users (n = 780)		Differences
	Mean	S.D	Mean	S.D	
Wheat yield	8.430	1.651	7.942	1.703	0.488 ***
Gender	0.902	0.298	0.904	0.295	0.002
Age	49.445	9.132	57.160	9.220	−7.715 ***
Education	9.065	2.520	6.140	3.221	2.925 ***
Poverty	21.94	7.59	24.22	7.88	−2.28 ***
Tube well	10.51	4.45	10.41	4.40	0.09
Electricity	11.10	2.17	10.11	2.07	0.98 ***
Load shedding	0.59	0.29	0.51	0.24	0.08 ***
Diesel	0.27	0.45	0.20	0.40	0.07 *
Farm size	7.747	28.333	1.021	3.800	6.7726 ***
Labor	0.286	0.307	0.466	0.419	−0.181 ***

Table 2. *Cont.*

Variables Name	SPIS Users (n = 300)		SPIS Non-Users (n = 780)		Differences
	Mean	S.D	Mean	S.D	
Direct seeding	0.411	0.489	0.480	0.511	−0.10
Hybrid	0.421	0.489	0.488	0.501	0.067
Agri-Extension	0.20	0.40	0.08	0.29	0.12 ***
Organic	0.715	5.550	0.624	3.556	0.091
Pesticide	11.807	12.085	17.165	19.121	−5.356 ***
Chemical	0.496	0.299	0.526	0.358	−0.029

Note: ***, and * denote significance at the 1%, and 10% levels, respectively.

4.2. Technical Efficiency Estimation

We approximated the Cobb–Douglas and translog specifications concerning the SFPF model (Table 3). We performed a likelihood ratio test to recognize the best specification. The χ^2 statistic was 215.244; however, it was not statistically significant (Prob > 2 = 0.579). This implies that the translog formulation of the Cobb–Douglas SFPF is nested inside of it. According to the SFPF model, an individual one percent increase in the cost of organic, chemical fertilizer, and technology can boost wheat production by 0.006, 0.017, and 0.003%, respectively. Manual labor input had, however, a very detrimental impact on wheat output. It may be challenging to separate the production influence of the workforce from that of other contributions due to the collinearity between labor input and other inputs. With the fast-technological advancement in agriculture, there is also a high likelihood of agricultural workforce surplus, which means that the marginal productivity of workforce contribution may tend to be zero. In comparison to non-hybrid varieties, the average wheat production from hybrid kinds is 5.7%. The irrigation from the SPISs does appear to have an impact on the TE of wheat production in the inefficiency equation.

Table 3. Estimated results of the SFPF model.

Variables Name	Coeff. (S.E.)
SFPF model	
LnLabor	−0.015 * (0.009)
LnOrganic	0.006 ** (0.002)
LnPesticide	−0.001 (0.005)
LnChemical	0.017 *** (0.005)
Hybrid	0.058 *** (0.076)
District affects	Yes
CONS	9.105 *** (0.074)
Equation of efficiency	
SPIS	−0.181 (0.169)
Gender	−0.204 (0.185)
Age	−0.007 (0.006)
Education	−0.040 ** (0.018)
Poverty	0.087 (0.065)
Tube well	0.218 *** (0.077)
Electricity	0.018 (0.022)
Load shedding	− 0.005 (0.075)
Diesel	0.119 (0.081)
Ln(Farm size	−0.044 (0.047)
Direct seeding	0.481 *** (0.131)
Hybrid	0.005 (0.0201)
Agri-Extension	0.121 *** (0.045)
District effects	Yes
CONS	−1.069 ** (0.464)
Log-likelihood	214.243 (Prob > χ^2 = 0.579)
Sample numbers	1080

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Furthermore, the results in Table 4 indicate that the use of SPISs for irrigation in wheat production significantly enhances overall efficiency. The average TE of farmers employing SPISs was found to be 83.656% higher compared to those who do not utilize this system, with a TE of 80.801%. These findings highlight the importance of implementing strategies to improve the efficiency of wheat yield. By adopting SPISs and other innovative irrigation techniques, farmers can potentially increase their productivity and contribute to meeting the growing demand for wheat in a more sustainable manner. Enhancing TE in wheat production is crucial for ensuring food security and maximizing the utilization of available resources.

Table 4. Difference of TE between growers using and not using SPISs.

Group	Mean (S.D)
Total	81.191 (11.255)
Farmers use SPISs	83.656 (10.027)
Farmers do not use SPISs	80.801 (11.393)
Differences	2.855 ***

Note: standard deviations are in parentheses. *** denotes significance at the 1%.

4.3. Determinants of Using SPISs

The estimation outcomes of the ESR model are shown in Table 5. The Wald test of independent calculations produced a substantial χ^2 statistic, indicating a dependency presence between the treatment and two outcome equations. Moreover, both the correlation coefficients $\rho_{\omega v1}$ and $\rho_{\omega v0}$ were substantial, confirming the existence of a self-selective bias caused by both observable and unobserved variables. That suggests that employing the ESR model was both suitable and required. Table 5 shows the statistical magnitude and consequence of the calculated coefficient of factors related to farmers' decision to get irrigation for agricultural production using SPISs in the ESR model. Farmers' age had a significantly negative coefficient, showing that older farmers had a decreased likelihood of receiving irrigation for agricultural production using SPISs. This conclusion is fair since elderly farmers may be less capable of employing SPISs. Because the coefficient of a grower's schooling is substantial at the level of one percent, a higher education level helps wheat growers to get irrigation for agricultural production using SPISs (Table 5). This is also plausible since more educated farmers would be more adept at using SPISs in agriculture.

Table 5. Valuation outcomes of the endogenous switching regression model.

Variables Name	SPIS		TE			
			Farmers Use SPISs for Irrigation		Farmers Do Not Use SPISs for Irrigation	
Gender	−0.305	0.202	6.952 ***	2.332	1.085	1.365
Age	−0.035 ***	0.007	0.032	0.086	0.078 *	0.041
Education	0.121 ***	0.021	0.660 **	0.342	0.264 **	0.113
Poverty	10.46	4.42	10.51	4.45	10.41	4.40
Tube well	0.50	0.50	0.49	0.50	0.51	0.50
Electric	0.14	0.34	0.19	0.39	0.08	0.27
Load shedding	0.36	0.48	0.40	0.49	0.31	0.46
Diesel	52.05	7.62	49.07	6.95	55.34	6.96
LnFarm size	0.195 ***	0.038	0.660	0.457	−0.384	0.300
Direct seeding	−0.204	0.132	−3.054	1.988	−4.290 ***	0.815
Hybrid	−0.161	0.167	0.687	3.344	−0.577	0.969
Agri-Extension	0.55	0.27	0.59	0.29	0.51	0.24
District effects	Yes	Yes	Yes	Yes	Yes	Yes
IV	0.611 ***	0.199				

Table 5. *Cont.*

Variables Name	SPIS		TE			
			Farmers Use SPISs for Irrigation		Farmers Do Not Use SPISs for Irrigation	
Constant	−0.220	0.455	58.22 ***	7.444	66.059 ***	3.040
$\rho_{\omega v1}$			0.211 **	0.096		
$\rho_{\omega v0}$					−0.269 ***	0.070
Indep. eqs. (χ^2)	18.539 ***					
Sample numbers	1080		300		780	

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

The falsification test was used to confirm the IV's validity. Table 6 presents the outcome of the falsification test. They observed that the IV had a significantly favorable association with farmers' decisions to acquire irrigation using SPISs, but no significant link with TE among farmers who did not receive irrigation using SPISs. Therefore, it is a legitimate IV.

Table 6. Valuation outcome of falsification test on IV.

Variables Name	SPIS		TE	
IV	0.452 ***	0.199	1.139	0.772
Gender	−0.309	0.199	0.882	1.358
Age	−0.033 ***	0.008	0.054	0.042
Education	0.123 ***	0.022	0.330 ***	0.115
Poverty	0.117 **	0.047	0.130 **	0.046
Tube well	0.110 ***	0.039	0.094 **	0.046
Electric	0.099	0.244	0.040	0.153
Load shedding	0.040	0.029	0.095 **	0.044
Diesel	0.077	0.043	0.132	0.045
LnFarm size	0.197 ***	0.040	−0.240	0.296
Direct seeding	−0.205	0.135	−4.511 ***	0.821
Hybrid	−0.300 *	0.159	−0.739	0.960
Agri-Extension	0.031	0.076	−0.045	0.063
District effects	Yes		Yes	
Constant	−0.109	0.451	67.436 ***	3.030
Samples numbers	1080		1080	

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

4.4. Impacts of SPIS Usage for Irrigation and Other Variables on TE

The ESR model offers support that wheat growers may profit from irrigation using SPISs by improving TE in wheat production. We were able to analyze the probable values of TE for the growers receiving irrigation for the crop from the SPISs in the definite and counterfactual conditions by applying the estimation outcomes of the ESR model (Table 7). This further allowed us to estimate irrigation treatment effects from the SPIS usage on TE in wheat productivity. Table 7 demonstrates that SPIS-based irrigation for crop production may boost TE in wheat yield. In particular, the degree of TE among farmers using SPISs for irrigation was 8.665% points greater than that among those who did not use it. This suggests that irrigation powered by SPISs improved TE in the production of wheat. The current study results suggest that using SPISs for irrigation systems can not only increase the TE of wheat production but may also be helpful for other crops and vegetables.

Table 7. ATT of irrigation from SPISs on TE for wheat growers.

Group	TE (%)		ATT
	SPIS Use	SPIS Non-Use	
Farmers obtain irrigation from SPISs	82.670	74.005	8.665 ***

Note: *** denote significance at the 1%.

Several factors can have an impact on the TE in the production of wheat (Table 5). The ESR model's estimation findings offer further information regarding the impact of other variables on TE in wheat production. For instance, male farmers who used SPISs for irrigation had a TE that was 6.952% points better than female growers who used the same technology. The TE increased by 0.078% points for each additional year of age among farmers who did not use SPISs for irrigation. Better education may not boost the TE of farmers using SPISs for irrigation, while each additional year of formal education raised the TE of farmers not using SPISs for irrigation by 0.264% points. Farmers who did not have access to irrigation for crop production using SPISs found that direct sowing affected their TE.

4.5. Robustness Check

In this study, we tried to assess the validity of the mentioned findings using the treatment effect model. This method, which consists of an outcome and treatment equation, should be emphasized since it has been used extensively in the literature to tackle self-selective bias. The critical variance between the ESR and treatment effect models is that there are two outcome calculations in the ESR model instead of just one in the treatment effect. The outcomes in the treatment effect estimates in Table 8 showed that there was significant dependence between outcome and treatment equations, as shown by the Wald test two statistical for independent equations. The negative correlation coefficient ($\rho_{\omega v}$) demonstrated that farmers with lower-than-average TE preferred to get irrigation for wheat production via SPISs, indicating the self-selective bias existence due to observable and unobservable aspects. According to the optimistic coefficient of irrigation from SPISs, TE increased in wheat yield among wheat farmers by 6.250%.

Table 8. Valuation outcome of treatment effect model.

Variables Name	SPIS		TE	
SPIS	0.328	0.155	6.250 ***	2.117
Gender	−0.283	0.204	2.046	1.272
Age	−0.035 ***	0.008	0.086 **	0.040
Education	0.124 ***	0.022	0.265 **	0.111
Poverty	0.009	0.008	0.008	0.008
Tube well	0.062 ***	0.019	0.056 ***	0.020
Electric	0.096	0.145	0.077	0.146
Load shedding	0.577 **	0.270	0.457	0.287
Diesel	0.034	0.025	0.034	0.026
LnFarm size	0.199 ***	0.040	−0.210	0.364
Direct seeding	−0.191	0.134	−4.090	0.749
Hybrid	−0.249	0.169	−0.284 *	0.935
Agri-Extension	0.429 ***	0.120	0.390 ***	0.120
District effects	Yes		Yes	
IV	0.540 ***	0.200		
Constant	−0.205	0.456	64.720 ***	2.950
$\rho_{\omega v}$	−0.250 ***	0.093		
Indep. eqs. (χ^2)	6.700 ***			
Sample numbers	1080		1080	

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

4.6. Investigation of Heterogeneity

Using the ESR model, we investigated the variability in the impacts of crop irrigation from SPIS on TE in wheat productivity among growers based on farm size and farming experience is presented in Table 9. The SPISs may boost TE in wheat output by 10.446% among farmers with farms over one ha, while it can improve TE by 4.279% among growers with farms less than one ha. In other words, growers with a lower farm size gain less irrigation for the crop from SPISs than those with a bigger farm size. Furthermore, growers with more than 35 years of agricultural knowledge boosted their TE in wheat yield by about 7.577%, though those growers with less than 35 years of cropping intensity improved it by about 10.446%. This means that farmers with less agricultural expertise may profit more when using SPISs to acquire irrigation for wheat production.

Table 9. ATT of irrigation from the SPIS on TE for growers by the group.

Farmers Use SPISs for Irrigation	**TE (%)**		**ATT**
	Usage of SPISs	**Non-Usage of SPISs**	
Farming experience (years)			
>35	83.055	75.478	7.577 ***
≤35	81.265	70.819	10.446 ***
Farm size (ha)			
>1	84.123	73.878	10.245 ***
≤1	81.578	77.299	4.279 ***
Across districts			
Ziarat and Loralai	84.558	81.150	3.408 ***
Qilla Saifullah and Harnai	80.400	70.140	10.26 ***

Note: ATT indicates the ATE on growers using SPISs for irrigation. *** denotes significance at 1%.

5. Discussion

Based on extensive data from Pakistan, this study examines the association between SPIS usage and crop yield TE for wheat farmers. Small contributions of this work to earlier studies can be found in the following: This study uses an ESR model to accommodate selection bias caused by observable and unobservable factors and assesses the effect of SPISs on farmers' TE of crop production. Firstly, we focus on the TE of resident wheat production and then explore the theoretical mechanism of SPISs to improve farmers' TE. The results could point to low-cost strategies for increasing TE production by farmers in less developed countries and provide a new reference point for addressing global TE issues and achieving resilience.

The "ignorance is fearless" mindset has been a stumbling barrier in the advancement of TE resilience. Due to the poor TE of wheat growers, particularly in emerging nations' rural regions, it is hard to motivate growers to deal with agricultural production TE. The findings of this research add to the evidence for the preceding assertion. According to this study, the typical farmers in rural Pakistan have a low level of SPIS perception. Several initiatives have been adopted by Pakistani authorities to improve farmers' TE of production, but farmers' reactions to these activities have been muted due to their low TE of yield. According to this study, increasing farmers' TE of agricultural productivity by SPIS use may inspire them to pursue environmentally friendly actions. As a result, it may serve as a new point of reference for officials in Pakistan and other nations seeking to improve crop output TE. This study is a reaction to and extension of prior research on the link between SPISs and their influence on the TE of agricultural productivity.

The SPIS revolutionized the world and created sustainable agricultural growth. Recent studies, in particular, have acknowledged the significant impact that SPISs play in emerging nations. The cost of irrigation for sustainable agriculture has decreased because of SPIS assistance initiatives. Additionally, this study incorporates SPISs into its investigation of wheat crop TE in rural areas. The implementation of SPISs, however, has a favorable effect and makes substantial contributions to the energy industry, according to this study. Consequently, producers are more likely to be inspired by this technology to act to reduce environmental pollution and increase agricultural output. For instance, farmers may decide to employ renewable energy to lessen air pollution and lower CO_2 emissions if they are aware of the issues with it and the high cost of fuel. As a result, this research offers empirical support for SPISs' beneficial effects on crop TE and sustainable development.

The beneficial effects of adoption have a big impact on the energy industry. The government of Pakistan has decided not to approve additional electrical connections for irrigation because of the country's energy difficulties. According to a current price comparison research, solar irrigation systems are now competitive with grid energy due to lowering costs, whereas diesel-based irrigation is becoming costlier due to rising diesel costs. Pakistan needs to make serious efforts to protect the agriculture industry from the adverse effects of fluctuating global diesel and other fossil fuel pricing and availability difficulties. Therefore, it makes more sense to put up enough solar-powered irrigation systems to make up for this loss and use the energy in other areas. The implementation of solar irrigation systems not only meets the water needs of farmers for irrigation but also encourages economies to utilize their energy and supports the energy sector by supplying any unused energy to the system. To provide a sustainable supply of food, energy, and water, scaled-up SPIS adoption may therefore make a substantial contribution, especially to water-stressed regions and the TE of agricultural output.

6. Conclusion, Policy Implications, Limitations, and Future Directions

6.1. Conclusions

The existing research analyzes solar energy technology's effect on the TE of wheat production utilizing data from 1080 farmers in Pakistan. We used the SFPF to determine the TE of wheat production. To assess solar technology impact and heterogeneity, self-selection biases caused by observed and unobserved variables were addressed using an ESR model. The robustness of the model was tested utilizing the treatment effect model. According to research findings, the TE across questioned wheat producers is over 80%, with 13.7% adopting solar technology. This analysis found that, while adopting solar technology improves TE in wheat production generally, it has varying impacts on TE in wheat production among farmers based on farm size, farming experience, and geography. Solar technology can boost wheat producers' TE by 6.657% points after eliminating the self-selectivity bias. It should be emphasized that the study's findings were also robust when a different model specification was utilized. According to a heterogeneity study, solar technology increases TE more among growers with larger farms and less agricultural practice.

6.2. Policy Implications

The outcomes of this analysis have important policy implications for promoting the adoption of solar energy technology in wheat production in Pakistan. The study suggests that the use of solar technology can increase the TE of wheat production by decreasing the charge of irrigation and expanding the quality of irrigation water. The government could offer subsidies or tax incentives to farmers who adopt solar technology in their wheat production practices. This would help to offset the initial cost of installing solar technology, making it more accessible to small and marginal farmers. The government could also promote awareness and education among farmers about the benefits of solar technology and how it can be integrated into their wheat production practices. This could be done through extension services, farmer training programs, and public awareness campaigns. To encourage the development and dissemination of new solar technology solutions, the government could support research and development initiatives in partnership with the private sector and academic institutions. The government could also invest in building the necessary infrastructure for the production, distribution, and maintenance of solar technology solutions, such as solar panels, water pumps, and other equipment. By implementing these policy recommendations, Pakistan could significantly increase the adoption of solar technology in wheat production, leading to improved TE, increased yields, and enhanced food security.

6.3. Limitations and Future Directions

The existing research has various deficiencies. First, since the study focused on wheat productivity, researchers should be cautious in extending the findings to other crops. This is because agricultural extension services vary by crop. To avoid generalizing the results to other crops, future research should be conducted to investigate the impact of solar technology on other crops. Researchers can also explore differences in agricultural extension requirements for different crops. Second, the number of participants in this study is still small due to the limitation of survey funding and the sample farmers are from one province. In this background, caution must be exercised when extending the findings of this paper to other provinces of Pakistan. To overcome the limitation of a small sample size, future investigations could increase the sample size by selecting farm households from multiple provinces. Alternatively, researchers could use data from national surveys to increase the sample size. Third, it is difficult to analyze the impact of SPIS usage on TE by employing cross-sectional data. To overcome the limitations of using cross-sectional data, future investigations could use panel data that capture changes over time. This will allow researchers to observe the dynamic influence of solar energy technology usage on TE.

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