Optimizing the Performance of Solar PV Water Pump by Using Response Surface Methodology

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Optimizing the Performance of Solar PV Water Pump by Using Response Surface Methodology

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Abstract: Diesel-powered irrigation pumps are widely used. However, due to the global increase in the price of oil, the hazardous pollutants released during combustion, the high cost of maintenance, and the short lifespan of conventional vehicles, innovators have been compelled to find an alternative. Scientists are now developing a solar-powered irrigation water pumping device. Solar is a good alternative because it can be used anywhere, even in remote areas. Studying what affects a solar photovoltaic water pump's efficiency is the primary objective of this effort. It was shown to be more economical, less harmful to the environment, and dependable than diesel-powered water pumps, requiring less maintenance and having a longer service life. In this investigation, the effects of AT (°C), SR (W/m^2), SAA (degrees), and TA (degrees) on SPVWPS were investigated. In order to maximize the output response discharge (m^3/hr) and the pump efficiency (%), the RSM was used to model to obtain optimal values of input parameters. At a parameter combination of solar radiation (451 W/m^2), ambient temperature (27°C), surface azimuthal angle (-18°), and tilt angle (55°), the maximum discharge (48.7 m^3/hr.) and pumping efficiency (58.8%) are reached (57°). It turned out that the formulated mathematical model could accurately predict the SPVWPS's performance and efficiency.

Keywords: Tilt angle; Surface azimuth angle; Solar panel; Solar pump.

1. Introduction

Energy is seen to be one of the most important inputs for every country's economic and social growth. India's energy consumption is steadily increasing, putting a huge strain on the country's finite resources. With a land size of 3.288 million square kilometers, it is the world's sixth-biggest country. However, India continues to face many developing issues [1].

Therefore, it is not a wise option to rely solely on rainfall water for crops. With the aid of a water pump, irrigation may be done from well, canals, rivers, and other sources. The bulk of farms in developing nations is between 0.5 and 2 hectares in size, with irrigation water demands ranging from 20 to 120 m^3/day. Irrigation of the summer crop requires water pumping, which is done with traditional lifts, diesel or electric motor pumps [2]. As a result, agricultural water pumping demand is highest in the summer, when solar energy availability is also highest, making solar water pumping a viable choice. The traditional pumping system (diesel or electric pump) has the benefit of being simple to install, but it has some drawbacks, including regular equipment repair, refueling, and the lack of diesel [3-5] Due to factors such as rising fossil fuel costs and the extension of new power lines. Energy from the sun is possibly more appropriate for irrigation than other renewable resources since crop water requirements are heavily dependent on incoming solar irradiation [6].

India has a large solar energy potential for powering water pumps due to its weather condition [7]. One such use is solar photovoltaic water pumping systems, which can help meet drinking and irrigation water demands in rural and isolated places where grid energy is not readily accessible. Also, the fuel costs have increased by approximately 250% [8]. To boost SPVWPS, the Indian government is taking a variety of actions, including providing subsidies. These incentives and initiative programs are assisting in encouraging farmers to use SPVWPS with minimal investment [9]. Also, due to air circumstances and the earth's rotation, solar radiation reaches the earth's surface in sporadic bursts. Intermittence and variability restrict the practical conversion of solar radiation by necessitating either intermediate energy storage or application to a job that tolerates intermittency. Irrigation water pumping is an operation where intermittent activity is usually acceptable. This fact, together with the possible economic rewards, has sparked interest in this field of study. However, in order to obtain widespread popularity, a more cost-effective design than the traditional pump is required [10].

Solar photovoltaic (PV) energy removes the need for power lines to be run to remote places. To carry the fossil fuels in remote regions might also be costly. Solar energy is advantageous for agricultural irrigation since the majority of irrigation occurs while the sun is shining strongly [11]. As a result, a solar PV pump system might be a potential method for assisting remote agricultural land in meeting its water requirements. In many regions, sprinkler and trickle irrigation systems are the most typical high-efficiency irrigation methods. It is now required to research the aspects that impact SPVWPS's performance and efficiency [12]. The environmental circumstances must be addressed while evaluating the performance and efficiency of a solar water pumping system. A selection of the elements that have the greatest influence on the system's performance and efficiency are studied in this investigation. Gad [13] used a computer simulation tool to build a methodology for performance prediction for PV water pumping systems. The tool replicates the system's hourly performance at any time of year and with various PV array orientations. PV array efficiency is calculated to range from 13.86% in the winter to 13.91% in the summer. Glasnovic and Margeta [14] used a similar method to develop an optimization model for sizing solar water PV pumps, which they tested in two sites in Croatia. Their study used the irrigation technology, the Solar PV pump, the crops, the ambient condition, the bore-holes, and the soil to establish the desired function. The solar generator's electrical power was observed to be lower using the innovative optimization technique than using the standard optimization method. Chandel and Naik [15] PV pumping was found to be one of the most promising uses of solar energy systems because it is good for the environment, doesn't need much maintenance, and doesn't cost anything for fuel. Waeli [16] conclude that RSM is similar to traditional water pumping systems, only it's solar-powered. Solar energy and PV array size affect pumped water flow rate. Mahmoud and Nather [17] carried out the effectiveness of Solar pump systems for irrigation systems (dripping and sprinkling) using batteries. Solar water pumps can be used to pump water in agricultural applications. It was found the, on comparison to diesel and grid connected water pump, solar pump is less expensive. Also, when compared to other common irrigation systems, solar water pumps work better during daytime hours. In addition to improving the quality of life in rural regions, the solar water pump system encourages socio-economic progress. According to Abdolzadeh et al. [18], the insolation, operational head, and PV array size all influence solar PV pump performance. They noted that the structure should be based on pump well parameters, among other things, in order to maximize pump efficiency.

The preceding literature study revealed that the performance of SPVWPS is affected by a variety of factors such as ambient temperature, tilt angle, solar radiation, wind speed, and solar azimuthal angle, among others. The effect of various input parameters on solar water pump performance must be optimized. RSM is an acceptable choice since it is a mathematical strategy used to determine optimal variables for a multi-variable system and is widely regarded as a capable instrument for the optimization of the process. RSM may be used to assess the regression correlation of various inputs and outputs [19]. Dhole et al. [20] used RSM to build mathematical models that connect brake thermal efficiency, unburned hydrocarbons, CO, and NO_X by modifying engine variables such as load and H_2 fuel substitution.

It was found that limited research was carried out on the performance of SPVWPS depending on solar radiation (W/m^2), solar azimuthal angle, tilt angle, and ambient temperature (ºC), according to the literature review. The goal of this research is to determine the influence of SR, AT, SAA, and TA on SPVWPS through experimental. According to the aforementioned literature review, very little research has been conducted on the parametric evaluation of different parameters on the performance and efficiency of solar photovoltaic water pumping systems, and no optimization analysis has been conducted on the most important parameter influencing solar pump performance. To the knowledge of the researcher, no study on the development of a regression model for forecasting solar pump performance using RSM has been conducted. Finally, in the conclusion, the findings are analyzed and a conclusion is offered. This work is unique in that it is the first to construct a polynomial model for forecasting SPVWPS productivity outputs. The primary purpose of this research is to investigate how four input parameters, AT, SR, SAA, and TA, impact on output response (discharge (m^3/hr.) and pumping efficiency (%) of a solar photovoltaic water pumping system used for Agriculture purpose.

2.1 Working principle of SPVWPS

The photovoltaic (PV) system is based on semiconductor technology, which turns sun radiation into electricity. According to the system design, the solar PV water pump system consist of PV panels, a motor, and a pump, batteries, and charger regulator. The motor is selected depending on the system's power needs and current output type. A direct current (DC) to alternating current (AC) converter must be fitted if the motor runs on an alternative current (AC). SPWPSs without batteries are less costly and require less maintenance than battery-powered devices. Storage batteries, on the other hand, deliver steady performance even during times when the sun isn't shining. A water storage tank is less expensive than a battery backup system in SPWPS. For countries with tropical climates, where direct sun radiation can approach $1000W/m^2$, solar photovoltaic energy is recognized as a valuable resource [21].

2.2 Response surface methodology (RSM) modelling

This research has two key goals. The first was to predict discharge (m^3/hr.) and pumping efficiency (%) as they were affected by parameters such as AT, SR, SAA, and TA and the second was to determine the optimum factor levels that allowed researchers to obtain the desired response values. It was necessary to identify the mathematical relationships between the aforementioned replies and the components for these goals. This would allow us to make forecasts and optimize.

RSM model's variable-response connections using orthogonal arrays. Modeling, prediction, and optimization were done using RSM. The RSM is necessary because the sample point must be chosen to create a credible model with the fewest feasible tests. Experiment design can find these spots. This inquiry's test matrix used CCRD. Using the maximum factorial design matrix, quadratic response surface models were built. Building relationships with least-squares. RSM always uses numeric inputs. RSM may generate an ANOVA-based model between response and independent variables. The 2nd polynomial regression model (quadratic) is employed, and it is represented as follows [22]:

$$Y = \beta_\circ + \sum_{i=1}^{k} \beta_i \, x_i + \sum_{i=1}^{k} \beta_{ii} \, x_i^2 + \sum_{j \geq 1}^{k} \beta_{ij} x_i x_j + \varepsilon \ldots \ldots (1)$$

where Y is the response, β_° is the average of the replies, and β_(i), β_ii, and β_ij are the response coefficients The second, third, and fourth terms, respectively, reflect linear, higher-order, and interaction effects and ε is the error or noise in the system.

Table 1 displays the experimental range for each parameter. Following the selection of the variables to be researched. Table 2 summarizes the specifics of RSM experimental designs. As can be seen, a 31 array matrix of experimentation with different formulations is required.

Table 1: Ranges of experimental of different variables and their level

Input parameters	**Unit**	**Coded Levels**				
		-2	**-1**	**0**	**1**	**2**
Solar Radiation (SR)	(W/m^2)	300	450	600	750	900
Ambient Temperature (AT)	(°C)	25	30	35	40	45
Surface Azimuthal angle (SAA)	(degree)	-20	-10	0	10	20
Tilt angle (TA)	degree	30	40	50	60	70

Table 2: Experimental results using CCRD

Exp. Run	**Solar Radiation (W/m^2)**	**Ambient Temperature (°C)**	**Surface azimuthal angle**	**Tilt angle**	**Discharge (m^3/hr)**	**Pumping efficiency (%)**
1	750	40	10	60	42.8	61.1
2	600	35	0	50	37.7	50
3	600	35	0	50	37.7	50
4	600	35	20	50	33.3	50
5	750	30	10	40	41.3	40.3
6	450	30	10	40	28.6	40.3
7	750	40	10	40	42.7	40.3
8	450	30	-10	60	29.3	60.5
9	450	30	10	40	28.9	40.3
10	600	35	0	30	37.2	31.9
11	600	35	0	50	37.7	50
12	600	35	-20	50	38.2	50
13	450	40	-10	60	28.8	60.5
14	600	35	0	50	37.7	50
15	600	35	0	70	38.6	31.9
16	750	40	-10	40	43.4	40.3
17	450	40	10	60	28.2	60.5
18	300	35	0	50	25	50
19	450	40	10	40	29.2	40.3
20	600	25	0	50	37.2	50
21	600	45	0	50	37.4	50
22	450	30	10	60	29.2	60.5

23	600	35	0	50	37.7	50
24	600	35	0	50	37.7	50
25	750	30	-10	60	43.4	61.1
26	750	40	-10	60	42.2	60.5
27	750	30	10	60	43.3	61.1
28	450	40	-10	40	29.6	40.3
29	600	35	0	50	37.7	50
30	750	30	-10	40	43.7	40.3
31	900	35	0	50	48.9	61.1

ANOVA further demonstrated that, at the 95% confidence level, inequality is unimportant for all high response models. Response regions and mountain sites are designed for each of the three separate variants of the concept. Visualize the cumulative influence of the three components in any response. For the replies, a quadratic polynomial model was produced. Surface plots were explained by holding one factor constant in each figure. The analysis of these charts reveals how variables affect the response. Table 3 shows the ANOVA findings for the studies that were carried out. For all models, the probability value (p-value) is <0.01. Therefore, ANOVA demonstrates that the model is statistically significant. The effects that are not statistically significant ($p > 0.05$) and R^2 [23]. A predicted-R^2 that is equal to the fitted R^2 indicates that the fit is good for predicting as shown in Table 4.

Table 3: ANOVA analysis of Discharge (m^3/hr.) and Pumping efficiency (%)

		Dischatge (m^3/hr)				Pumping efficiency (%)			
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	14	506.290	36.164	10.24	0.000	1782.78	127.342	3.09	0.017
Linear	4	96.217	24.054	6.81	0.002	414.82	103.706	2.52	0.082
SR(W/m^2)	1	3.496	3.496	0.99	0.335	36.10	36.103	0.88	0.363
AT(^{o}C)	1	79.172	79.172	22.42	0.000	9.00	8.998	0.22	0.646
SAA(Degree)	1	1.498	1.498	0.42	0.524	2.80	2.799	0.07	0.798
TA(Degree)	1	0.668	0.668	0.19	0.669	230.84	230.844	5.61	0.031
Square	4	115.046	28.762	8.14	0.001	645.64	161.411	3.92	0.021
SR*SA	1	3.362	3.362	0.95	0.344	114.43	114.426	2.78	0.115
AT*AT	1	100.259	100.259	28.39	0.000	11.06	11.064	0.27	0.611
SAA*SAA	1	6.806	6.806	1.93	0.184	11.06	11.064	0.27	0.611
TA*TA	1	6.806	6.806	1.93	0.184	439.06	439.060	10.66	0.005
2-Way Interaction	6	25.633	4.272	1.21	0.351	3.13	0.522	0.01	1.000
SR*AT	1	14.481	14.481	4.10	0.060	0.10	0.103	0.00	0.961
SR*SAA	1	0.779	0.779	0.22	0.645	1.16	1.158	0.03	0.869
SR*TA	1	2.320	2.320	0.66	0.429	0.89	0.894	0.02	0.885
AT*SAA	1	3.711	3.711	1.05	0.321	1.16	1.158	0.03	0.869
AT*TA	1	0.209	0.209	0.06	0.811	0.10	0.103	0.00	0.961
SAA*TA	1	0.779	0.779	0.22	0.645	1.16	1.158	0.03	0.869
Error	16	56.501	3.531			658.72	41.170		
Lack-of-Fit	9	56.501	6.278	*	*	658.72	73.191	*	*
Pure Error	7	0.000	0.000			0.00	0.000		
Total	30	562.791				2441.50			

Table 4: Assessment of model

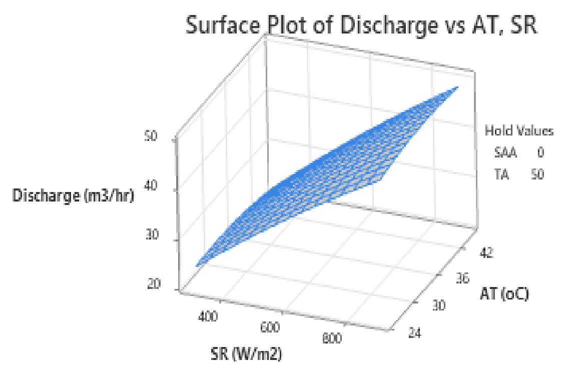
Model	SD (Standard deviation)	R^2	Adjusted R^2	Predicted R^2
Discharge	1.06913	98.30%	96.81%	89.07%
Pumping efficiency (%)	6.41639	73.02%	49.41%	84.66%

3. Results and discussion

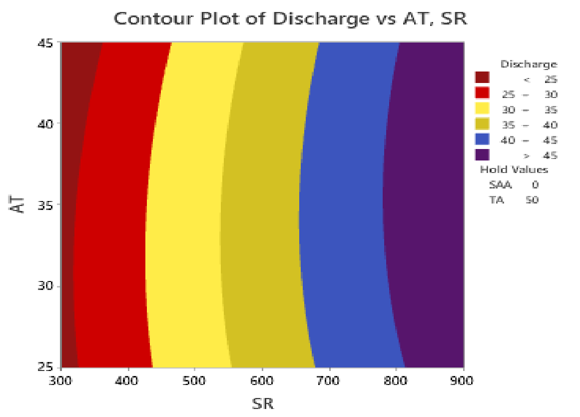
3.1 The influence of control factors on discharge

The quadratic models for the discharge (m^3/hr) were produced using actual factors and are shown below in equation (2) using MINITAB 17 software.

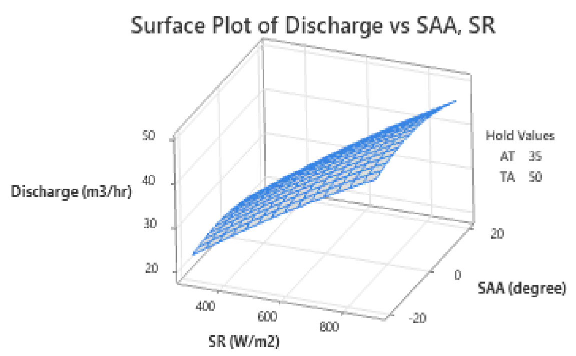
$$\text{Discharge } (m^3/hr) = -1.8 + 0.0384*SR\,(W/m^2) + 0.757*AT\,(^{o}C) - 0.558*SAA\,(degree) + 0.101*TA(degree) - 0.000011*SR(W/m^2)*SR\,(W/m2) - 0.01105*AT\,(^{o}C)*AT\,(^{o}C) - 0.00660*SAA(degree)*SAA(degree) - 0.00114*TA(degree)*TA(degree) + 0.000224*SR(W/m^2)*AT(^{o}C) + 0.000088*SR(W/m^2)*SAA(degree) + 0.000190*SR(W/m^2)*TA(degree) + 0.00627*AT(^{o}C)*SAA(degree) - 0.00297*AT(^{o}C)*TA(degree) + 0.00428*SAA(degree)*TA\,(degree) \quad (2)$$



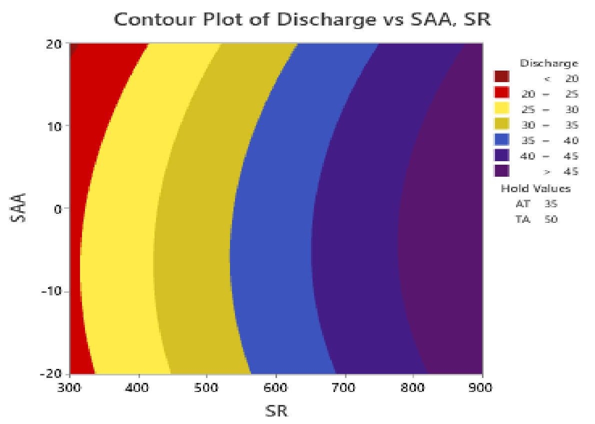
(i)a



(i)b



(ii)a



(ii)b

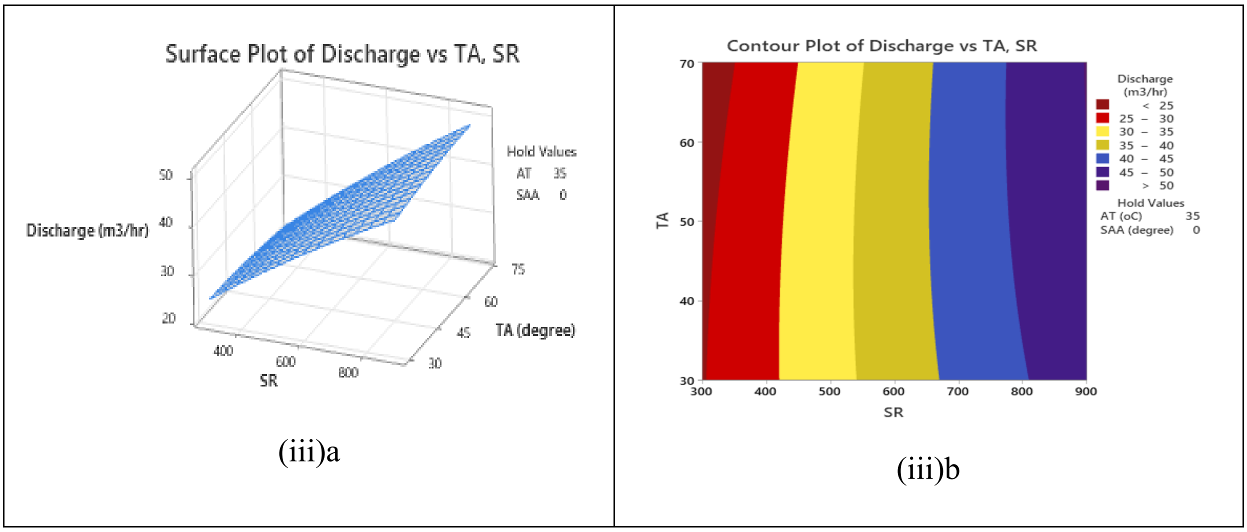


Figure 1: The impact of input parameters on discharge

Figures 1 (i), (ii), and (iii) (a & b) show the variation of input parameters on the discharge from the SPVWPS through surface plot and contour surface. It was observed that the discharge of a solar water pump is proportional to the amount of incident solar radiation. The maximum discharge was found to be 48.86 m^3/hr. at maximum radiation of 900W/m^2. It was determined that when solar radiation increased, pump discharge increased until the pump achieved its maximum power. The surface map revealed that when the ambient temperature rises, the discharge of SPVWPS gents rises as well. This is because when the temperature rises, the photovoltaic cell charges more and provides more power to the SPVWPS [24].

The solar azimuth angle is the angle formed by the projection of the sun's center onto the horizontal plane and due south. These angles are physical features of the Sun's position in relation to a certain spot on Earth, and so are independent of the inclination and orientation of the surface. The azimuth angle should be south for the Northern Hemisphere and north for the Southern Hemisphere. The discharge of the solar pump rose in direct proportion to the solar azimuthal angle (SAA). The quantity of solar energy reaching the planet grew as the SAA rose [25]. The angle produced by the horizontal plane and the solar panel is known as the tilt angle. It is generally advised that solar systems be built with a tilt angle equivalent to the latitude of the location. As the solar cell absorbs more solar energy, the discharge from the SPVWPS rises as the tilt angle increases [26].

3.2 The influence of control factors on pumping efficiency

The quadratic models for the pumping efficiency (%) were produced using actual factors and are shown below in equation (3) using MINITAB 17 software.

Pumping efficiency (%) = -12 - 0.113 SR (W/m^2) - 1.92 AT (°C) - 0.47 SAA (degree) + 4.44 TA (degree) + 0.000089 SR (W/m^2)*SR (W/m2) + 0.0249 AT (°C)*AT (°C) + 0.0062 SAA (degree)*SAA (degree) - 0.0393 TA (degree)*TA (degree) + 0.00011 SR (W/m^2)*AT (°C) + 0.00019 SR (W/m^2)*SAA (degree) + 0.00016 SR (W/m^2)*TA (degree) + 0.0057 AT (°C)*SAA (degree) + 0.0017 AT (°C)*TA (degree) + 0.0029 SAA (degree)*TA (degree)
(3)

Figures 2 (i), (ii), and (iii) (a&b) depict the effect of input parameters on the pumping efficiency of SPVWPS through surface plot and contour surface. The Figure shows that when solar radiation increases, the input power to the SPVWPS increases, causing the components to run near or at their rated conditions, resulting in better SPVWPS efficiencies. It was shown that when the ambient temperature rises during the day, the intensity of solar radiation rises, and photovoltaic cells charge more and produce higher efficiency for the solar water pump [23].

The tilt and azimuth angles of a photovoltaic (PV) system affect its performance because they change the amount of solar energy received by the PV modules' surface. When compared to all other PV systems with varying azimuth angles, the PV system with azimuth angles of 20° has the highest determination factor, meaning that this PV installation supplies the maximum output power to the SPVWPS. It was also discovered that the pumping efficiency of an SPVWPS rises with tilt angles, since the pump absorbs more energy as the intensity of the sun increases [27].

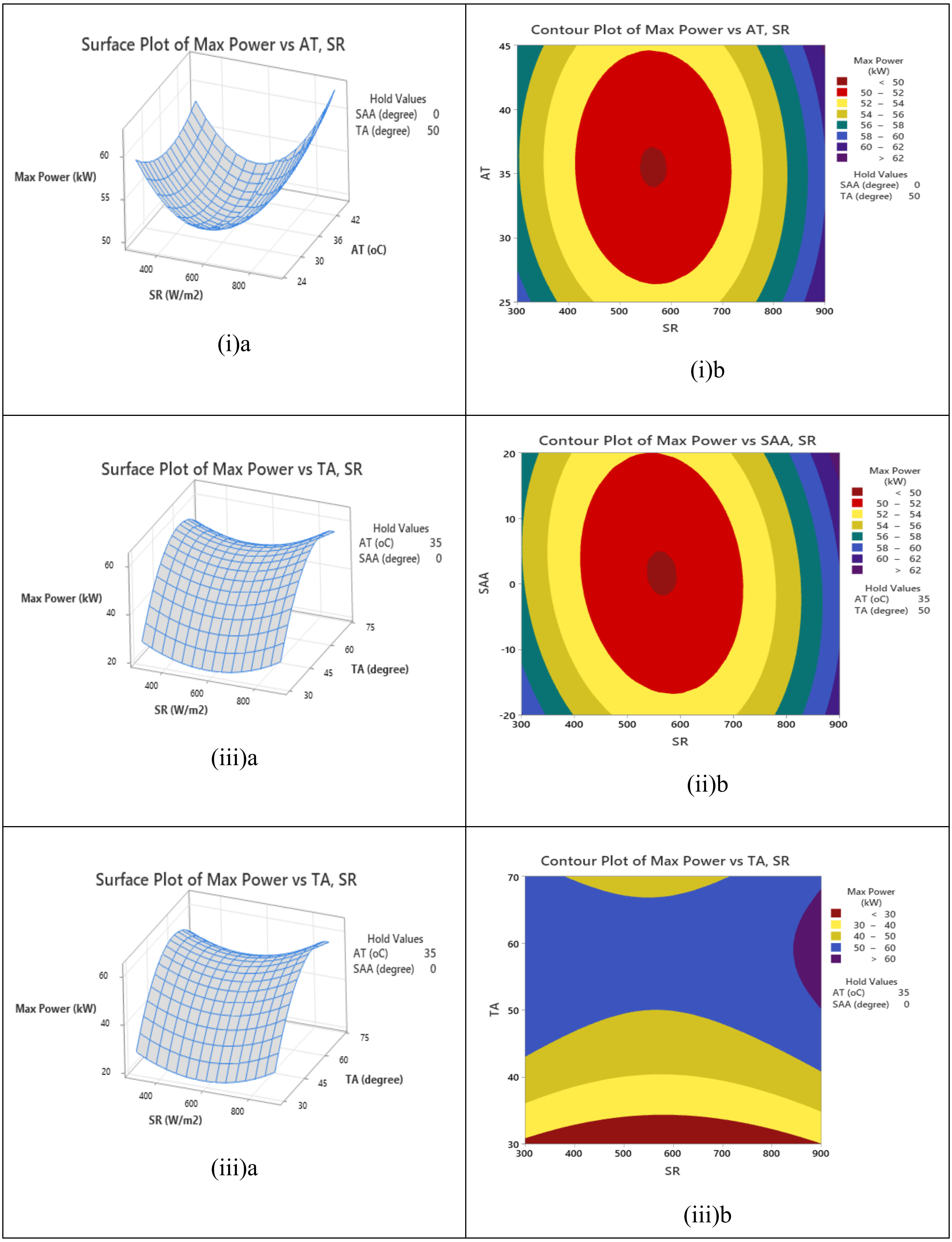


Figure 2: Pumping efficiency variation

4. Conclusions

In the present study, the impact of various affecting parameters (Solar radiation, ambient temperature, surface azimuthal angle, and tilt angle) on the discharge and pumping efficiency of solar photovoltaic water pumping systems (SPVWPS) was investigated. These input variables are optimized to get maximum output response i.e. discharge and pumping efficiency of the solar pump. An empirical connection was developed using RSM to model pump performance and efficiency. From the ANOVA analysis, the quadratic models created and built using RSM from the experimental data for discharge and maximum power were shown to be the most important at 95% confidence levels. Based on the contour plots, it is established that discharge (48.7 m^3/hr) and pumping efficiency (58.8%) are optimised at a parameter combination of solar radiation (451W/m^2), ambient temperature (27 ^{o}C), surface azimuthal angle (-18^o), and tilt angle (57^o). The R^2 value for discharge and pumping efficiency was 98.3% and 73.02% where as R^2(Predicted) for discharge and pumping efficiency were 89.07% and and 84.66, respectively. According to the findings of this study, multiple objective optimizations using RSM on a complete factorial L31 would be very accurate in forecasting values that are near to the experimental results. As a result, the current study will give a quick overview of the tool's capabilities for future research on SPVWPS. The suggested model can also do multi-objective optimization on greater details of solar photovoltaic water pumping systems features.

Nomenclature

ANOVA	Analysis of variance
DoE	Design of expert
AT	Ambient Temperature
PV	Photovoltaic
RSM	Response surface methodology
SR	Solar radiation (W/m2)
SAA	Solar Azimuthal angle
SPVWPS	Solar photovoltaic water pump system
TA	Tilt angle (degree)
W/m^2	Watt per square meter
m^3/hr.	Meter Cube per hour
CO	Carbon Monoxide
NOx	Nitrogen Oxide
H_2	Hydrogen
CCRD	Central composite rotatable design

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