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Economic Analysis and Demographic Determinants of Solar Energy for Agricultural Sustainability in North Region of Bangladesh

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Abstract

This study investigates the economic viability and demographic determinants of solar-powered agricultural systems in Bangladesh, emphasizing their potential to enhance agricultural sustainability. Through a comprehensive analysis of economic metrics such as payback period, return on investment, and net present value, the findings indicate that while the initial investment is substantial, these systems can yield significant returns. Variability in operational costs and area coverage suggests that local conditions play a crucial role in influencing system efficiency and profitability. A logistic regression analysis reveals that family size, motivation, and education are significant predictors of solar adoption. In contrast, age, land size, and income did not affect the decision of farmers to adopt the SIP. Based on these insights, the study recommends targeted outreach and education initiatives, customized financial solutions, and further exploration of site-specific factors to promote solar energy adoption among farmers. By addressing these areas, solar-powered agricultural systems can become more accessible and economically viable, supporting sustainable agricultural practices and rural development in Bangladesh.

Keywords: Solar-powered Agricultural Systems, Economic Viability, Demographic Determinants, Sustainable Agriculture**,** Adoption Factors

1. Introduction

Bangladesh is a small South Asian country struggling with a vast population. Despite its relatively small land area of approximately 148,000 square kilometres, Bangladesh, a densely populated developing country, is no exception to this trend. The deployment of solar energy has emerged as a promising solution to address the country's energy needs, particularly in rural areas where grid extension is not economically feasible (Wohiduzzaman *et al*., 2014) [18]. The livelihood of around 70% of the population in Bangladesh depends on agriculture (Nikita *et al*., 2016) [14]. Rajshahi region of Bangladesh, located in the northern part of the country, presents a unique context for the exploration of solar energy's potential. This region is characterized by its marshy lands, which are not suitable for traditional agricultural activities. This territory is mainly agrarian, with fertile land that produces rice, wheat, maize, and various fruits like mango and litchi. This part is often considered one of the more economically disadvantaged portions of the country, with slower industrial development. Efforts to develop agriculture and rural industries are ongoing to improve the livelihood of the population in this region. Agricultural sustainability is crucial for ensuring a better future in Bangladesh. Improved sustainable irrigation management can mitigate the scarcity of non-renewable resources. Investment in modern agricultural technology in solar-powered irrigation can increase yields while minimizing environmental harm. Sustainable energy sources have gained increasing attention in recent years as the world grapples with the challenges of climate change and the need to reduce greenhouse gas emissions. Solar-powered irrigation systems, for instance, provide farmers with a reliable and cost-effective solution for water management, especially during dry seasons in the long run. By using renewable energy, farmers can reduce their dependence on polluting diesel engines. Thus, agricultural sustainability practice is essential for the future betterment of the mass population in the study area.

2. Literature Review

Rajshahi region in Bangladesh is known for its agricultural activities, including the cultivation of crops, fruits, and vegetables. As the country's population continues to grow, the demand for food and water resources is steadily increasing, putting a strain on the local environment and the availability of traditional energy sources. In this context, the integration of solar energy into agricultural practices can offer a sustainable solution, not only by reducing the reliance on fossil fuels but also by enhancing the overall productivity and profitability of the agricultural sector (Ahmed & Fernando, 2017) [1]; (Kata *et al*., 2021) [9]. The use of renewable energy sources has become increasingly crucial in addressing the global energy crisis and promoting sustainable development (Mallan *et al*., 2021) [11]. One area where solar energy can play a pivotal role is in the agricultural sector, particularly in regions like Rajshahi, Bangladesh, where the growing population and limited access to traditional energy sources present significant challenges (Mallan *et al*., 2021) [11] (Fluck, 1984) [4]. The use of solar-powered irrigation systems, for instance, can significantly improve water management and crop yields, especially in areas with limited access to reliable electricity.

Moreover, the adoption of solar photovoltaic and solar thermal technologies by farmers can not only reduce household expenses but also increase agricultural income, thereby driving sustainable agricultural development in the region (Kata *et al*., 2021) [9]. Furthermore, the integration of solar energy into agricultural practices can have a positive impact on the local environment. The use of solar-powered equipment can minimize the release of harmful emissions, contributing to a cleaner and more sustainable ecosystem. Moreover, the use of solar irrigation pumps has gained traction in recent years, particularly in developing regions like sub-Saharan Africa, due to its numerous benefits (Falchetta *et al*., 2023) [3].

On the other hand, diesel engines are widely used in the agricultural sector due to their high thermal efficiency, good fuel efficiency, and higher power (Wang & Li, 2022) [17]. However, the use of diesel engines in agriculture has led to serious problems, such as energy shortages and environmental pollution (Wang & Li, 2022) [17]. The exhaust from diesel engines contains various pollutants, such as particulate matter, nitrogen oxides, and carbon monoxide, which can have significant negative impacts on human health and the environment (Reşitoğlu *et al*., 2014) [15]. Researchers have found that diesel-powered systems not only have adverse environmental impacts but also contribute to financial inefficiency for companies (Markovic *et al*., 2016) [12]. As a consequence, sustainable energy alternatives, like solar energy, have the potential to address these issues and provide a cleaner and more cost-effective solution for the agricultural sector (Yadava *et al*., 2017) [20].

Recent studies have highlighted the significant business potential of the solar energy sector in Bangladesh, with positive perceptions towards renewable energy products in terms of convenience and comfort for society. (Hossain *et al*., 2017) [7] Moreover, the introduction of solar home systems in rural areas has shown promise in improving lifestyles and fostering socio-economic development by enhancing opportunities for small business owners and providing additional time for study and other household activities (Wohiduzzaman *et al*., 2014) [18]. One key advantage of solar irrigation pumps is their economic viability. The economic benefits of solar energy compared to diesel and grid electricity are substantial in Bangladesh. Additionally, solar energy systems, especially in off-grid rural areas, offer long-term savings. The adoption of solar-powered irrigation systems has gained traction in various regions, including Sub-Saharan Africa and India, due to their potential to reduce the reliance on fossil fuels and provide a sustainable and cost-effective alternative (Durga *et al*., 2023) [2]. A study on the economic viability of solar irrigation pumps in Jaipur, Rajasthan, India, found that the payback period, net present value, benefit-cost ratio, and internal rate of return all indicated the economic feasibility of these systems (Gautam, 2021) [5]. Similarly, a review of the literature on solar energy for irrigation in sub-Saharan Africa suggests that the economic prospects for solar pumping are particularly favourable in the region due to the large availability of aquifers and surface water basins combined with high solar irradiance and increasingly cheap photovoltaic-powered pumps (Falchetta *et al*., 2023) [3].

Bangladesh faces significant challenges in providing reliable and accessible electricity to its growing population, particularly in rural areas (Hossain *et al*., 2017) [7]. With an average daily solar energy potential of 4-6.5 kWh/m2, Bangladesh has immense opportunities to harness solar power as a sustainable energy solution (Nikita *et al*., 2016) [14]. The country's high population density and limited availability of arable land, however, present unique obstacles in deploying large-scale solar photovoltaic projects**.** One of the key barriers to the adoption of solar irrigation pumps is the high upfront cost associated with the technology (Durga *et al*., 2023) [2]. The level of awareness and understanding about the benefits of solar irrigation pumps can also influence their adoption. Farmers who are well-informed about the potential savings on fuel costs, the positive environmental impact, and the availability of government support are more likely to embrace the technology. The socio-economic and demographic factors that influence the acceptance of solar irrigation pumps, such as age, education, and farm size, can also shape the adoption of solar irrigation pumps.

Furthermore, farmers with larger landholdings may be more inclined to invest in solar pumps, as they can reap greater benefits from the technology (Kumar *et al*., 2020) [10] (Durga *et al*., 2023) [2]. Moreover, Targeted policies, financial assistance, and awareness campaigns can help accelerate the adoption of this transformative technology and unlock its potential to enhance agricultural productivity and sustainability in the region. (Gautam, 2021) [5] (Falchetta *et al*., 2023) [3] (Kafy *et al*., 2018) [8] (Durga *et al*., 2023) [2].

Despite the growing emphasis on solar energy for agricultural sustainability, limited research exists on its economic feasibility and adoption in the Rajshahi region. Additionally, there is a lack of region-specific cost-benefit analyses that evaluate the long-term impacts of solar energy in rural farming communities. This research aims to evaluate the economic viability of solar-powered irrigation systems in greater Rajshahi and analyze how demographic factors influence the adoption of solar energy.

3.Materials and Method

3.1 Study site and data collection

The study was conducted in two districts of Bangladesh, Thakurgoan and Rajshahi. A total of 200 data were collected with 100 respondents from Thakurgoan district, specifically from the sub-districts of Thakurgoan Sadar and Pirgong, and another 100 from Rajshahi district, from Durgapur and Charghat sub-districts. The selection of these districts was purposive to explore regional variations in solar energy adoption for agricultural sustainability. Thakurgoan represents a northern district with distinct climatic and agricultural practices, while Rajshahi, located in the northwest, has a more established farming culture. Sub-districts and respondents were selected randomly to ensure a representative sample of the rural farming population. The random selection of respondents from different socio-economic backgrounds helps provide a diverse perspective on the demographic and economic factors influencing solar energy adoption. Data collection was carried out through a structured questionnaire with farmers focusing on economic, demographic, and sustainability-related variables. This approach ensures that the study captures both local insights and broader patterns of solar technology use in agriculture. The purposive selection of districts allows for an in-depth comparison of different regional dynamics of economic analysis and accepting solar-powered agricultural irrigation solutions. A map of the study site is shown in Fig 1.

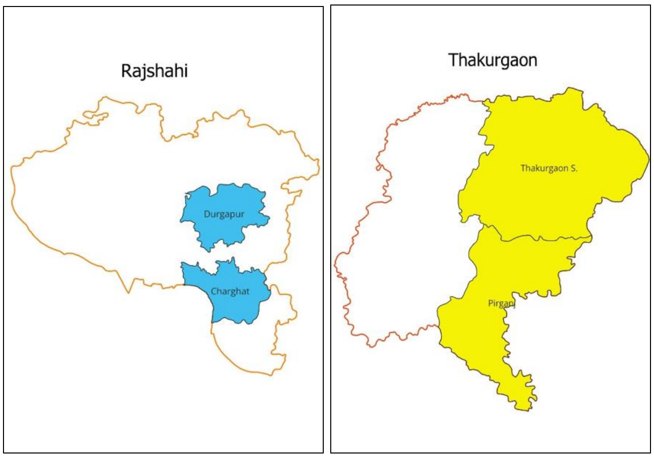

Fig 1

3.2 Framework for Economic Analysis

The return on investment (ROI) is a metric used in economics to assess the efficacy of capital expenditures and the management of various investment initiatives (Tiwari & Sahota, 2018) [16]. By comparing the solar irrigation systems' ROI to that of the diesel-operated system, this study finds that the former is more cost-effective. For the computation of ROI, the return is divided by the initial investment that is indicated in Equation (1):

$$ROI = \frac{\sum_{t=1}^{T} R_t - I}{I} \quad (1)$$

In the above equation, R is the net annual cash inflow, t is the valuation time, T is the technical lifespan of solar PV, and I is the initial investment for solar irrigation project.

Another economic tool is the PBP, which is defined by calculating the time needed to recover an investment. In this study, the PBP is the amount of time that takes to recover the cost of the initial investment in a solar-operated irrigation pump. It is equal to the cost of the investment, I, divided by the net annual cash flow, Rt, as described in Equation (4).

$$PBP = \frac{I}{R_t} \quad (2)$$

Lastly, the NPV is a well-accepted criterion to decide if a project is feasible or not. The following points characterize the function of an NPV: (a) a positive denotes that the financial position of the investor is better by performing the endeavor; (b) a negative NPV indicates a financial loss; and (c) zero or null NPV shows that the present value of all benefits over the lifespan is equal to the present value of all the expenses (Wu & Buyya, 2015) [19]. The required formula is shown in (3).

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t} - I \quad (3)$$

In the equation r is the discount rate. Since solar and diesel irrigation projects are mutually exclusive alternative investments, the project with the highest positive NPV should be preferred.

3.3 Empirical Model for Demographic Determinants

In order to analyses the demographic determinants that influence farmers' decision to accept solar irrigation pumps, a logistic regression model is used whether a farmer will accept the service or not. The model includes a total of seven explanatory variables to elucidate farmers' adoption of sustainable agricultural practice in terms of accepting the technology. The variables used in this study were chosen based on existing literature and objectives of the study. The regression model takes the form of equation (1).

$$\text{Ln}\left[\frac{P(Y)}{1-P(Y)}\right] = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + u \quad (4)$$

Where, the dependent variable is the log of odd ratio of the probability of respondents' acceptance of solar pump, and P(Y) stands for probability that the respondent is adopting of solar irrigation pump service and 1-P(Y) is the probability that the respondent is not is accepting of solar irrigation pump service. Specification of the regression model as shown in equation (2).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + u \quad (5)$$

Where, Y is a dummy variable assuming value 1 if the farmer accepts solar irrigation pump and zero otherwise, X_1 stands for age of the respondent, X_2 for family type, X_3 for family size of the respondent, X_4 for family motivation of the respondent, X_5 for educational status of the respondent, X_6 for land size of the respondent, and X_7 for income of the household head. $\beta_0 \ldots \beta_7$ are coefficients to be estimated and *u* is the error term.

3.4 Measurement of Dependent and Independent Variables

Unit of measurement for all variables are not similar since different variables are used in the model. The dependent variable, the adaption of the solar irrigation pump, is a dummy variable, while the explanatory variables are both dummy and continuous variables education, farming experience, land size, peer relation, income, training, relative price, and social capital. These types of variables were used in the earlier literature (Guta, 2014; Mathijs, 2000 [13]).

Table 1: Variables used in the regression model

Required variables	Type	Measurement unit
Acceptance of solar energy	Dummy	1= yes, and zero otherwise
Age of the respondent	Continuous	Year
Family type	Dummy	1= unitary, and zero otherwise
Family size	Continuous	Number
Family motivation	Dummy	1= yes, and zero otherwise
Education of the respondent	Continuous	Year
Land size of the farmer	Continuous	Bigha (1bigha = 33 decimals)
Income	Continuous	Taka

4. Result and Discussion

The descriptive statistics in Table 2 provide key insights into the costs and area coverage of solar-powered agricultural systems. The initial investment ranges from 5,900,000 BDT to 6,900,000 BDT, with an average of 6,251,500 BDT, indicating relatively consistent setup costs across the surveyed sites. Yearly operational costs vary more significantly, from 80,000 BDT to 280,000 BDT, with an average of 180,800 BDT. This variation suggests that factors such as system size, maintenance, and energy demand may affect ongoing expenses.

Table 2: Descriptive statistics of various cost and area coverage

Variables	Minimum	Maximum	Mean
Initial investment	5900000	6900000	6251500
Yearly operational cost	80000	280000	180800
Area coverage per site	62	100	89.60

Source: Based on field survey data, January 2024

In addition, area coverage per site ranges from 62 to 100 hectares, with an average of 89.60 hectares, indicating that solar systems can support large agricultural areas, though local conditions may influence efficiency.

Table 3 presents key economic metrics—Payback Period (PBP), Return on Investment (ROI), and Net Present Value (NPV)—to assess the financial performance of solar-powered agricultural systems. The PBP, which extends from 10.08 to 17.07 years, with an average of 11.64 years, signifies that solar investments typically require a significant financial commitment over a long period. This underscores the long-term benefits of these systems, which could influence adoption decisions, especially for small-scale farmers.

Table 3: Descriptive statistics of economic matrics

Economic matrics	Minimum	Maximum	Mean
PBP (in years)	10.08	17.07	11.64
ROI (percentage)	17.16	98.33	75.71
NPV	-2034132.32	824590.50	52471.74

Source: Based on field survey data, January 2024

ROI shows significant variability, from 17.16% to 98.33%, with a high average of 75.71%. This suggests that while some systems yield modest returns, others are highly profitable, reflecting differing site-specific efficiencies and operational factors. The NPV ranges from a negative -2,034,132.32 BDT to a positive 824,590.50 BDT, with an average of 52,471.74 BDT.

The regression results highlight in Table 4 the impact of various socio-demographic factors on solar-powered system adoption. Family type, with a negative coefficient (-0.898) and a p-value of 0.077, suggests that some family structures are less likely to adopt solar systems, with marginal significance at the 10% level.

Table 4: Regression Result

Variables	Coefficient	Standard error	P-value
Age	-0.013	0.018	0.462
Family type	-0.898	0.508	0.077*
Family size	0.513	0.158	0.001***
Family motivation	1.620	0.382	0.000***
Education	0.272	0.070	0.000***
Land	0.006	0.005	0.213
Income	0.000	0.000	0.905
Constant	-5.222	1.311	0.000

Source: Based on field survey data, January 2024

Moreover, family size is a significant positive factor, with a coefficient of 0.513 and a highly significant p-value of 0.001, meaning larger families are more likely to adopt solar energy. Similarly, family motivation is a particularly strong predictor, with a large coefficient (1.620) and a highly significant p-value of 0.000, indicating motivated families are much more likely to adopt. Besides, education also plays a crucial role, with a coefficient of 0.272 and a highly significant p-value of 0.000, showing that higher education levels increase the likelihood of adoption. On the other hand, land size and income did not impact on the adoption decision.

5. Major findings

The major findings from the regression analysis reveal key socio-demographic factors that influence the adoption of solar-powered systems. Age does not significantly affect adoption, as indicated by its non-significant coefficient and p-value. Family type shows a marginally significant influence, with certain family structures being less likely to adopt solar systems. Family size emerges as a strong predictor, with larger families showing a higher likelihood of adoption. Family motivation is a particularly important factor, with highly motivated families being much more inclined to adopt solar energy. Education also plays a critical role, with higher levels of education significantly increasing the probability of adoption. On the other hand, land size and income do not significantly impact adoption decisions, as their p-values indicate no statistical relevance. As a consequence, family dynamics (size and motivation) and education are the most influential drivers of adoption, while age, land size, and income had no effect. This suggests that non-economic factors, such as social structure and awareness were key determinants of solar irrigation adoption.

6. Challenges of the study

Different soil types across regions affect irrigation efficiency. Diverse crops have different irrigation needs, which can fluctuate throughout the growing season. Solar energy availability depends on weather conditions, and in regions with inconsistent sunlight, this could limit the system's ability to pump enough water during crucial periods. Although solar systems have long-term benefits, the high upfront cost can be a barrier for many farmers, particularly in resource-limited areas. The wide range of yearly operational costs, as shown in the data, highlights the challenge of maintaining these systems efficiently, especially in remote areas. Farmers may lack the expertise to manage and maintain solar-powered systems effectively, leading to suboptimal performance. In areas with scarce or irregular water sources, even a well-functioning solar irrigation system might not be enough to support all agricultural needs. The profitability of solar systems can vary, with some areas showing low net present values (NPV), making it a less attractive option for certain farmers. Insufficient government support or lack of access to subsidies can deter farmers from investing in solar irrigation systems. After all, the research conducted on the areas where project-based solar irrigation pumps were run by Infrastructure Development Company Limited (IDCOLL) through government initiatives may not be effective for smallholder farmers.

7. Conclusion and recommendations

The adoption of solar-powered irrigation systems offers substantial potential for promoting sustainable agriculture, but several socio-demographic and operational challenges should be addressed. While family size, education, and motivation are key drivers, factors like soil quality, crop water needs, and the high initial cost hinder widespread adoption. Additionally, the lack of technical knowledge and inconsistent sunlight further complicate system effectiveness.

Policymakers should focus on providing financial incentives, such as subsidies or low-interest loans, to offset the high initial investment. Training programs to educate farmers on system maintenance and optimal usage are essential for maximizing efficiency. Research should be directed towards developing solar systems that are adaptable to different soil types and water needs, ensuring they can meet diverse agricultural demands. Equally important is the need to expand infrastructure in rural areas to support installation and maintenance efforts. Moreover, future studies should explore region-specific data to tailor solutions to local challenges, ensuring that solar-powered irrigation systems can be a viable and sustainable option for all agricultural sectors.

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