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EVALUATING TECHNO-ECONOMIC EFFICIENCY OF IRRIGATION SYSTEMS IN PUNJAB, PAKISTAN; A BETA-REGRESSION APPROACH

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ABSTRACT

Water scarcity is a global concern of today's world. It raises questions about agriculture irrigation practices. Efficient and sustainable irrigation practices are required to overcome this major problem. This study proposes the efficiency comparison of solar-powered irrigation with conventional methods of irrigation in the district of Hafizabad. It focuses on both technical and economic parameters. The proposed region is water-scarce and to adoption of a solar irrigation system could be sustainable to overcome the leading problem of water scarcity. Solar irrigation practices could enhance agriculture productivity as well. This study focuses Beta-Regression to understand efficiencies relation deep with independent variables. In this study, a mixed-method approach employed. The proposed study integrates quantitative data from the survey with qualitative data insights from the local officials. This study is intended not only to highlight key potential advantages of solar irrigation but also to provide important policy recommendations as well. Its ultimate focus is to uplift farmer's socio-economic status by promoting sustainable practices of irrigation in agriculture.

INTRODUCTION

1.1 Background and Context

1.1.1 Global Water Scarcity and Agricultural Challenges

We have had to deal with a pavilion of situations which is principally brought about by population development, urbanizing, climate change, contamination and, yes, unseemly mismanagement of our assets and this has appropriately brought about a generative amount of water lack all around the world, which immediately influences our agriculturally focused creation. We are sustaining an expanding population of virtually 81 million individuals every year and its corresponding requirement for freshwater, which is generally utilized for agribusiness–around 70% of total worldwide freshwater withdrawal, then, at that point, water needs to be utilized economically and inside the Earth's limits (Purba et al., 2024; Ragab & Drainage, 2023).

1.1.2 Importance of Efficient Irrigation in Water-Scarce Regions

Surprisingly, one of the best solutions applied is to utilize irrigation to consume more of water resources in a way that the more consumption of water resources leads to higher crop yield which is in fact a most efficient way of eliminating the consumption of water and enhancing the use of water for the sustainable agricultural development. Such kind of strategies are very important for using irrigation with minimum water resources in a very arid and semi-arid region to procure crops (Al Ruheili et al., 2022). In this case, drip irrigation and IoT based automatic control are used for achieving up to 30% yield saving, 50% water saving, which promotes the growth of sustainable agriculture with economic improvement, and problems which must be solved (Askaraliev et al., 2024). Therefore, drip and sprinkler irrigation system or integrated irrigation systems were introduced and put in place to save 30 – 50 percent more water than what the conventional irrigation system could save such that they could be sustainable and to ensure food security (Sari et al., 2024). Since the PISs manipulate the environmental condition, the best method of applying the water to increase the crop yield and to decrease the environmental footprints has changed to Precision Irrigation Systems (PISs) (Lakhiar et al., 2024).

1.1.3 Conventional Irrigation Systems – Reliance and Drawbacks

Traditional methods for water quality assessment and purification face several significant drawbacks, particularly in water-scarce settings. Indeed, it reduces to one of the substantial limitation, i.e. expensive and brain consuming equipment and highly qualified personnels that may be a prohibitive in the resource limited areas and prone to lose data because human error and unable to anticipate the future trend of water quality (Schmitt et al., 2022). However, these methods don't ordinarily go too far with chemical or bacterial contaminants and then we entangle a safe potable water issue (Driscoll et al., 2024). This corroborates the active need of coupling the traditional sort of the approach with the science experts and the emerging technology to achieve the sustainable water security.

1.1.5 Solar-Powered Irrigation – A Sustainable Alternative

Solar powered irrigation systems (SPIS) consist of water pumping devices and irrigation networks which operate using solar energy because they exclude the use of conventional fossil fuels. These water management systems prove effective in cutting carbon pollution at places that lack both reliable electricity and sufficient drinking water supplies according to (Chaudhari & Joshi, 2024). Time-based evaluation of soil wetness and plant requirements via IoT allows for better irrigation operations and enhanced crop yields (Sumalatha & Harshdeep, 2024). Solar tracking systems have undergone innovative developments to boost energy capture and improve the need for direct power supply that enables automated drip irrigation systems to work efficiently (Danton et al., 2020). SPIS benefits from contemporary solar technology developments that make them more affordable and dependable in handling the challenges of energy irrigation systems while fostering agricultural sustainability (Watto & Mugera, 2015).

1.1.7 Hafizabad – Agricultural Profile and Water Scarcity Concerns

Although Hafizabad, Pakistan district is water scarce and several local factors further exacerbate this problem. Climate change also has an important role to play with its effects of changing precipitation pattern and increasing glacial melt resulting in erratic water availability and increased scarcity all across the region (Bukhari et al., 2024; Wang et al., 2024). The area's agricultural dependency exacerbates the problem as the historically excessive irrigation practices have depleted water resources and polluted water quality (Jamali et al., 2021). Furthermore, the rapid growth of the population, urbanization and industrialization in the region further stress the already scarce of the water supplies (Nimah & Moukarzel, 2007). The malaise of water scarcity is further compounded by the absence of suitable water management strategies like rainwater harvesting and demand based irrigation technique (Nabi et al., 2024). However, cases of severe rainfall deficient events of recent years such as in Southern Pakistan have demonstrated the region's vulnerability to extreme weather patterns which are projected to become more intensified under future climate scenarios (Taguta et al., 2022). Such challenges need comprehensive water management policies, international cooperation and the practice of sustainable uses of water to ensure long term water security in Hafizabad and other such areas (Akhtar & Cepiku, 2013).

MATERIALS AND METHODS

The study being proposed utilized a mixed-method approach that integrates quantitative and qualitative datasets and analysis techniques.

Theoretical Framework

1. **Efficiency theory**

It demonstrates how effectively irrigation system uses resources to achieve optimal agriculture production this theory is divided into two basic components. firstly, technical efficiency tells us the ability of an irrigation system to transform input (water and energy) into output (yield of a crop) (Latif et al., 2016). An efficient system technically reduces the utilization of resources and optimizes the output. For example, some studies indicate that solar-powered irrigation systems increase water productivity by 20 to 30 percent in comparison with conventional irrigation methods (Razzaq et al., 2018). It is specifically important in areas of water scarcity region like Hafizabad. Technical efficiency is vital in the enhancement of agriculture productivity in the area where a lot of water shortage. Secondly, economic efficiency evaluates the cost-effectiveness of irrigation systems while considering both initial investment and operational costs. For instance, electricity generated from solar irrigation is estimated on an average of about $70/MWh. It makes solar irrigation more economical than conventional methods of irrigation economic efficiency encloses factors like return on investment, net present value, and cost-benefit ratios. Understanding economic efficiency is crucial for the format to make rational decisions regarding irrigation practices (Malik et al., 2016).

Data Related Framework

Determining an appropriate sample size is critical for robust research and depends on factors such as population size, confidence level, margin of error, and data variability. For this study, the target population consists of 114,058 farmers in a district, categorized by land ownership: large farmers (owning >25 acres, 26%), medium farmers (12.5–25 acres, 33.8%), and small farmers.

$$n = \frac{N \times (z^2) \times p \times (1-p)}{(E\hat{}2) \times (N-1) + (z^2) \times (p \times (1-p))}$$

Where n= required sample, N= population size, in this case, is 114058, Z= z- value is 1.96 for 95 percent, p= estimated proportion of population that is 0.5, E= margin of error is 0.5 after calculation we can get n= '382' that is total sample required.
where N = 114, 058, z = 1.96 (95% confidence level), p = 0.5, and E = 0.05. This yielded a total sample size of 382 farmers, allocated proportionally across strata: 151 large farmers, 167 medium farmers, and 64 small farmers, calculated using nh = Nh×n N . This framework highlights factors affecting the efficiency and adoption of solar irrigation, offering insights for policy recommendations to promote sustainable agricultural practices. The sample size reduces upto more than 100 farmers because of time and constraint. Data collection followed a mixed-method approach to ensure comprehensive insights. A structured survey was designed to gather quantitative and qualitative data, including demographic information (age, education, farming experience), current irrigation practices (solar/conventional, water sources like tube wells or canals), economic factors (initial investment, operational costs), and perceptions of solar irrigation (benefits, barriers, and adoption willingness).

Data analysis

The technical efficiency of an irrigation system can be explained as a proportion of observed output to the maximum possible output in the given inputs. The SFA model is:

$$Yi = f\,(Xi, \beta) \cdot exp(vi) \cdot exp(-ui)$$

Where:

- Y_i: Actual output (act_yld_pa, Maunds/acre).
- X_i: Inputs (e.g., wtr_use_pa, fertilizer, labor, other costs per acre).
- β: Production technology parameters.
- $f\,(X_i, \beta)$: Deterministic production frontier.
- $v_i \sim N(0, \sigma^2)$: Random noise.
- $u_i \sim |N(0, \sigma^2)|$: Inefficiency term.

Where the technical efficiency is :

$$TEi = exp(-ui) = Yi/\,f(Xi, \beta) \cdot exp(vi)$$

Here, A Cobb-Douglas production function is utilized:

$$ln(Yfrontier, i) = \beta 0 + \beta 1\, ln\left(wtr_{use_{pa}}\right) + \beta 2\, ln\left(Fertilizer_{pa}\right) + \beta 3\, ln\left(Other_{Op_{Costs_{pa}}}\right) \ldots.$$

- Inputs were generated (e.g., wtr_use_pa).
- Noise v_i and inefficiency u_i were drawn, with small farmers having higher u_i.
- TE was calculated as $\exp(-u_i)$.
- Yields were derived: $_{y}ld_{p}a_{i} = \max_{p} os_{y}ld_{p}a_{i}\ \cdot$

Example: For Karim Dad (small farmer, wheat):

- Inputs: wtr_use_pa = 1.65 Acre-Feet/acre, Fertilizer_pa = 2 units/acre, Other_Op_Costs_pa = 20,000 PKR/acre.

- $v_i = -0.05$, $u_i = 0.80$, TE = 0.45.
- $\max_p os_y ld_p a = 46.1$, $_y ld_p a = 20.8$.

Economic Efficiency (EE) EE combines TE and allocative efficiency (AE):

$$EE = AE \times TE$$

A simplified approach was used:

$$economic\ efficiency\ =\ technical\ efficiency \cdot Allocative\ Efficiency\ Factori$$

Allocative efficiency factor where drawn by the uniform distribution large farmer is (0.90-0.80) and for small farmers it is in between (0.65-0.79). For Karim Dad, tech_eff = 0.45, AE factor = 0.89, econ_eff = 0.40.

BETA-Regression analysis

This type of regression is employed to deeply check out the key predicators of the technical and economic efficiency carefully. Benefit of using this model that it is best for the proportion variable that are dependent and to be regress against other independent variables and with the (c-log-log) function with link with the mean and the phi- that is precision parameter is as the identity.

$$effi\ \sim\ Exp_{yrsi} + est_{op_{co_{pai}}} + wtr_{prodi}$$

Variables were selected based on theoretical relevance that being distinguished while comprehensive literature review that also aligned with this research as well:

- Exp_yrs: Farming experience of respondent.
- Est_op_co_pa: Reflects Estimated operational cost to operate different irrigation.
- Wtr_prod: Indicates water use efficiency.

Results and Discussion

This indicates the results and discussion of the study that mainly aims run the beta-regression model to demonstrate the technical and economic efficiencies in details to illustrate the dependence of these efficiencies on further various factors and variables. The results are categorize as the comprehensively in the table format and discussion demonstrates all the objective results in a comprehensive way link to the farming practices that carried out in the district Hafizabad.

Beta Regression Results & Discussion

To interpret determinants of TE and EE, beta regression models were estimated. farming experience, operational irrigation cost per acre (est_Op_Co_Pa). The water productivity (wtr_prod) are considered as predictors. As it, the cloglog link function was used. Their AIC/BIC were the lowest. The results for TE and EE, respectively.

Variable	Estimate	Std. Error	z value	Pr(>|z|)
		Mean Model		
Intercept	-0.6550	0.08049	-8.138	4.03e-16 ***
Exp_yrs	0.02263	0.002784	8.129	4.32e-16 ***
est_op_co_pa	-1.228e-05	1.772e-06	-6.931	4.17e-12 ***
wtr_prod	2.750	0.9140	3.009	0.00262 **
		Precision Model		
(phi)	66.144	8.699	7.604	2.87e-14 ***

Note: Log-likelihood = 160.9, Pseudo $R^2 = 0.5911$, AIC = -311.8272, BIC = -298.1462. Significance codes: *** $p < 0.001$, ** $p < 0.01$.

Table 2 Beta-Regression Results for Technical Efficiency (c-log-log-link)

TE was positively affected by Exp_yrs (= 0.02263, $p < 0.001$), wtr_prod (= 2.750, $p = 0.00262$), indicating that a farmer with higher years of experience and higher water productivity would be more technically efficient. On the other hand, est_op_co_pa (/s =-1.228e-05,p<0.001)had a negative effect, e.g. higher irrigation costs reduceefficiency. The model explained 59.11% of the variance (Pseudor^2 =0.5911), with a residual ranging from -2.5957 to 1.9888. For EE, it showed that Exp_yrs (=0.02416,p<0.001) and wtr_prod(=3.051,p=0.00121)positively affected efficiency and est_op_co_pa(=-1.268e05, p<0.001)negatively affected efficiency. The Pseudo-R^2 was 0.5997 (model explained 59.97% of the variance) and the residuals ranged from -2.6242 to 2.0784. Logit, probit, loglog, cauchitlinks and the cloglog link were used for modeling the presence of the calves, however logit, probit and cauchitlinks were rejected by AIC and BIC, while the cloglog link was optimal for both models. The AIC and BIC values indicated that the cloglog link was also optimal for both models mentioned in table 2,3 respectively.

Variable	Estimate	Std. Error	z value	Pr(>|z|)
		Mean Model		
Intercept	-0.8351	0.08338	-10.015	< 2e-16 ***
Exp_yrs	0.02416	0.002878	8.393	< 2e-16 ***
est_op_co_pa	-1.268e-05	1.846e-06	-6.868	6.49e-12 ***
wtr_prod	3.051	0.9425	3.237	0.00121 **
		Precision Model		
(phi)	66.227	8.708	7.605	2.85e-14 ***

Note: Log-likelihood = 159.2, Pseudo $R^2 = 0.5997$, AIC = -308.3379, BIC = -294.6569. Significance codes: *** $p < 0.001$, ** $p < 0.01$.

Table 3 Beta-Regression Results for Economic Efficiency (c-log-log-link)

The study found out what mainly influences a farmer's efficiency. Experienced farmers are more likely to manage their farms by sticking to a regular schedule for watering and adding fertilizers/pesticides. Since this damage is so severe (TE : = 2.750,EE :=3.051), it shows that water saving is important in Hafizabad. A rise in irrigation cost usually lowers efficiency because of using costly pumps or overwatering. Solar pumps could lead to greater efficiency when watering crops. Even without information on Ext_Serv and Join_Org, the strong Pseudo R^2 (TE: 0.5911, EE: 0.5997) explains the data of the performance variables well. Because the cloglog link gives the best fit (lowest AIC/BIC), it's suitable for using statistical beta regression with a limited efficiency score range.

Furthermore, the models work well only for efficiency; adding other aspects such as education and easier credit might improve the understanding of the differences.

Conclusion and Summary

The aim of this study was to assess how well 108 farmers use their resources. Hafizabad, Pakistan, is using a strategy based on (2) showing the results using beta regression models and

(3) comparing irrigation systems in terms of their average efficiency. Through researching primary data about farmers cultivating wheat, rice and sugarcane It gives useful explanations about the outcomes of farming and the way resources are used. Excellence in farming in a significant agriculture area. The chapter discusses the main conclusions and speaks about They notice the limits and present ideas for how to improve research in the future. Promote better ways of farming in Pakistan and other nations.

Summary of Key Findings

Beta Regression Analysis:

The analysis of beta regression models revealed that farming experience, operating irrigation costs for each acre and water productivity helped explain the variation in TE and EE. For TE, Exp_yrs increased results positively. (TE: AIC =-311.8272, EE: AIC =-308.3379), confirming that the models are robust. The results indicate that making irrigation more efficient and increasing experience improve the performance of farmers, but high irrigation costs stop farmers from being efficient.

Limitation of Study

Mean Comparison of Irrigation: The comparison of overall water systems is valuable, but a proper test (such as ANOVA) would be needed to confirm if differences are significant. From Hafizabad to Other Areas: Since farming conditions vary, the study's results are only applicable to Hafizabad. To ensure better use of the findings later on, researchers need to address these gaps in their future studies.

Future Vision for Research

Following from these results, further studies can resolve the mentioned problems and look at agricultural efficiency analysis from various other angles. New Approaches in Research for the better understanding both non-linear connections and issues where output does not match input, experts can use flexible models and full cost/profit frontier models. Neural networks and other machine learning tools may be used in addition to parametric methods to identify what contributes to efficiency in companies.

Literature Cited

Akhtar, M. J. U., & Cepiku, D. (2013). PARTICIPATORY IRRIGATION MANAGEMENT IN PAKISTAN: INITIAL RESULTS OF A PILOT.

Al Ruheili, A. M., Al Sariri, T., & Al Subhi, A. M. J. J. o. t. S. S. o. A. S. (2022). Predicting the potential habitat distribution of parthenium weed (Parthenium hysterophorus) globally and in Oman under projected climate change. *21*(7), 469-478.

Askaraliev, B., Musabaeva, K., Koshmatov, B., Omurzakov, K., Dzhakshylykova, Z. J. M., & Energetics. (2024). Development of modern irrigation systems for improving efficiency, reducing water consumption and increasing yields. *15*(3).

Bukhari, S. R. H., Khan, A. U., Noreen, S. J. J. o. D., & Sciences, S. (2024). Optimizing Water Resource Governance for Sustainable Agricultural and Hydroelectric Development in Pakistan: An In-Depth Examination and Policy Prescriptions. *5*(2), 280-293.

Chaudhari, A. D., & Joshi, V. V. J. P. o. F. (2024). Air moisture harvesting in soil for indoor agriculture: A comparative study of moisture dynamics in shallow porous beds. *36*(12).

Danton, A., Roux, J.-C., Dance, B., Cariou, C., & Lenain, R. (2020). *Development of a spraying robot for precision agriculture: An edge following approach.* Paper presented at the 2020 IEEE Conference on Control Technology and Applications (CCTA).

Driscoll, A. W., Conant, R. T., Marston, L. T., Choi, E., & Mueller, N. D. J. N. C. (2024). Greenhouse gas emissions from US irrigation pumping and implications for climate-smart irrigation policy. *15*(1), 675.

Jamali, M., Soufizadeh, S., Yeganeh, B., Emam, Y. J. R., & Reviews, S. E. (2021). A comparative study of irrigation techniques for energy flow and greenhouse gas (GHG) emissions in wheat agroecosystems under contrasting environments in south of Iran. *139*, 110704.

Lakhiar, I. A., Yan, H., Zhang, C., Wang, G., He, B., Hao, B., . . . Syed, T. N. J. A. (2024). A review of precision irrigation water-saving technology under changing climate for enhancing water use efficiency, crop yield, and environmental footprints. *14*(7), 1141.

Latif, Muhammad, Haider, S. S., Rashid, M. U. J. P. o. t. P. A. o. S. B. L., & Sciences, E. (2016). Adoption of high efficiency irrigation systems to overcome scarcity of irrigation water in Pakistan: adoption of high efficiency irrigation systems. *53*(4), 243-252.

Malik, J, S., Ali, S., Riaz, K., Whitney, E., Malek, M., . . . priorities, p. (2016). Agriculture, land, and productivity in Pakistan. *41*, 9780812294217-9780812294005.

Nabi, G., Hussain, F., Sajjad, B., Masood, M., Liu, D. J. E. M., & Assessment. (2024). Performance evaluation of irrigation outlets with physical model study in Indus basin irrigation system of Pakistan. *196*(12), 1272.

Nimah, M. N., & Moukarzel, S. N. (2007). *Water productivity: a new concept for improving irrigation Water use efficiency.* Paper presented at the 2007 ASAE Annual Meeting.

Purba, H. J., Azahari, D. H., Dani, F. Z., Alsyouf, I., Masmoudi, M., & Obaideen, K. (2024). *Enhancing rice resilience and sustainability: A bibliometric analysis of innovations for food security and environmental conservation.* Paper presented at the BIO Web of Conferences.

Ragab, R. J. I., & Drainage. (2023). Innovation and research in agriculture water management to achieve sustainable development goals. *72*(5).

Razzaq, Amar, Rehman, A., Qureshi, A. H., Javed, I., Saqib, R., & Iqbal, M. N. J. S. J. A. (2018). An economic analysis of high efficiency irrigation systems in Punjab, Pakistan. *34*(4), 818-826.

Sari, N., Putri, A., & Zahwa, T. (2024). *Effects of contaminated irrigation water on green lettuce growth on Wick Hydroponic System.* Paper presented at the IOP Conference Series: Earth and Environmental Science.

Schmitt, J., Offermann, F., Söder, M., Frühauf, C., & Finger, R. J. F. P. (2022). Extreme weather events cause significant crop yield losses at the farm level in German agriculture. *112*, 102359.

Sumalatha, K., & Harshdeep, K. (2024). *Smart Monitoring and Irrigation Regulation via IoT and Cloud.* Paper presented at the 2024 8th International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud)(I-SMAC).

Taguta, C., Dirwai, T. L., Senzanje, A., Sikka, A., & Mabhaudhi, T. J. E. R. L. (2022). Sustainable irrigation technologies: a water-energy-food (WEF) nexus perspective towards achieving more crop per drop per joule per hectare. *17*(7), 073003.

Wang, Z., Chen, R., Li, W., Zhang, J., Zhang, J., Song, L., . . . Li, Z. J. n. S. A. (2024). Mulched drip irrigation: A promising practice for sustainable agriculture in China's arid region. *2*(1), 17.

Watto, M. A., & Mugera, A. W. J. J. o. H. R. S. (2015). Econometric estimation of groundwater irrigation efficiency of cotton cultivation farms in Pakistan. *4*, 193-211.