Journal of Agricultural Policy and Transformation (AgriPaT)
ISSN: 3134-819X
Journal Homepage: http://www.ageconfrontiers.com/agripat
Vol. 2(4) Open Access

Comparative Cost-Benefit and Environmental Performance of Solar, Electric, and Diesel Irrigation Systems: Evidence from Jhang District, Punjab, Pakistan

Muhammad Farhan Azmat[1,*], Neelam Rana[2], Muzaffar Ali[3], Abida Waqas[2], Abrar Hassan[4] & Almazea Fatima[5]
[1]CTI Economics, Govt. Graduate College, 18 Hazari, Jhang
[2]Institute of Agricultural and Resource Economics, University of Agriculture, Faisalabad, Pakistan
[3]Govt. Graduate College
[4]CTI Economics, Government Associate College Maurusipur Toba Tek Singh
[5]Research Affiliate, Sydney institute of agricultural-SIA, School of life and environmental sciences, the University of Sydney, NSW, Australia
[*] *Corresponding author:* farhanmalikk29@gmail.com

ARTICLE INFO

Keywords
- *Solar Irrigation*
- *Cost-Benefit Analysis*
- *Net Present Value*
- *CO_2 Emissions*
- *Technology Adoption*
- *Punjab*
- *Pakistan*

Article History
Received: 02 April 2026
Revised: 29 June 2026
Accepted: 17 July 2026
Available online: 28 July 2026

DOI
10.66529/agripat.2026.2.4.68

ABSTRACT

Pakistan's agricultural sector faces rising irrigation energy costs and unreliable electricity supply, increasing interest in solar-powered irrigation systems as alternatives to diesel and electric pumps. This study evaluates the economic viability, environmental performance, and adoption determinants of diesel, electric motor, and solar photovoltaic (PV) irrigation systems among 240 rice and wheat farmers in Jhang District, Punjab. Data were collected through a stratified random survey of 80 farmers using each irrigation technology. Economic performance was assessed using a 25-year net present value (NPV) framework, while carbon emissions were estimated using system-specific emission factors. Chi-square analysis revealed that solar adopters were significantly younger and more educated than users of conventional systems. Capital constraints were the primary barrier for diesel and electric motor users, whereas solar adopters cited rising fossil-fuel costs and energy independence as key motivations. Despite having the highest initial investment cost, solar irrigation generated the greatest long-term returns, with NPVs of PKR 804,681 and PKR 435,921 for rice and wheat rotations, respectively, while producing substantially lower carbon emissions than diesel-based systems. The findings demonstrate that solar irrigation is the most economically and environmentally sustainable option in the study area. However, high upfront costs remain a major adoption barrier, highlighting the need for targeted financing mechanisms, carefully designed subsidies, and complementary groundwater governance measures to support an equitable and sustainable energy transition in agriculture.

Citation: *Azmat, M.F., Rana, N., Ali, M., Waqas, A., Hassan A. & Fatima, A. (2026). Comparative Cost-Benefit and Environmental Performance of Solar, Electric, and Diesel Irrigation Systems: Evidence from Jhang District, Punjab, Pakistan.* J. Agric. Pol. & Transf. 2(4): 172-184. https://doi.org/10.66529/agripat.2026.2.4.68

1. INTRODUCTION

Pakistan's agricultural sector, which supports roughly two-fifths of the national workforce, is increasingly constrained by the rising cost and unreliability of conventional irrigation energy. Diesel-powered tube wells expose farmers to volatile fuel prices and contribute to local air pollution, while grid-connected electric pumps are subject to load-shedding and steadily rising tariffs (Tahir & Asim, 2018). Against this backdrop, solar-powered irrigation has emerged as a technically mature and increasingly affordable alternative that can reduce both energy expenditure and greenhouse gas emissions while improving water access for smallholder and commercial farmers alike (Akram & Asif, 2020; Ghazi et al., 2021).

The economic case for solar photovoltaic (PV) irrigation rests on a straightforward trade-off: substantially higher upfront capital cost in exchange for near-zero recurring energy expenditure. As global PV module prices have fallen and diesel prices have risen and become more volatile, this trade-off has shifted progressively in favor of solar systems even in capital-scarce settings (Hussain et al., 2023; Terang & Baruah, 2023). Pakistan's high solar irradiance, averaging close to 1,000 W/m², reinforces this advantage (Rafique et al., 2020), and a growing body of work documents shorter payback periods and lower lifetime costs for solar pumps relative to diesel and electric alternatives across South Asia (Bukhari et al., 2023; Shouman et al., 2016; Ul Hussan et al., 2023).

Nevertheless, adoption of solar irrigation in Pakistan remains modest relative to its technical potential. Reported barriers include high initial investment, limited access to formal credit, uneven awareness of long-run savings, and weak after-sales service infrastructure (Agrawal & Jain, 2018; Hussain et al., 2023; Mindú et al., 2021). Resolving which of these constraints binds most tightly and for which group of farmers requires evidence that links farmers' technology choices to both the underlying economics of each system and the socioeconomic profile of adopters. Most existing Pakistani studies, however, either model the technical and financial feasibility of solar pumps in isolation (Tamoor et al., 2021; Ullah et al., 2022) or examine adoption determinants without a matched financial and environmental comparison against the diesel and electric alternatives that solar must displace (Raza et al., 2021; Ullah et al., 2023).

Three gaps motivate the present study. First, district-level studies that simultaneously estimate capital, ownership, maintenance, and operational costs; CO_2 emissions; and net present value (NPV) across all three irrigation technologies rather than comparing solar against only one alternative are scarce for central Punjab. Second, prior comparative work in Pakistan rarely reports formal tests of association between irrigation-system choice and farmer socioeconomic characteristics, relying instead on descriptive percentages that cannot establish whether observed differences exceed what sampling variation alone would produce. Third, the policy literature has yet to reconcile the well-documented capital constraint facing diesel and electric-motor users with the design of financing instruments intended to enable their transition to solar a gap with direct implications for the credibility of subsidy and loan-based interventions. This study addresses these gaps by jointly estimating the comparative economics, environmental performance, and statistically tested adoption determinants of all three systems among rice and wheat growers in Jhang District, and by translating the capital-constraint finding into financing-design implications rather than generic recommendations. Building on this rationale, the study pursues three specific, empirically testable objectives:

1. To compare the financial performance of diesel engines, electric motors, and solar PV irrigation systems for rice (CR1) and wheat (CR2) cultivation using a structured cost-benefit framework (capital, ownership, maintenance, and operational costs; net present value over a 25-year horizon).
2. To quantify the effect of solar system adoption on crop output (kg/acre) and irrigation-related cost savings (PKR/acre) relative to diesel and electric alternatives, and to estimate the associated reduction in CO_2 emissions (kg/acre).
3. To identify the socioeconomic determinants (age, education, and stated adoption motive) associated with the choice of irrigation system, and to translate these determinants into specific, implementable financing and policy recommendations for accelerating equitable solar adoption.

2. LITERATURE REVIEW

The literature on solar-powered irrigation can be organized into three broad strands: (a) studies establishing the technical and financial feasibility of solar PV pumping relative to conventional alternatives; (b) studies examining the socioeconomic and policy determinants of adoption; and (c) an emerging strand that critically reassesses the environmental and resource-sustainability claims made on behalf of solar irrigation. This review synthesizes each strand and identifies the specific gap that the present study addresses.

Technical and Financial Feasibility

Kelley et al. (2010) provided one of the earliest systematic feasibility frameworks for solar-powered irrigation, showing through discounted cash-flow analysis that PV pumping is technically and financially viable where adequate array space and aquifer characteristics permit. Building on this foundation, Shouman et al. (2016) compared solar, solar-diesel hybrid, and diesel pumping in Egypt and found that PV systems carry a lower net present cost over their operating life because of longer equipment lifespans and the absence of recurring fuel expenditure. Mehmood et al. (2015) reached a similar conclusion across five Pakistani cities, reporting that solar water pumping alleviates farm-level energy cost pressure and improves the financial sustainability of irrigated agriculture. More recently, Terang and Baruah (2023) conducted a techno-economic and environmental assessment of solar, diesel, and electric pumps for irrigation in Assam, India, confirming that solar systems offer the lowest life-cycle cost and emissions despite the highest capital outlay, a finding directly consistent with the cost structure analyzed in the present study. Within Pakistan specifically, Bukhari et al. (2023) documented a capital recovery period of only 1.38 years for solar-powered tube wells in Bhakkar, Punjab, with favorable internal rates of return, while Ul Hussan et al. (2023) used a benefit-cost ratio, life-cycle cost, and one-way ANOVA with post-hoc and chi-square tests to compare solar-, electric-, and diesel-powered drip irrigation for maize in Punjab, finding the lowest CO_2 emissions for solar (0.02 t/ha) but the highest benefit-cost ratio for electric power (1.65), a nuance that underscores the importance of disaggregating financial return from environmental performance rather than treating solar as uniformly dominant on every metric.

Adoption Determinants and Socioeconomic Factors

A second strand of research moves beyond feasibility to ask why adoption nonetheless remains uneven. Agrawal and Jain (2018) identified fourteen factors shaping the viability of solar irrigation pumps in developing-country settings, emphasizing that policy design must account for farm size, credit access, and local market conditions rather than treating solar adoption as a purely technical decision. Hussain et al. (2023) similarly found that while Pakistani solar irrigation systems can deliver water savings of approximately 31% relative to diesel and electric alternatives and a return on investment within four to five years, high upfront cost, maintenance difficulty, and regulatory gaps continue to constrain uptake, particularly among smallholders. Closer to the present study area, Ashfaq and Tehreem (2025) used binary logistic regression on 200 rice growers in Hafizabad District, Punjab, and found that education level, farm income, landholding size, access to credit, awareness, and extension contact significantly predicted solar-pump adoption, while high initial investment cost and weak institutional support remained the binding constraints on diffusion, a determinant profile that closely parallels the capital- and education-related findings reported in Section 4 of this study. Raza et al. (2021) examined a government subsidy scheme in Punjab and reported that subsidized solar adoption improved crop productivity and reduced both poverty and reliance on diesel, suggesting that capital-side interventions can shift adoption when properly targeted. Tanvir et al. (2017) and Mindú et al. (2021) extended this picture regionally, showing that ownership-based solar models outperform service-based models economically and that farmer involvement in system installation improves both productivity outcomes and long-run system reliability. Prutzer et al. (2023), reviewing climate-smart irrigation across Bangladesh, India, Nepal, and Pakistan, identified funding shortfalls and power imbalances as the most persistent cross-country barriers, alongside cost savings and water-management pressure as the principal drivers of adoption, a framing that anticipates the capital-constraint finding reported in Section 4 of this study.

Environmental Performance and Emerging Sustainability Concerns

A third, more critical strand of literature complicates the straightforward narrative that solar irrigation is unambiguously beneficial. Ullah et al. (2023) and Ullah et al. (2022) confirmed that solar-powered irrigation improves technical efficiency in wheat production and supports smart monitoring of tube wells in Pakistan, while Terang and Baruah (2023) and Bukhari et al. (2023) quantified the CO_2 emission advantage of solar over diesel pumping in similar settings to those reported here. However, Balasubramanya et al. (2024), writing in Science, caution that the rapid, subsidy-driven expansion of solar-powered groundwater irrigation across South Asia and Sub-Saharan Africa may not deliver the emissions reductions typically assumed, because near-zero marginal pumping cost can induce farmers to substantially increase groundwater extraction, a rebound effect that risks accelerating aquifer depletion even where unit-area emissions fall. This concern is directly relevant to the Jhang context, where intensive tube-well irrigation already raises sustainability questions independent of energy source (Campana, 2015) and is addressed explicitly in the Discussion and Policy Recommendations sections of this study rather than treated as an unqualified co-benefit of solar adoption.

Synthesis and Justification of the Present Study

Collectively, the reviewed literature establishes that (a) solar PV irrigation is generally cost-competitive with diesel and electric alternatives over a multi-year horizon despite higher capital cost; (b) adoption nonetheless lags technical feasibility because of capital constraints, awareness gaps, and weak supporting infrastructure; and (c) the environmental case for solar irrigation, while strong on a per-unit-area emissions basis, requires qualification once groundwater-use rebound effects are considered. What remains underexplored, and what this study contributes, is a single, statistically tested comparison of all three irrigation technologies on cost, output, emissions, and adoption motive within one Pakistani district, paired with policy recommendations that explicitly reconcile the capital-constraint evidence with financing-instrument design. The Materials and Methods section below details how this comparison was constructed.

3. MATERIALS AND METHODS

Research Design

This study employed a cross-sectional comparative design to evaluate three irrigation technologies i.e. diesel engines, electric motors, and solar PVs, at a single point in time. The design was selected because the research objectives (Section 1) call for a direct, simultaneous comparison of cost structure, output, and emissions across technologies rather than a model of change over time and are well suited to the scope of district-level agricultural-economics fieldwork.

Study Area

The study was conducted in Jhang District, located in the Faisalabad division of central Punjab, Pakistan, between approximately 30°37′ and 31°59′ N latitude and 71°37′ and 73°13′ E longitude. The district covers approximately 6,162 km² and is bordered by Sargodha and Chiniot districts to the north, Khanewal district to the south, Layyah, Bhakkar, and Khushab districts to the west, and Faisalabad and Toba Tek Singh districts to the east. Jhang city, the district headquarters, lies approximately 90 km southwest of Faisalabad. The district is bisected by the Chenab and Jhelum rivers, which converge at the Trimmu Headworks, and is served by the Haveli and Rangpur canal systems alongside extensive tube-well irrigation. Agriculture, livestock, and fisheries together account for over 44% of district employment, and rice and wheat are among the dominant crop rotations, making Jhang an appropriate and representative site for comparing irrigation-technology economics. Sampling was distributed across the district's constituent tehsils to capture variation between canal-command and tube-well-dependent farming areas.

Two crop rotations were considered: rice (CR1) and wheat (CR2), reflecting the dominant cropping pattern in the district and allowing irrigation-technology comparisons to be made on a like-for-like basis across both a high-water-demand kharif crop (rice) and a lower-water-demand rabi crop (wheat).

Sample and Sampling Technique

The target population comprised farmers in Jhang District using diesel engine, electric motor, or solar PV irrigation systems. A stratified random sampling design was used, with irrigation-system type (diesel, electric, solar) serving as the stratification variable. Stratification ensured adequate representation of each technology including solar, which remains a numerical minority among irrigation choices in the district and allowed for statistically valid between-group comparison rather than a sample dominated by the most common technology.

A target stratum size of 80 farmers (240 total) was adopted, consistent with standard precision-based sample-size formulae for comparing proportions across independent groups (Cochran, 1977): for an assumed population proportion of $p = 0.5$, a 95% confidence level ($Z = 1.96$), and a margin of error of approximately ±11%, the minimum required sample per stratum is $n = Z^2p(1-p)/e^2 \approx 80$. This sample size also exceeds the minimum conventionally used for parametric and non-parametric between-group comparisons ($n \geq 30$ per group) and is comparable to stratum sizes used in closely related Pakistani irrigation studies (e.g., Ul Hussan et al., 2023). Within each stratum, individual respondents were selected using simple random sampling from village-level farmer lists obtained through local agricultural extension offices.

Variable Definitions

Table 1 operationalizes the principal variables used in the cost-benefit and adoption analyses.

Table 1. Operational Definitions of Key Study Variables

Variable	Type	Operational Definition / Unit
Irrigation system	Categorical (independent / grouping)	Diesel engine, electric motor, or solar PV (self-reported primary system)
Capital cost	Continuous (dependent)	One-time procurement and installation cost, PKR/acre
Ownership cost	Continuous (dependent)	Depreciation + imputed interest, PKR/acre/year
Maintenance cost	Continuous (dependent)	Repair, upkeep, and operator wage cost, PKR/acre/year
Operational cost	Continuous (dependent)	Recurring fuel/electricity expenditure, PKR/acre/year (0 for solar)
Crop output	Continuous (dependent)	CR1 (rice, 40 kg units/acre) and CR2 (wheat, 100 kg units/acre)
CO_2 emission	Continuous (dependent)	kg CO_2/acre/year, by system-specific emission factor
Net present value	Continuous (outcome)	PKR, discounted over a 25-year horizon (Section 3)
Farmer age	Continuous (independent)	Years, self-reported
Education level	Categorical, ordinal (independent)	Illiterate / Primary / Middle / Matric / Intermediate / Graduate
Adoption reason	Categorical, nominal, single response (independent)	Lack of capital / High price of alternatives / Energy independence

Cost Components and Model Specification

Per-acre costs for each irrigation system were estimated using four standard cost categories, consistent with farm-machinery costing conventions:

- Capital cost: the one-time cost of procuring and installing the pump, motor or PV array, and associated fittings.

- Ownership cost: the annualized cost of capital ownership, comprising straight-line depreciation (machine value divided by expected useful life) plus the opportunity cost of capital (imputed interest on the undepreciated balance).
- Maintenance cost: routine repair and upkeep expenditure and operator wages.
- Operational cost: recurring energy expenditure (diesel fuel purchase or grid electricity tariff); solar PV systems incur no recurring operational energy cost once installed.

Land-ownership and tractor-related input costs were excluded from the comparison because they do not vary systematically with irrigation-pump choice and were held constant across the three technologies.

Net present value (NPV) for each system and crop rotation was computed over a 25-year planning horizon, reflecting the typical serviceable life of tube-well infrastructure and solar PV arrays using the standard discounted cash-flow identity:

$$NPV = \Sigma \left[(Rt - Ct) / (1 + r)^{t} \right] \text{ for } t = 1 \text{ to } 25, \text{ less the initial capital outlay at } t = 0,$$

where Rt is annual crop revenue (Section 3), Ct is the sum of ownership, maintenance, and operational cost in year t, and r is the discount rate applied to future cash flows. A real discount rate of 12% was applied, consistent with Pakistan's estimated social discount rate for public and agricultural investment appraisal (Harrison, 2010) and with rates conventionally used by multilateral development banks for project evaluation in South Asia.

Revenue Estimation

Annual crop revenue was calculated as the product of estimated per-acre crop yield (kg/acre) and the prevailing market price (PKR/kg) for each crop, separately for each irrigation system, consistent with the yields reported in Table 8.

CO_2 Emission Estimation

Environmental performance was assessed using system-specific CO_2 emission factors (Table 2), with emission factors drawn from Terang and Baruah (2023). Emissions were estimated as follows:

- Solar PV emission = Operation hours × Pump power rating × Emission factor
- Diesel engine emission = Operation hours × Pump power rating × Fuel consumption rate × Emission factor
- Grid-electric emissions = Operation hours × Pump power rating × Emission factor

Table 2. Emission Factors for Irrigation Energy Sources

Energy Source	CO_2 Emission Factor (EF)	Reference
Diesel	3.130 kg/kg fuel	Terang & Baruah (2023)
Grid electricity	0.830 kg/kWh	Terang & Baruah (2023)
Solar PV	0.085 kg/kWh	Terang & Baruah (2023)

CO_2 emissions were monetized using a uniform shadow price of carbon of PKR 3.90/kg CO_2-equivalent for grid-electricity- and solar-displaced emissions. Diesel emissions were costed at PKR 13.90/kg to additionally capture the local air-quality externality (particulate matter and NOx) associated with direct on-farm combustion, consistent with standard practice of applying a combustion-source externality premium over and above a uniform carbon price.

Data Collection

Data were collected through structured face-to-face interviews conducted on farms, supplemented by telephonic follow-up surveys to extend geographic reach within the district. All instruments used a standardized questionnaire covering demographic characteristics, system-specific costs, crop output, and stated reasons for irrigation-system choice. Respondents provided informed consent prior to participation, and confidentiality was maintained through anonymous identification codes.

Statistical Analysis

Data were entered and analysed in SPSS (IBM SPSS Statistics, v.26). Descriptive statistics, frequencies for categorical variables (education level, adoption reason) and means, standard deviations, and ranges for continuous variables (cost, output, emissions), were generated for the overall sample and for each irrigation-system stratum.

Chi-square tests of independence were used to test whether irrigation-system choice is statistically associated with farmer education level (Table 3) and with stated adoption motive (Table 5). Cramér's V is reported alongside each chi-square statistic as a standardized effect-size measure. The adoption-motive variable (Table 5) was coded as a single, mutually exclusive forced-choice response, consistent with its use as a categorical grouping variable in the chi-square analysis.

4. RESULTS AND DISCUSSION

All variables were analyzed using SPSS. Descriptive statistics are presented first, followed by cost-benefit and environmental comparisons, and a discussion that links each result to the literature reviewed in Section 2.

Demographic Profile: Age and Education

Respondents ranged in age from 25 to 71 years (overall M = 43.09, SD = 9.57). Diesel engine users were, on average, the oldest and most age-heterogeneous group (M = 43.35, SD = 11.17), while solar system users were the youngest (M = 40.02, SD = 8.95) and electric motor users showed the narrowest age range (28–65 years). Educational attainment followed a parallel pattern: diesel engine users had the highest illiteracy rate (13.8%) and no university graduates, whereas solar system users had the lowest illiteracy rate (2.5%) and the highest graduation rate (5.0%) (Table 3).

Table 3. Age and Education Profile by Irrigation System

Demographic Variable	Overall (N=240)	Diesel Engine (n=80)	Electric Motor (n=80)	Solar System (n=80)
Age, Mean (SD), years	43.09 (9.57)	43.35 (11.17)	42.69 (8.25)	40.02 (8.95)
Age range (Min–Max)	25–71	25–71	28–65	25–66
Illiterate, n (%)	15 (6.3)	11 (13.8)	2 (2.5)	2 (2.5)
Primary, n (%)	40 (16.7)	16 (20.0)	12 (15.0)	12 (15.0)
Middle, n (%)	55 (22.9)	21 (26.3)	16 (20.0)	18 (22.5)
Matric, n (%)	103 (42.9)	29 (36.3)	38 (47.5)	36 (45.0)
Intermediate, n (%)	21 (8.7)	3 (3.8)	10 (12.5)	8 (10.0)
Graduate, n (%)	6 (2.5)	0 (0.0)	2 (2.5)	4 (5.0)
Total, n (%)	240 (100.0)	80 (100.0)	80 (100.0)	80 (100.0)

Note. Age reported as Mean (SD) and Range; education reported as Frequency (%). $\chi^2(10, N = 240) = 21.31$, $p = .019$, Cramér's V = 0.21, confirming a statistically significant association between irrigation-system type and education level.

This association is consistent with the technology-adoption literature, which links formal education to greater willingness to absorb the upfront cost and technical learning curve associated with PV systems (Agrawal & Jain, 2018; Hussain et al., 2023). It also echoes a broader pattern documented for Punjab agriculture more generally: in a 100-farmer study of climate-adaptation behavior across the province, Shakeel et al. (2026) found education to be the single most consistent positive determinant of adaptive practices, including the adoption of water-efficient irrigation methods, ahead of farm size or climate awareness. Economically, the pattern indicates that information and capability constraints, not only capital constraints, partly explain the age and education gradient in adoption, reinforcing the case for awareness-focused interventions discussed in Section 6.

Irrigated Land Area

Diesel engine users irrigated the largest mean land area (M = 8.744 acres, SD = 3.613) and showed the widest range (2–22 acres), consistent with diesel engines' higher power output and flexibility for large or non-contiguous holdings. Electric motor users irrigated the smallest mean area (M = 6.369 acres) with the lowest variability, consistent with a fixed power capacity suited to smaller, more uniform plots. Solar system users fell between the two (M = 7.050 acres), indicating moderate scalability (Table 4).

Table 4. Irrigated Land Area by Irrigation System (acres)

	N	Minimum	Maximum	Mean	SD
Overall	240	2.0	22.0	7.387	3.439
Diesel Engine	80	2.0	22.0	8.744	3.613
Electric Motor	80	2.0	16.0	6.369	3.107
Solar System	80	2.0	20.0	7.050	3.170

This pattern shows that solar adoption is not confined to the smallest landholders, as is sometimes assumed in the subsidy-design literature; solar users span a comparable land-size range to diesel users, indicating that farm size alone is not the binding constraint on adoption, a point developed further in Section 4.

Reasons for Irrigation-System Choice

Table 5 reports each respondent's single, primary self-reported reason for selecting their current irrigation system. Diesel engine users overwhelmingly cited lack of capital (100.0%) as their primary reason, as did the large majority of electric motor users (92.5%). No solar system user cited lack of capital; instead, solar adopters cited the high price of fossil-fuel alternatives (76.3%) and energy independence (23.8%).

Table 5. Primary Reason for Selecting Current Irrigation System

Adoption Reason	Diesel Engine (n=80)	Electric Motor (n=80)	Solar System (n=80)
Lack of Capital	80 (100.0%)	74 (92.5%)	0 (0.0%)
High Prices of Alternatives	0 (0.0%)	6 (7.5%)	61 (76.3%)
Energy Independence	0 (0.0%)	0 (0.0%)	19 (23.8%)
Total	80 (100.0%)	80 (100.0%)	80 (100.0%)

Note. Single-response item; percentages sum to 100% within each irrigation-system column. $\chi^2(4, N = 240) = 216.58$, $p < .001$, Cramér's V = 0.67, indicating a very strong association between irrigation-system type and stated adoption motive.

This variable captures the reason farmers chose their current (diesel or electric) system in the first place namely, that diesel and electric systems require substantially lower upfront capital than solar (Table 9) rather than a reason for refusing to switch to solar. Lack of capital therefore explains why these farmers are on diesel or electric systems rather than solar and directly implies that targeted capital relief is the appropriate policy lever for inducing their transition, since solar's capital cost is two to three times higher than diesel's or electric's. This reasoning underpins the targeted financing recommendation developed in Section 6.

Daily Irrigation Capacity

Diesel engines achieved the highest mean daily irrigation capacity (M = 3.800 acres/day), followed by electric motors (M = 3.550 acres/day) and solar systems (M = 2.512 acres/day) (Table 6). This ordering reflects the lower instantaneous power output typically associated with smallholder-scale PV pump configurations rather than any inherent inefficiency of solar technology, and is consistent with comparable findings by Ul Hussan et al. (2023), who likewise reported lower throughput but the highest benefit-cost ratio for electric power and lowest emissions for solar in a similarly designed Punjab comparison.

Table 6. Per-Day Maximum Irrigation Capacity (acres/day)

	N	Minimum	Maximum	Mean	SD
Overall	240	1.5	5.0	3.056	0.836
Diesel Engine	80	2.0	5.0	3.800	0.710
Electric Motor	80	3.0	4.0	3.550	0.501
Solar System	80	2.0	4.0	2.512	0.484

Table 7. Comparative Summary of Irrigation Technology Profiles

Feature	Diesel Engine	Electric Motor	Solar System
Mean age (years)	43.35 (oldest)	42.69 (moderate)	40.02 (youngest)
Illiteracy rate	13.8% (highest)	2.5%	2.5%
Graduate rate	0.0%	2.5%	5.0% (highest)
Primary adoption motive	Lack of capital (100%)	Lack of capital (92.5%)	High alternative price / energy independence (100%)
Daily irrigation capacity	3.80 acres/day (highest)	3.55 acres/day	2.51 acres/day (lowest)
Relative system strength	Power and flexibility	Reliability and consistency	Sustainability and zero operating-energy cost

Crop Output

Solar system users achieved the highest mean output for both crop rotations: 46.02 units/acre for CR1 (rice) and 18.50 units/acre for CR2 (wheat), compared with 39.79 and 16.45 units/acre, respectively, for diesel engine users (Table 8). This output advantage is consistent with more reliable, on-demand water delivery free from fuel-availability or load-shedding interruptions and aligns with the yield gains reported for solar irrigation elsewhere in Pakistan (Hussain et al., 2023).

Vol. 2(4) | Open Access | ISSN: 3134-819X

Table 8. Per-Acre Crop Output by Irrigation System

System	Crop	Minimum	Maximum	Mean	N
Diesel Engine	CR1 (rice), 40 kg units	35.00	43.00	39.79	80
Diesel Engine	CR2 (wheat), 100 kg units	14.00	20.00	16.45	80
Electric Motor	CR1 (rice), 40 kg units	40.50	43.50	42.00	80
Electric Motor	CR2 (wheat), 100 kg units	15.00	17.00	16.00	80
Solar System	CR1 (rice), 40 kg units	43.33	47.50	46.02	80
Solar System	CR2 (wheat), 100 kg units	16.87	19.25	18.50	80

Diesel engine output showed the greatest within-group variability (range: 35.0–43.0 units/acre for CR1), plausibly reflecting heterogeneity in engine condition, fuel access, and operator practice across the sample, whereas solar systems showed comparatively narrow variation, consistent with more standardized commercial PV installations.

Capital, Ownership, and Maintenance Costs

Solar systems required the highest capital investment (M = PKR 110,366/acre) and ownership cost (M = PKR 32,558/acre), reflecting the cost of PV panels, mounting structures, and inverter hardware (Table 9). Electric motors were the least capital-intensive (M = PKR 31,109/acre) and had the lowest ownership cost (M = PKR 9,177/acre), while diesel engines occupied an intermediate position. Maintenance costs were broadly comparable across systems (PKR 4,609–5,175/acre), indicating that the principal cost differentiator between technologies is capital and ownership cost rather than ongoing upkeep.

Table 9. Per-Acre Capital, Ownership, and Maintenance Costs

System	Cost Item	Minimum (Rs.)	Maximum (Rs.)	Mean (Rs.)	N
Diesel Engine	Capital cost	25,000.00	86,666.66	51,602.87	80
Diesel Engine	Ownership cost	7,375.00	25,566.66	15,222.84	80
Diesel Engine	Maintenance cost	2,857.14	8,333.33	5,174.64	80
Electric Motor	Capital cost	15,909.09	50,000.00	31,109.31	80
Electric Motor	Ownership cost	4,693.18	14,750.00	9,177.24	80
Electric Motor	Maintenance cost	2,363.63	7,400.00	4,609.26	80
Solar System	Capital cost	80,000.00	142,500.00	110,366.18	80
Solar System	Ownership cost	23,600.00	42,037.50	32,558.02	80
Solar System	Maintenance cost	2,500.00	8,100.00	4,670.00	80

This cost structure shows that electric motors offer the lowest barrier to entry, diesel engines a moderate one, and solar systems by far the highest, directly explaining the capital-constraint pattern documented in Section 4 and reinforcing that financing design, rather than awareness alone, is the first-order lever for accelerating solar uptake among existing diesel and electric users.

Operational (Energy) Costs

Diesel engines incurred substantially higher per-acre operational costs than electric motors for both crops, while solar systems incurred no recurring operational energy cost by construction (Table 10). For rice (CR1), diesel operational cost (M = PKR 61,169/acre) exceeded electric motor cost (PKR 55,000/acre) by approximately 11%; for wheat (CR2), diesel cost (M = PKR 12,216/acre) exceeded electric motor cost (PKR 9,650/acre) by approximately 27%.

Table 10. Per-Acre Operational (Energy) Costs

System	Crop	Minimum (Rs.)	Maximum (Rs.)	Mean (Rs.)	N
Diesel Engine	Rice (CR1)	52,630.0	68,419.0	61,169.2	80
Diesel Engine	Wheat (CR2)	9,972.0	14,958.0	12,215.7	80
Electric Motor	Rice (CR1)	48,000.0	60,000.0	55,000.0	80
Electric Motor	Wheat (CR2)	8,000.0	12,000.0	9,650.0	80
Solar System	Rice (CR1)	0.0	0.0	0.0	80
Solar System	Wheat (CR2)	0.0	0.0	0.0	80

 | https://doi.org/10.66529/agripat.2026.2.4.68

This gap is consistent with diesel price volatility documented for Pakistan during the study period (Rafique et al., 2020) and explains why solar's cost advantage compounds over the multi-year NPV horizon used in Section 4, even though solar's upfront capital cost is highest.

CO_2 Emissions and Emission Costs

Diesel engines produced by far the highest per-acre CO_2 emissions for both crops (691.19 kg for rice; 145.97 kg for wheat), followed by electric motors (427.87 kg and 78.42 kg, respectively), with solar systems lowest for both crops (48.93 kg for rice and 8.03 kg for wheat) (Table 11). Solar irrigation therefore reduces per-acre rice-season emissions by approximately 93% relative to diesel and 89% relative to electric motors and reduces wheat-season emissions by an even larger margin.

Table 11. Per-Acre CO_2 Emissions (kg/acre)

System	Crop	Minimum (kg)	Maximum (kg)	Mean (kg)	N
Diesel Engine	Rice (CR1)	594.70	773.11	691.19	80
Diesel Engine	Wheat (CR2)	119.16	178.74	145.97	80
Electric Motor	Rice (CR1)	383.11	487.60	427.87	80
Electric Motor	Wheat (CR2)	65.01	97.52	78.42	80
Solar System	Rice (CR1)	44.22	53.50	48.93	80
Solar System	Wheat (CR2)	7.40	8.85	8.03	80

The corresponding emission costs (Table 12) follow the same ordering. As described in Section 3, diesel emissions were costed at a higher per-kilogram rate (PKR 13.90/kg) than electric and solar emissions (PKR 3.90/kg) to capture the additional local air-quality externality of direct diesel combustion, which compounds solar's cost advantage on this dimension beyond the carbon-equivalent comparison alone. The diesel and electricity-driven emissions reported here are broadly consistent in magnitude with other recent Punjab farm-energy footprints: Farooq et al. (2026), applying a comparable input-based carbon-accounting approach to cotton production in Vehari District, found that electricity and diesel together accounted for nearly 89% of an average on-farm carbon footprint of 613.2 kg CO_2-eq per acre, reinforcing that energy source, more than any other input, is the principal lever for reducing the carbon intensity of irrigated agriculture in central Punjab.

Table 12. Per-Acre CO_2 Emission Cost (PKR)

System	Crop	Minimum (Rs.)	Maximum (Rs.)	Mean (Rs.)	N
Diesel Engine	Rice (CR1)	8,266.33	10,746.22	9,607.54	80
Diesel Engine	Wheat (CR2)	1,656.32	2,484.48	2,028.99	80
Electric Motor	Rice (CR1)	1,494.15	1,901.65	1,668.70	80
Electric Motor	Wheat (CR2)	253.55	380.33	305.84	80
Solar System	Rice (CR1)	172.49	208.65	190.85	80
Solar System	Wheat (CR2)	25.96	38.94	31.80	80

Table 13. Annual Per-Acre Cost of Irrigation, by Component

Item	Crop	Diesel Engine	Electric Motor	Solar System
Capital cost (Rs.)	—	51,603	31,109	110,366
Ownership cost (Rs.)	—	15,223	9,177	32,558
Maintenance cost (Rs.)	—	5,175	4,609	4,670
Operation cost (Rs.)	CR1	61,169	55,000	0
CO_2 cost (Rs.)	CR1	9,608	1,669	191
Operation cost (Rs.)	CR2	12,216	9,650	0
CO_2 cost (Rs.)	CR2	2,029	306	32

Table 14. Estimated Annual CO_2 Emissions by Irrigation System (kg/acre/year)

Crop	Diesel Engine	Electric Motor	Solar System
CR1 (rice)	691.19	427.87	48.93
CR2 (wheat)	145.97	78.42	8.03

Revenue and Cost-Benefit Analysis

Annual per-acre revenue was highest for the solar system for both crop rotations (PKR 216,352 for CR1; PKR 129,756 for CR2), exceeding diesel engine revenue by approximately 16% for rice and 13% for wheat (Table 15), reflecting the combined effect of higher yields (Section 4) and zero operational energy deduction.

Table 15. Annual Revenue per Acre by Irrigation System (PKR)

Crop	Diesel Engine	Electric Motor	Solar System
CR1 (rice), Rs.	185,911	197,400	216,352
CR2 (wheat), Rs.	114,997	112,000	129,756

Net present value (NPV) over the 25-year planning horizon, discounted at 12% (Section 3), confirms that the solar system is the most financially advantageous option for both crop rotations: PKR 804,681 for CR1 and PKR 435,921 for CR2, compared with PKR 432,971 and PKR 366,741, respectively, for diesel engines (Table 16). All three systems returned a positive NPV, confirming that each is independently viable, but the solar system's NPV advantage over diesel, approximately 86% higher for rice and 19% higher for wheat, is driven primarily by the elimination of recurring operational cost (Section 4) and secondarily by higher yields (Section 4) and lower CO_2 cost (Section 4), more than offsetting its substantially higher capital cost (Section 4).

Table 16. Net Present Value of Irrigation Systems over a 25-Year Horizon (PKR)

Crop	Diesel Engine	Electric Motor	Solar System
CR1 (rice), Rs.	432,971.11	558,453.43	804,681.40
CR2 (wheat), Rs.	366,740.98	332,166.44	435,920.72

This finding is consistent with comparable techno-economic assessments in South Asia: Terang and Baruah (2023) similarly found that solar PV pumps carry the lowest life-cycle cost despite the highest capital outlay, and Bukhari et al. (2023) reported a capital recovery period of only 1.38 years for solar tube wells in nearby Bhakkar district, confirming that the NPV advantage documented here is not specific to Jhang District alone.

Reconciling Financial and Environmental Performance with Adoption Behavior

Taken together, the results in Sections 4.1–4.9 show that solar irrigation dominates diesel and electric systems on NPV, yield, and emissions, yet adoption remains concentrated among younger, more educated farmers (Section 4), while the large majority of diesel and electric users cite capital, not technology performance, as the reason they remain on their current, financially inferior system (Section 4). This pattern mirrors the adoption-barrier literature (Agrawal & Jain, 2018; Hussain et al., 2023; Prutzer et al., 2023) and indicates that the principal constraint on solar diffusion in Jhang District is access to upfront capital rather than farmer awareness, system performance, or output potential.

A second synthesis point follows from the environmental literature reviewed in Section 2. While the emissions results in Section 4 confirm solar's substantial per-acre advantage, this advantage is calculated holding water use constant. Balasubramanya et al. (2024) document that the elimination of marginal pumping cost under solar irrigation can induce farmers to increase groundwater extraction, particularly where, as in Jhang District, tube-well irrigation already raises groundwater-sustainability concerns independent of energy source (Campana, 2015). This consideration motivates the groundwater-monitoring recommendation developed alongside the financing and awareness measures in Section 6.

5. CONCLUSION

This study compared the cost-benefit and environmental performance of diesel engines, electric motors, and solar PV irrigation systems among 240 rice and wheat farmers in Jhang District, Punjab, and tested the socioeconomic determinants of system choice. The principal findings are summarized below.

- Solar PV irrigation delivers the highest 25-year net present value for both rice (PKR 804,681/acre) and wheat (PKR 435,921/acre), despite requiring 2–3 times the upfront capital cost of diesel or electric alternatives, because it eliminates recurring operational energy cost and achieves the highest crop yields.
- Solar irrigation reduces per-acre CO_2 emissions by approximately 93% for rice and a comparable margin for wheat relative to diesel engines, and by a smaller but still substantial margin relative to electric motors.
- Irrigation-system choice is statistically associated with both farmer age/education ($\chi^2(10, N=240) = 21.31$, $p = .019$) and stated adoption motive ($\chi^2(4, N=240) = 216.58$, $p < .001$): solar adopters are significantly younger and more educated, and are driven by long-run cost savings and energy independence, while diesel and electric users are driven by the lower upfront capital requirement of their current system.

- The principal barrier to solar adoption among diesel and electric users is access to capital, not awareness of solar's financial or agronomic benefits, a finding with direct implications for how financing interventions should be designed (Section 5 below, Recommendations).
- Solar irrigation's environmental advantage is robust on a per-unit-area emissions basis, but the broader sustainability case requires explicit attention to the groundwater-extraction rebound effect documented in the recent international literature.

These findings confirm that solar-powered irrigation is the most productive and financially viable technology for the study area over the long run and clarify precisely why adoption nonetheless lags this financial advantage, together with the specific policy levers that follow.

6. POLICY IMPLICATIONS AND RECOMMENDATIONS

The following recommendations are derived directly from the findings in Section 4 and are framed to be specific and implementable for policymakers, financing institutions, and agricultural extension practitioners.

Targeted Concessional Financing for Diesel and Electric Users

Because lack of capital, not unfamiliarity with solar technology, is the dominant reason diesel (100%) and electric motor (92.5%) users remain on their current systems (Section 4), financing interventions should be targeted specifically at this population rather than offered as a blanket scheme. Concretely:

1. Design concessional, multi-year leasing or hire-purchase arrangements (rather than conventional lump-sum loans) that allow diesel and electric users to substitute the upfront PKR 110,366/acre solar capital cost with a repayment stream sized against the operational-cost savings documented in Section 4 (diesel users alone could redirect approximately PKR 60,000–PKR 73,000/acre/year in foregone fuel and CO_2 cost toward loan repayment without a net cash-flow loss).
2. Calibrate loan or lease tenor to the 25-year NPV horizon used in this study (Section 3), so that repayment obligations do not exceed the period over which solar's cost advantage is realized.
3. Prioritize eligibility for this financing instrument toward diesel users specifically (rather than electric motor users), since diesel users face both the highest operational cost (Section 4) and the highest emission cost (Section 4), implying the largest welfare gain per farmer reached.

This instrument design is consistent with emerging evidence on incentive-based environmental governance in Punjab: Tanveer et al. (2026), evaluating a payments-for-ecosystem-services scheme across four ecological zones of the province, found that redesigned, outcome-linked subsidies significantly increased both household income and adoption of sustainable practices, and recommended decentralized institutional coordination and timely payment disbursement as conditions for success, considerations directly applicable to the leasing and hire-purchase mechanism proposed above.

Education- and Awareness-Linked Extension Programming

Given the statistically significant association between education level and solar adoption (Section 4), awareness campaigns should be paired with, rather than substituted for, the financing instruments above. Specific actions include: (a) delivering solar cost-benefit information through farmer field schools and agricultural extension officers already engaged with lower-education diesel and electric user groups, using the concrete per-acre NPV figures in Table 16 rather than generic messaging; and (b) recruiting early solar adopters within the same tehsil as peer demonstrators, consistent with evidence that farmer-to-farmer involvement improves both uptake and post-installation system reliability (Mindú et al., 2021).

Strengthening Local Supply and Maintenance Infrastructure

Solar system maintenance is comparable in cost to diesel and electric systems on average (Section 4) but is more sensitive to availability of inverter and panel servicing expertise. The Punjab Agriculture Department and private-sector solar suppliers should be supported in expanding certified local installation and after-sales service points within Jhang District, reducing downtime risk that could otherwise undermine the daily-capacity disadvantage already noted for solar (Section 4).

Groundwater Monitoring as a Condition of Solar Subsidy Programs

In view of the documented risk that near-zero marginal pumping cost under solar irrigation can increase groundwater extraction even where per-unit-area emissions fall (Balasubramanya et al., 2024; Section 4), any subsidy or financing program implemented under Recommendation 6.1 should be paired with metered groundwater-use monitoring and, where feasible, volumetric pricing or extraction caps for newly solarized tube wells. This safeguard ensures that the financial and emissions gains documented in Sections 4.8–4.9 are not offset by unmonitored aquifer depletion.

7. LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

As with any cross-sectional, survey-based study, several limitations should inform the interpretation of these findings and the design of future work.

- Cross-sectional design. The study captures a single point in time and therefore cannot establish causal sequencing between, for example, farmer education and technology adoption, or between solar adoption and the yield differences reported in Section 4. A panel or quasi-experimental design (e.g., comparing farmers before and after a subsidy-driven solar conversion) would strengthen causal inference in future work.
- No direct measurement of groundwater extraction. Consistent with the emerging literature on solar-irrigation rebound effects (Balasubramanya et al., 2024), this study cannot determine whether solar adoption in Jhang District is accompanied by increased water withdrawal, since groundwater-table or pumping-volume data were not collected. This is a priority area for follow-up research, ideally using metered tube-well data.
- Single-region, single-crop-pair scope. Findings are specific to rice-wheat rotations in Jhang District and may not generalize to other cropping systems, agro-ecological zones, or provinces without further validation.
- Self-reported cost and output data. As with most farm-survey research of this kind, capital, maintenance, and yield figures rely on farmer recall rather than independently verified records, introducing the possibility of reporting error or social-desirability bias.
- Sample restricted to current adopters. Because the sample was drawn from existing users of each system, the analysis characterizes the relative performance and profile of adopters rather than the preferences of non-adopters or the counterfactual outcomes had a given farmer adopted a different system; future work could usefully incorporate a matched or longitudinal non-adopter comparison group.

References

Agrawal, S., & Jain, A. (2018). Sustainable deployment of solar irrigation pumps: Key determinants and strategies. WIREs Energy and Environment, 7(5), e325. https://doi.org/10.1002/wene.325

Akram, M. W., & Asif, M. (2020). Suitability study of on-farm solar PV system for energy-efficient drip irrigation. Scientific Letters, 8(1), 1–6.

Ashfaq, M. A., & Tehreem. (2025). Determinants of solar-powered irrigation system adoption among rice farmers in Hafizabad, Pakistan. Journal of Agricultural Policy and Transformation, 1(1). https://doi.org/10.66529/agripat.2025.1.1.13

Balasubramanya, S., Garrick, D., Brozović, N., Ringler, C., Zaveri, E., Rodella, A.-S., Buisson, M.-C., Schmitter, P., Durga, N., Kishore, A., Minh, T. T., Kafle, K., Stifel, D., Balasubramanya, S., Chandra, A., & Hope, L. (2024). Risks from solar-powered groundwater irrigation. Science, 383(6680), 256–258. https://doi.org/10.1126/science.adi9497

Bukhari, M. D., Khan, H. F., Hameed, M. S., Yasir, M., Safdar, M., Ahmad, U., & Khawaja, W. A. (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(2), 1070–1081.

Campana, P. E., Li, H., Zhang, J., Zhang, R., Liu, J. B., & Yan, J. (2015). Economic optimization of photovoltaic water pumping systems for irrigation. Energy Conversion and Management, 95, 32–41. https://doi.org/10.1016/j.enconman.2015.01.066

Cochran, W. G. (1977). Sampling techniques (3rd ed.). John Wiley & Sons.

Farooq, M. U., Javaid, A., Mateen, A., & Irfan, H. M. (2026). Carbon and water footprints of cotton production in Punjab, Pakistan: Implications for climate-smart agricultural policy. Journal of Agricultural Policy and Transformation, 2(3), 127–139. https://doi.org/10.66529/agripat.2026.2.3.96

Ghazi, A., Korkmaz, F., & Ahmed, A. (2021). Design and evaluation of solar energy powered groundwater pumping system for irrigation farm in desert. Kufa Journal of Engineering, 12(3), 69–83.

Harrison, M. (2010). Valuing the future: The social discount rate in cost-benefit analysis (Visiting Researcher Paper). Productivity Commission, Australian Government. https://www.pc.gov.au/research/supporting/cost-benefit-discount

Hussain, F., Maeng, S. J., Cheema, M. J. M., Anjum, M. N., Afzal, A., Azam, M., & Iqbal, T. (2023). Solar irrigation potential, key issues and challenges in Pakistan. Water, 15(9), 1727. https://doi.org/10.3390/w15091727

Kelley, L. C., Gilbertson, E., Sheikh, A., Eppinger, S. D., & Dubowsky, S. (2010). On the feasibility of solar-powered irrigation. Renewable and Sustainable Energy Reviews, 14(9), 2669–2682. https://doi.org/10.1016/j.rser.2010.07.061

Mehmood, A., Waqas, A., & Mahmood, H. T. (2015). Economic viability of solar photovoltaic water pump for sustainable agriculture growth in Pakistan. Materials Today: Proceedings, 2(10), 5190–5195. https://doi.org/10.1016/j.matpr.2015.11.034

Mindú, A. J., Capece, J. A., Araújo, R. E., & Oliveira, A. C. (2021). Feasibility of utilizing photovoltaics for irrigation purposes in Moamba, Mozambique. Sustainability, 13(19), 10998. https://doi.org/10.3390/su131910998

Prutzer, E., Patrick, A., Ishtiaque, A., Vij, S., Stock, R., & Gardezi, M. (2023). Climate-smart irrigation and responsible innovation in South Asia: A systematic mapping. Ambio, 52(12), 2009–2022. https://doi.org/10.1007/s13280-023-01900-3

Rafique, M. M., Rehman, S., & Alhems, L. M. (2020). Assessment of solar energy potential and its deployment for cleaner production in Pakistan. Journal of Mechanical Science and Technology, 34(8), 3437–3443. https://doi.org/10.1007/s12206-020-0801-4

Raza, F., Tamoor, M., & Miran, S. (2021). Socioeconomic and climatic impacts of photovoltaic systems operating high-efficiency irrigation systems: A case study of the government subsidy scheme for climate-smart agriculture in Punjab, Pakistan. Engineering Proceedings, 12(1), 36. https://doi.org/10.3390/engproc2021012036

Shakeel, M., Anwar-Ul-Haq, Bibi, J., Sarfraz, Z., & Bukhari, H. N. (2026). Climate change and agricultural adaptation in Punjab, Pakistan. Journal of Agricultural Policy and Transformation, 2(2), 94–103. https://doi.org/10.66529/agripat.2026.2.2.39

Shouman, E., Shenawy, E., & Badr, M. (2016). Economics analysis of diesel and solar water pumping with case study water pumping for irrigation in Egypt. International Journal of Applied Engineering Research, 11(2), 950–954.

Tahir, Z. R., & Asim, M. (2018). Surface measured solar radiation data and solar energy resource assessment of Pakistan: A review. Renewable and Sustainable Energy Reviews, 81(2), 2839–2861. https://doi.org/10.1016/j.rser.2017.06.090

Tamoor, M., Zaka Ullah, P., Mobeen, M., & Zaka, M. A. (2021). Solar powered automated irrigation system in rural area and their socio-economic and environmental impact. International Journal of Sustainable Energy and Environmental Research, 10(1), 17–28.

Tanveer, A., Hussain, S., & Tehrem, S. (2026). Innovation subsidy design and payments for ecosystem services: A mixed-methods approach to multilateral environmental governance. Journal of Agricultural Policy and Transformation, 2(1), 12–18. https://doi.org/10.66529/agripat.2026.2.1.29

Tanvir, R. U., Shahadat, M. R. B., Ghosh, M., & Khan, M. (2017). Prospects and utilization of renewable energy in Bangladesh: A review article. International Journal of Scientific & Engineering Research, 8(4), 1–10.

Terang, B., & Baruah, D. C. (2023). Techno-economic and environmental assessment of solar photovoltaic, diesel, and electric water pumps for irrigation in Assam, India. Energy Policy, 183, 113807. https://doi.org/10.1016/j.enpol.2023.113807

Ul Hussan, I., Nadeem, M., Yamin, M., Ali, S., Omar, M. M., Ahmad, S., Zulfiqar, M., & Mahmood, T. (2023). Socioeconomic and environmental impact assessment of different power-sourced drip irrigation systems in Punjab, Pakistan. AgriEngineering, 5(1), 236–256. https://doi.org/10.3390/agriengineering5010016

Ullah, I., Khan, N., Dai, Y., & Hamza, A. (2023). Does solar-powered irrigation system usage increase the technical efficiency of crop production? New insights from rural areas. Energies, 16(18), 6641. https://doi.org/10.3390/en16186641

Ullah, S., Hafeez, G., Rukh, G., Albogamy, F. R., Murawwat, S., Ali, F., & Rehman, K. (2022). A smart sensors-based solar-powered system to monitor and control tube well for agriculture applications. Processes, 10(8), 1654. https://doi.org/10.3390/pr10081654

Declarations

Funding: The authors declare no specific funding for this work.

Conflict of Interest: The authors declare no conflict of interest.

Data Availability: Available on request.

Author Contributions: Azmat, M.A. - conceptualization, writing (original draft), review & editing. *Rana, N., Ali, M., Waqas, A., Hassan A.* –writing (review & editing), & *Fatima, A.* – Supervising, writing (review & editing), revision.