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Research paper

An energy-efficient pumping system for sustainable cities and society: Optimization, mathematical modeling, and, impact assessment

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ABSTRACT

In this research work, we have focused on one of the reasons called drawdown (difference between static and pumping heads) for getting maximum efficiency. Therefore, various mechanical attachments have been designed and fabricated for performance evaluation. Since pump performance and drawdown are inversely related, the primary goal is to reduce drawdown as much as possible. The effect of various types of mechanical attachments on pump performance is investigated in this research work. Three bowl-type mechanical attachments can be integrated at once and can increase efficiency by up to 58%, which is 8% more than utilizing no attachment. Additionally, the impact of bore well diameter on pump performance has been studied. In addition, the impact of applying mechanical attachment at two pumping sites has been investigated, and a considerable amount of energy savings has been found. The response surface methodology (RSM)-based optimization of the various input parameters has also been examined. It was found that the maximum 62.04 % could be achieved through a head of 66.5 m, a discharge of 0.012 m^3/s, an input power of 12,605 W, and a bore well diameter of 0.215054 m, having three bowl-type mechanical attachments at a time. The mathematical modeling was also performed using analysis of variance (ANOVA) and formulated some equations for pumping efficiency with various pumping input parameters. Since there is very little variation between actual and anticipated performance, it can be used to evaluate the pumping system's performance in relation to various input parameters. As a result, maintaining sustainable cities and societies might greatly benefit from the energy-efficient pumping system.

1. Introduction

Hydraulic pumps convert mechanical energy into hydraulic energy. A pump provides fluid energy by converting mechanical energy. The energy of the fluid may be boosted in one of two ways: by its pressure or motion. Submersible pumps use centrifugal motion to move fluids. Moreover, a submersible pump is a particular kind of underwater centrifugal pump. Both the pump and the motor are housed inside the well. The motor is responsible for turning the pump, which generates the centrifugal force that forces the water or oil contained within the well to rise to the surface. It finds widespread use in the irrigation of agricultural land as well as in the extraction of oil (Bai et al., 2019; Joel Romero and Hupp, 2014). Submersible pumps are also used in mechanical, pharmaceutical, chemical, petrochemical, and residential water pumping all over the world (Rahman and Mahbub, 2012). A population needs to have a reliable supply of water and energy to maintain a high quality of life and for an area to see sustained economic growth (Carrillo and Frei, 2009). As a direct result of this, there has been an increase in the need for energy to provide this access. Urban pumping systems may utilize up to 3.3 kWh/m^3 of energy from the point of the collection up to the ultimate usage by customers in major cities (Plappally, 2012).

Regarding water supply concessionaires, the amount of money spent on energy for pumping systems accounts for around 90% of the power used in this industry (Shimizu et al., 2012). Electric motors account for about 46% of global and 70% of industrial electricity consumption. Approximately 22% of the world's total electricity used in electric motors is used by pumping systems (Waide and Brunner, 2011). Access to sustainable energy is a critical requirement for the development and growth of any economy. In many developing countries, a significant portion of the population relies on agriculture for their livelihoods, making access to energy for irrigation and pumping applications especially essential. The use of submersible pumps for irrigation, drinking, household, and industrial pumping applications has increased due to their high efficiency, reliability, and cost-effectiveness.

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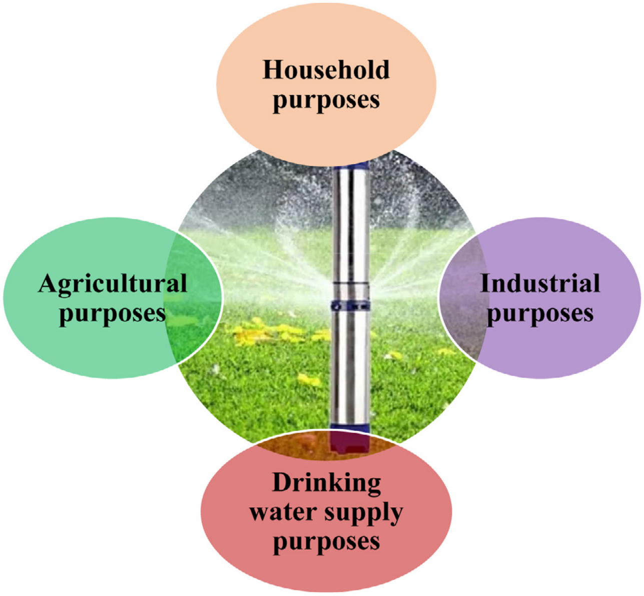


Fig. 1. The application of the submersible pumping sector worldwide.

Agriculture dominates most developing countries, like Bangladesh. Bangladesh's agriculture industry employs most of its workforce. According to BBS's preliminary assessment, agriculture is the nation's most significant economic sector, contributing 11.50% to GDP in FY 2021-22 (Manik, 2023). Irrigation requires enormous amounts of water. Our nation's rivers are a good source of water for agriculture, but they dry up during the summer. Moreover, Groundwater levels fluctuate year-round. Groundwater levels change from 7 to 30 meters a year (Shahid and Hazarika, 2010). So centrifugal pumps cannot extract water from the subsurface because the aquifer's water level decreases dramatically beyond its suction limit (Sayeed et al., 2020). As a result, the requirement for a submersible pump is rising during the irrigation season. But a recent study indicated that submersible pumps in this location operate at 25%–40% efficiency year-round, substantially lower than the standard laboratory efficiency of 64% (Shahid and Hazarika, 2010). This low efficiency is a tremendously concerning issue in the context of energy sustainability. The application of the submersible pumping system is presented in Fig. 1.

In recent years, there has been a growing interest in designing and optimizing submersible pumps for sustainable energy applications. Several researchers have spent the last few decades focusing on how to make submersible pumps more effective. Only a few of the numerous performance optimization methods have been created for structural factors like installation angle, number of blades, and blade wrap angle, including orthogonal (Stefani and Rebora, 2009; Waide and Brunner, 2011; Xiaoping et al., 2020), numerical computation (Li et al., 2018; Yang et al., 2019; Zhou, 2018; Zhou et al., 2020a), and neural network genetic algorithm (Mohammadzaheri et al., 2016; Wu et al., 2016). The intricate clearance in the pump has been the subject of much research (Li et al., 2019; Pang et al., 2019). Hsu and Brennen (2002) found that the input eddy current greatly affects the dynamic properties of the impeller's rotation by examining the fluctuating force caused by leakage at the impeller's tip. When San Andrés et al. (2018) evaluated the impacts of six distinct ring seals on multistage electric submersible pump leakage, experimental results revealed that specific annular seal designs had the best attributes. When Zhou et al. (2020b) employed numerical calculation to assess the impacts of ring clearance on submersible performance, they found that performance decreased more quickly when the ring clearance was more than 0.7 mm. Researchers Ma and Devenport (Ma and Devenport, 2007) were investigating the tip clearance flow and the curling process of the tip leakage vortex when they noticed a wall jet-like appearance of the leakage flow. The radial clearance of the sealing gaps may have a substantial impact on centrifugal pump losses, as indicated by the formula developed by Tamm and Stoffel (2002). Schleer and Abhari (2008) used particle image velocimetry to study the impact of the clearing flow on the flow structure at the impeller outlet during partial load operation (PIV). A new flow model that took into consideration tip leakage in addition to the conventional jet-wake mechanism was developed in order to better define the flow structure under partial load situations. Kulkarni (2017) looked at variables affecting pump performance. The impeller head descended as the slot height rose. To select a pump, be aware of the design constraints, irrigation system operating conditions, and system adaptability. Centrifugal pumps have less friction when impeller, volute, and disk friction losses are studied. According to research by Haque et al. (2017), submersible water pumps may be able to save 10%–30% of their energy expenses by moving to a different method of operation and control. The financial values of the lifetime cycle cost features of submersible pumps have also been investigated. Islam et al.'s investigation of how drawdown affects pump performance was published in 2017 (Islam et al., 2017). Researchers found that a tube well with a 0.10 m diameter and a 0.30 m filter could achieve a maximum decline of 1.4 m at 228 liters per minute discharge with a matching pump efficiency of 10%. The pump drawdown for a 0.15 m diameter tube well at a filter length of 0.30 m with a 9% efficiency maximum was 0.18 m. Optimal efficiency was from 36% to 40%, and discharge was measured at between 95% and 125% of a standard set rate. The applicability of submersible pumps for various pumping applications is greatly influenced by their efficiency. A number of variables, such as flow rate, pressure, head, and efficiency, affect a pump's performance. By improving these factors, the pump's energy efficiency can be increased, resulting in lower energy expenses and consumption. The static water level, the condition of the aquifer, the dependability of the electrical supply, and the pump drawdown features are other factors that affect a submersible pump's efficiency (Hossain et al., 2023). The bore well's position prevents changing the static water level. The aquifer and the power source can both be changed to suit different needs. The expenses of altering the current environment, however, are exorbitant. Consequently, we were concerned that the drawdown's characteristics would change. In a well or borehole, the term "drawdown" describes the difference between the static water level and the level to which the water level is dropped or "drawn down" when pumping takes place. In other words, it is the vertical distance between a well or borehole's maximum water level and the point at which pumping causes the water level to fall. A key factor in evaluating the effectiveness and performance of a pumping system is drawdown. Submersible pumps' high drawdown necessitates a greater pumping head, which reduces their efficiency (Rahman and Mahbub, 2012). In fact, drawdown and efficiency are inversely related (Hossain et al., 2023). This work's originality is the employment of mechanical attachments to move the working point close to the ideal position, which maximizes efficiency while minimizing drawdown. In actuality, this work is a continuation of earlier research by Hossain et al. (2023). In our previous research work, energy consumption behavior of submersible pumps has been studied along with performance improvement by means of mechanical attachment. However, the previous analysis did not include optimization and data prediction, which are essential for the practical improvement of this novel concept. In this research work, the type of combination of mechanical attachment has been changed as well as clearance effect has also been analyzed. In addition, optimization and mathematical modeling have been employed for finding the impact of various input parameters. As it is a novel technique for performance improvement, therefore, it is not supported by other literature. That is the comparison of it with other research work.

This research paper focuses on the design of mechanical attachments, optimization, prediction, and mathematical modeling of all input parameters of submersible pumping operations in different bore wells for sustainable energy applications. With an emphasis on increasing energy efficiency and minimizing environmental effect, our objective is to offer insights into the design and optimization of submersible pumping operation by lowering drawdown for sustainable energy applications. In this study, a mathematical model for submersible pump performance optimization is presented. The model takes into account a number of characteristics, including discharge, bore well diameter, head, input power, and mechanical attachments. The performance of several submersible pump configurations will be assessed using the model, and the most effective design for various pumping applications will be determined. Additionally, it has been examined how efficiency gains in submersible pump operation may affect the study's findings.

2. Materials and methods

2.1. Design and fabrication of various types of mechanical devices

The mechanical attachments are used primarily to lessen the amount of drawdown during pump operation. When a pump is in operation, centrifugal force at the impeller's eye creates a negative pressure, which causes well water to flow toward the pump's input. Since the pumping level has decreased, more energy is required to raise the water. In addition, mechanisms prevent water from being sucked upward in the bore well, forcing the pump to draw more water from the aquifer below. In order to examine the efficacy of the submersible pumping system, mechanical attachments of the plane, bowl, and propeller kinds have been developed to account for this impact. The thickness of these attachments was determined by considering the water pressure acting on them as they remained submerged. The basis of mechanical attachment is to make an obstacle during the pumping operation so that the drawdown gets reduced. As a result, the pumping head will be lowered. The thickness of these attachments was determined by considering the water pressure acting on them as they remained in submerged condition. The bore well diameter, delivery pipe diameter (3 in), and clearance between the bore wall and the outer perimeter of the attachments (1 inch) were all taken into account during the first stages of the design process, which took place in the SolidWorks program. The performance was also assessed by maintaining the clearance 0.5 inches. It is a novel process, hence there is no existing literature to support it. The fabrication of the mechanical attachments took place at the machine shop laboratory, RUET. The devices were made from 4 mm-thick cast iron obtained from a nearby market . The design, along with the fabrication of these attachments for an 8-inch bore well, are presented in Fig. 2.

2.2. Experimental setup and experimentation

The experimental research work has been carried out at the experimental site of the fluid mechanics laboratory, RUET, in three different bore wells (8-inch, 10-inch, and 12-inch), as well as in the open pond. There is no specific reason for choosing 8-inch, 10-inch, and 12-inch bore well sizes, only for the availability of bore well in the experimental site. We have just examined the impact of these three types of bore well and concluded that this is true for another type of bore well too. Moreover, the performance of the pump falls as the bore well size increases as a result of the huge consumption of electricity for delivering huge water. In the experiment, four uPVC pipes are used. Each pipe is 76.2 mm (3 in) in diameter and 6,096 mm (20 ft.) in length. The pipeline is used to discharge the water from the pump to the measuring tank (3.04m×2.43 m × 1.72 m). One end of the pipeline is connected to the submersible pump, and another end is opened at the measuring tank. A 15 HP (11 kW) submersible pump (Brand: Pedrollo; model: 6SR44/8-PD) was used for the research work.

The volume flow rate was measured by routing the discharge pipeline to the measurement tank in the pump test bed and comparing the readings with the flow meter. A pressure gauge (Bardon type), secured with thread tape has been inserted into the tee socket in order to measure the pressure head in the discharge pipe. The static head, or static level, is then measured with the wetted tape arrangement before the pump is turned on. A metallic needle is linked to one end of the electric tape, while the other end is linked to a piece of electronics. Current flows through the circuit of the electrical gadget when the two ends, positive and negative, of the wire linked with the metallic needle contact the water. The circuit is powered by two pencil batteries that have been put in the electronic equipment. As soon as the needle comes into contact with the water, a buzzer will activate and make a beeping noise as confirmation. The foot scale is printed on the electric wire of the damp tape. The static level is converted to meters using the clearly stated scale of the wetted tape. A stopwatch was used to measure the amount of time needed for the water volume to be measured, allowing the volume flow rate to be determined. At the conclusion of the experiment, for a single set of data, the static water level and drawdown are measured using the same wetted tape. The electrical energy consumption was measured with a digital power analyzer (Lutron Power Analyzer DW-6092). All of the procedures mentioned were likewise carried out for the month of August 2022, and the tests were repeated three times. Bernoulli's equation was used for the experimental setup presented in Fig. 3, and a mathematical formula has been formulated considering different types of losses. Applying Bernoulli's equation, taking into account the head loss between points 1 and 2, we get:

$$Y_1+\frac{P_1}{\rho g}+\frac{V_1^2}{2g}+H_p=Y_2+\frac{P_2}{\rho g}+\frac{V_2^2}{2g}+h_{ls}+h_{fm}+h_{lb}+nh_{lf}+h_{lo} \quad (1)$$

Here,

$$Y_1=0;\ Y_2=H_1+H_2;\ P_1=\rho g H_1;\ V_1=\frac{d_2^2}{d_1^2}(V_2);$$

$$h_{ls}=\frac{V_2^2}{2g}.(f_{ls});\ h_{ls}=\frac{V_2^2}{2g}.(f_{ls});\ h_{fm}=f_{m}.\frac{L}{d_2}\frac{V_2^2}{2g};$$

$$h_{lb}=f_{lb}\frac{V_2^2}{2g};\ h_{lf}=f_{lf}.\frac{V_2^2}{2g};\ h_{lo}=f_{lo}.\frac{V_2^2}{2g}$$

Putting these values in Eq. (1), we get,

$$H_1+\left(\frac{d_2}{d_1}\right)^4.\frac{V_2^2}{2g}+H_p=H_1+H_2+\frac{P_2}{\rho g}+\frac{V_2^2}{2g}+\frac{V_2^2}{2g}.(f_{ls})+f_{m}.\frac{L}{d_2}\frac{V_2^2}{2g}+f_{lb}\frac{V_2^2}{2g}+n.f_{lf}\frac{V_2^2}{2g}+f_{lo}\frac{V_2^2}{2g}$$

$$Or,\ H_p=H_2+\frac{V_2^2}{2g}\left\{1-\left(\frac{d_2}{d_1}\right)^4+f_{ls}+f_{m}.\frac{L}{d_2}+f_{lb}+nf_{lf}+f_{lo}\right\}+\frac{P_2}{\rho g} \quad (2)$$

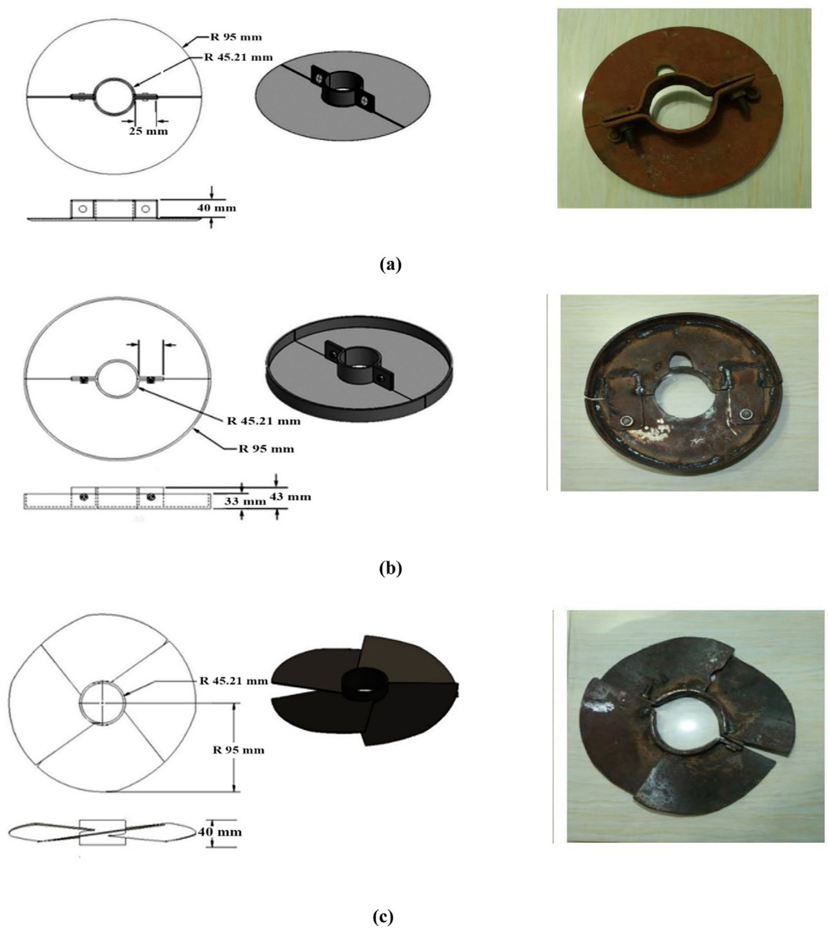


Fig. 2. Design and fabrication of mechanical attachments (a) plane, (b) bowl, and (c) propeller types.

The quantity in the second bracket of Eq. (2) remains constant for a particular pumping system, and hence the equation becomes

$$H_p = H_2 + K.\frac{V_2^2}{2g} + \frac{P_2}{\rho g} \tag{3}$$

$$\text{Where, } K = \{1 - \left(\frac{d_2}{d_1}\right)^4 + f_{ls} + f_m.\frac{L}{d_2} + f_{lb} + nf_{lf} + f_{lo}\} \tag{4}$$

Thus, the overall efficiency of the pump can be written as

$$\eta_o = \frac{\gamma \times g \times Q \times H_p}{P} \tag{5}$$

The pumping head and overall efficiency of the submersible pump have been calculated for every set of data values of the experiment using Eqs. (4) and (5). The explanation of the different symbols is illustrated in the **Nomenclature table**.

2.3. Impact assessment using mechanical attachment

In this research work, different types of mechanical attachments were used in the delivery pipe in front of the pump to investigate the effect of drawdown on submersible pump performance. The attachments of propeller type, plane type, bowl type, plane, bowl, and propeller at a time and three bowls at a time in front of the pump in the delivery pipe are shown in Fig. 4. The effect of using mechanical attachments is mainly to reduce drawdown. As a result, the total pumping head of the submersible pump is reduced, and the overall performance of the submersible pump is increased. The mechanical attachment acts as a barrier that reduces the vertical lift of water inside the bore well and forces the pump to lift water from the lower position. Therefore, the pump is forced to lift water from a lower position instead of freeing water from the bore well. Thus, the overall performance of the submersible pump is increased as well. Since pump performance and drawdown have an inverse connection, our goal was to use mechanical attachments to build a barrier to prevent drawdown. In this regard, we have considered three alternative mechanical attachment shape types for research of performance through various combinations. As a result, it is without a doubt true to say that there are additional forms of mechanical attachments that can be used in addition to these three. At first, propeller-type mechanical attachment was used and create a small amount of obstacle in order to find out impact of using it. Then, plane-type, bowl-type, plane, bowl and propeller type at a time and three bowl-type at a time was used for investigate the effect of mechanical attachment on pump performance. It is a novel process, hence there is no existing literature to support it. The impact of using mechanical attachments is shown in Fig. 5(a).

2.4. Optimization of the pumping process and mathematical model for obtaining efficiency

Since CCD of RSM is specifically made to represent quadratic effects and interactions between input variables, we chose it for this research project over other optimal methods. It involves a central point that is typically the average of the input variable values, a string of star points that are spaced out from the central

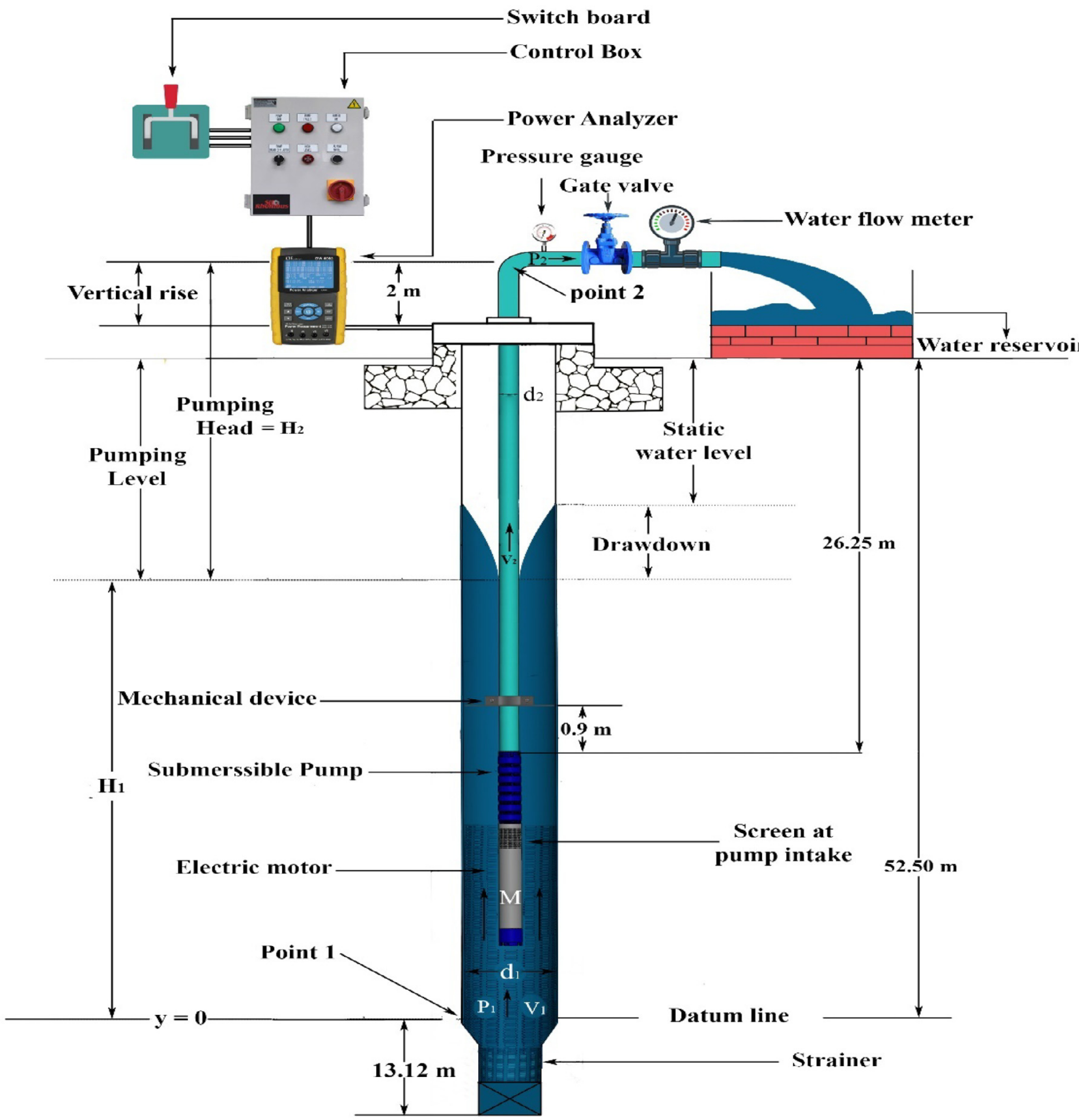


Fig. 3. Experimental tests schematic of the submersible pumping system.

point, and a final point that is the result of the process. The star points are employed to determine the ideal input variable settings and to estimate the response surface's curvature. CCD is also more effective in terms of the quantity of experiments needed to create the model and determine the ideal input variable settings. Additionally, this technique entails dividing the available data into numerous subsets and is used to train and validate the model. One subset is utilized for validation in each iteration, with the remaining subsets being utilized for model training. In contrast to hold-out validation, this method uses all available data for both training and validation, which results in a more reliable estimate of the model's performance. By looking at the model's coefficients and conducting a statistical analysis of the data, one can assess whether interactions are present in the RSM model. The presence of significant interaction terms in the model suggests a relationship between the amount of one input parameter and the impact it has on the response variable. We can deduce the interactions between the input and output parameters by looking at the F-value data. There is a significant interaction between the input parameters if the model's performance is improved by the inclusion of the interaction term, which is indicated by a higher F-value. The performance of the submersible pump must be assessed so that improvements may be made in efficacy without corresponding cost increases. We optimized the efficiency of a submersible pumping process and determined the effect that changes in the process's parameters have on the optimization using Design Expert Software® Version 7. Moreover, the effect of various input parameters on submersible pump performance was also investigated. Based on the preliminary experiments, the parameters range for discharge (A: 0.0044–0.0178 m^3/s), head (B: 11.70–83.67 m), bore well diameter (C: 0.2032–0.3048 m), input power (D: 10107.76–13307.70 W), and mechanical attachments (E: 1-6) were determined. The design expert software-based response surface methodology (RSM) was used here for process optimization of the submersible pumping system. In this study, the discharge, head, bore well diameter, input power, and mechanical attachments were chosen as input process parameters and studied with a standard RSM design using central composite design (CCD). This is basically a regression method used to find out the relative effects of various process

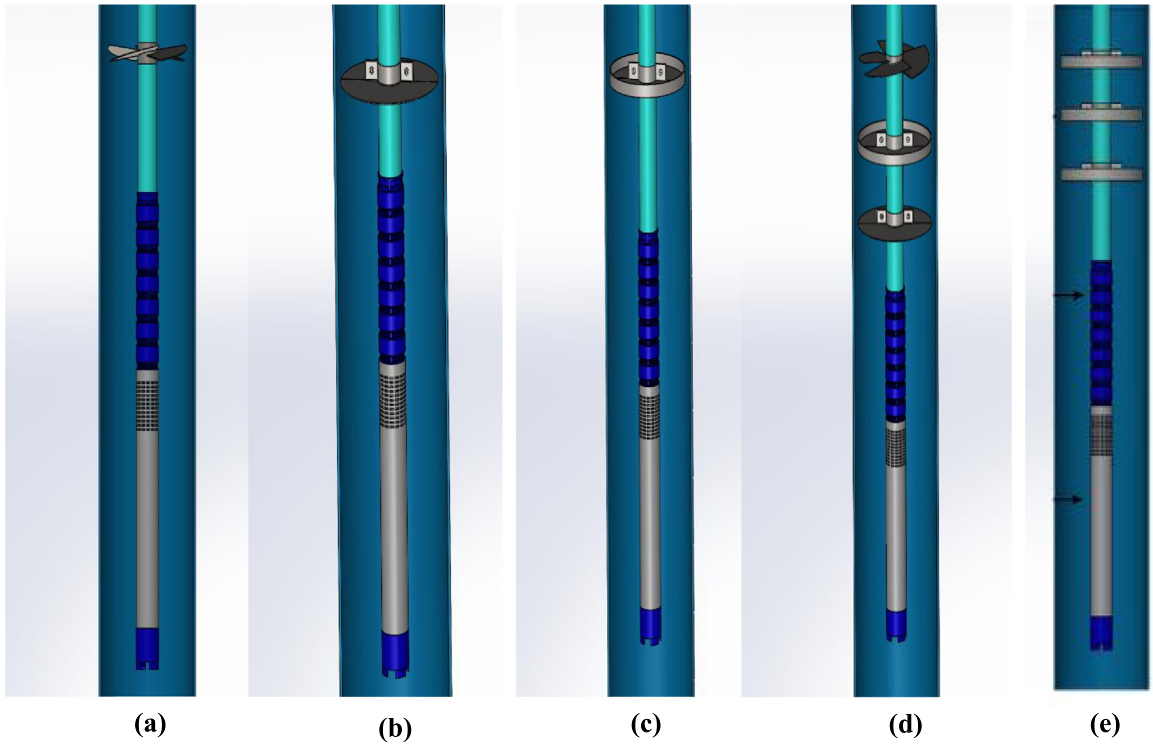


Fig. 4. Different types of mechanical attachments attached in the delivery pipe in front of the pump (a) propeller type, (b) plane type, (c) bowl type, (d) plane, bowl, and propeller at a time, and (e) three bowls at a time.

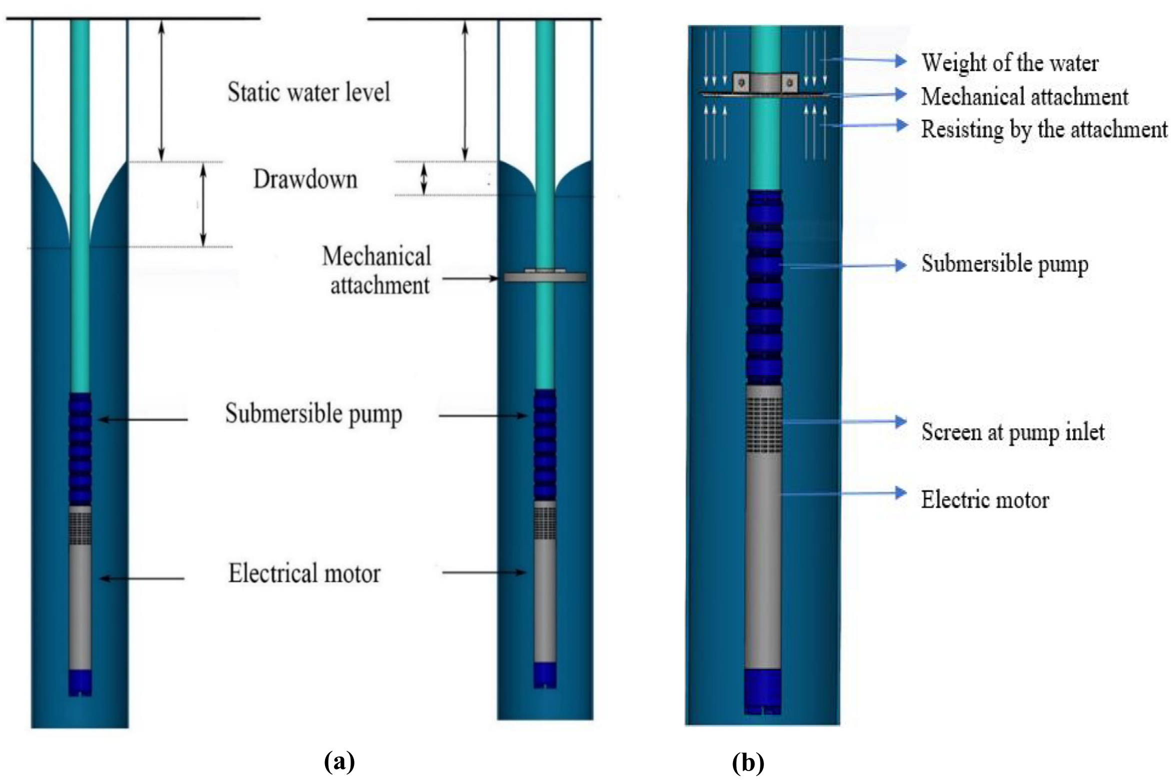


Fig. 5. (a) Effect of mechanical attachment on drawdown and (b) impact of mechanical attachment.

Table 1
Experimental data obtained for 8-inch bore well with three bowl-type attachments at a time.

Sl. No.	Static water level (m)	Pumping level (m)	Discharge (m^3/s)	Current (A)	Voltage (V)	Power factor	Input power (W)	Efficiency (%)
1	5.10	7.77	0.0171	23.4 23.4 22.5	399.1 398.3 399.1	0.75	11579.36	17.29
2	5.10	7.64	0.0160	23.7 23.9 23	401.7 400.7 400.3	0.78	12332.28	34.67
3	5.20	7.54	0.0154	23.8 24.7 23.5	403.8 402.9 400.9	0.75	12824.68	46.74
4	5.18	7.21	0.0134	24.3 24.8 24	404.4 403.7 404.5	0.78	12957.49	54.31
5	5.10	6.73	0.0109	24.5 24 23.8	407 403.4 405.2	0.77	12601.20	58.02
6	5.13	6.09	0.0065	22.5 22.8 21.8	404.4 404 403	0.74	11048.91	46.26

parameters on submersible pump performance. As a result, a total of 108 experimental runs were conducted, called design matrixes of the experiments, which are shown in Table A.1. The obtained experimental results were analyzed by the analysis of variance (ANOVA) using design expert software, including the experimental design, data analysis, quadratic model buildings, and three dimensional (3D) response surface graph according to input process parameters.

2.5. Uncertainty analysis

The errors caused during experiments due to the tools utilized, calibration, calculation accuracy, methodologies used in an ambient condition, etc. were identified using uncertainty analysis. Variables such as changing climatic conditions, wear and tear on machine parts, the caliber of fuel used, and others can all contribute to uncertainty (González et al., 2001). Additionally, there was uncertainty in the experiments because of numerous calibration method flaws (Ağbulut, 2022). Uncertainties can be divided into two categories: fixed uncertainties and random uncertainties. Fixed errors happen frequently, whereas random errors happen because of important quantities. In this experiment, the root mean square approach using Eq. (6) has been used to calculate the combined uncertainty for engine performance and exhaust emission (Nema et al., 2023). In this case, y1, y2, y3, …, yn are the independent variables, each with their own unique error, and U is defined as the overall uncertainty. It was determined that this experiment's overall level of uncertainty was 0.92%. The detail uncertainty of the individual measurement is presented in Table A.2.

$$\Delta U = \sqrt{(y_1)^2 + (y_2)^2 + (y_3)^2 + \cdots\cdots\cdots\cdots\cdots + (y_n)^2} \quad (6)$$

3. Results and discussions

3.1. Submersible pump performance in different bore well with mechanical attachment

The performance of the 11 kW (15 HP) submersible pumping system has been analyzed in three different bore wells by attaching various types of mechanical attachments and comparing it with no attachment and with lab test results. In every experimental condition, a set of data was measured to calculate the efficiency of the pump, and three sets of data were taken at different times of the day for better accuracy. The sample data table for calculating the efficiency of the submersible in an 8-inch (0.2032 m) bore well by attaching three bowl-type attachments at a time in front of the pump in the delivery pipe is presented in Table 1. It has been found that the maximum efficiency was obtained for these conditions at 58.02%.

The use of mechanical attachments increases the efficiency of the submersible pump by reducing drawdown as well as pumping level. The performance of the submersible pump in different bore wells with various types of mechanical attachments is presented in Fig. 6. It has been found that propeller-type attachments decrease drawdown in a very small amount and increase efficiency in a small amount, which is 51.50%, 50.77% and 49.92% for the highest value of efficiency for an 8-inch, 10-inch, and 12-inch bore well, respectively. Because of its wide surface, the bowl-type connection limits more water from the top side and minimizes drawdown in greater amounts. As a result, the bowl-type attachment provides a bigger boost in efficiency. The highest values of efficiency for bowl-type attachments are 55%, 54%, and 52.5% for 8-inch, 10-inch, and 12-inch bore wells, respectively. Furthermore, when the three bowl-type attachments are used together, the drawdown is the smallest and the efficiency is the highest. The highest value was obtained for three bowl-type attachments, which are 58.02%, 56.08%, and 55.16% for 8-inch, 10-inch and 12-inch bore wells, respectively. The 8-inch bore well shows better performance than any other bowl due to the lower availability of water inside the bore well. When drawdown is minimized, the pump's pumping head also decreases, resulting in greater performance since the pump uses less energy and consumes less electricity to provide water. The pump performance in the open pond was found to be 49.5% since the pump tries to lift more water due to the availability of water, which increases electricity consumption; therefore, pump performance fell. In the event of a standard condition, the pump can easily lift more water and consume less power owing to the availability of a large volume of free water. Thus, it can be said without any hesitation that mechanical attachments increase the pump efficiency owing to the combined impact of the decreased drawdown as well as pumping level and lowering the power consumption. The variation of efficiency with lab test results occurs due to a mismatch of actual discharge and head with the best condition of operation (lab report), placement of the pump at a position lower than that of the practical head that causes extra friction loss, variation of groundwater level at different season throughout the year, the pump drawdown which

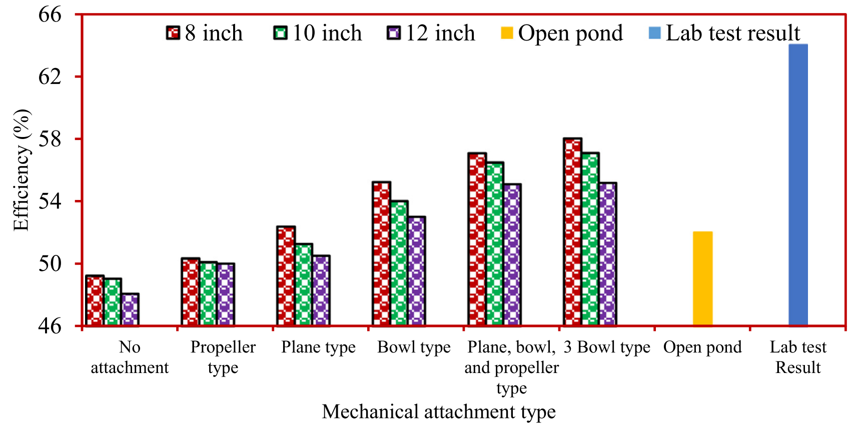


Fig. 6. Comparison of the efficiency of an 11 kW submersible pump at different arrangements with different bore well.

imposed extra pumping head on the submersible pump, etc. In addition, lab test results are simulated results measured under standard laboratory test conditions, where the aquifer conditions remain unchanged. and it varies from actual efficiency. But in actual practice, various types of losses occur including major and minor losses and it is difficult to maintain standard, unchanged aquifer conditions. Therefore, the variation between the lab test result and the actual performance occurs.

The highest efficiency was obtained from an 8-inch bore well, and the attachments were three bowl-type attachments at a time, with a value of 58.02% shown in Fig. 7. The maximum efficiency determined for the tube well (8 inches) without any attachment is 49.22%, and the efficiency increases when mechanical attachments are utilized. The bowl type attachment shows the highest efficiency among the three kinds of attachments, and it is 8% greater than the situation when no attachment is utilized. As a result of applying mechanical attachments, the efficiency of the pump in the tube well is also increasing. Therefore, an 8-inch bore well is called the best efficiency bore well. The operating characteristics curves of an 11 kW submersible pump for a 0.2032 m (8 inches) bore well with a different type of mechanical attachment are presented in Fig. 8. The maximum 55% efficiency is obtained with bowl-type mechanical attachment under the head of 57.27 m and a discharge of 0.0122 m^3/s (Fig. 8(a)). On the other hand, plane, bowl, and propeller-type attachments at a time in front of the pump in the delivery pipe show 57% efficiency under the head of 7.56 m and discharge of 0.0126 m^3/s when the power consumption is 16.9 hp (Fig. 8(b)). Moreover, it has been found from Fig. 8(c) that the maximum efficiency of 58.02% is obtained with three bowl-type attachments under the head of 65.55 m and a discharge of 0.01124 m^3/s when the power consumption is 16.70 hp.

3.2. Effect of clearance and drawdown on submersible pump performance

The performance of the submersible pumping system was measured in different bore wells with bowl-type mechanical attachments keeping a 1-inch clearance at first and then 0.5-inch clearance. It has been found that there is an inverse relation between pump performance and clearance between the bore wall and the outer periphery of the mechanical attachment. The pump performance in different bore wells for 1-inch and 0.5-inch clearance is presented in Fig. 9(a). It has been found that the highest efficiency obtained from an 8-inch bore well with a bowl-type attachment keeping 0.5-inch clearance was 56.5%. But for the same bore well with 1-inch clearance, we obtained 54.5% efficiency, which is 2% lower than the previous results. A similar trend in nature is obtained for 10-inch and 12-inch bore wells as well. The relation between pump drawdown and efficiency with different types of mechanical attachment in 8-inch bore wells is presented in Fig. 9(b). It has been found that there is an inverse relationship between pump drawdown and performance. When the drawdown is minimum, we get maximum efficiency since a smaller drawdown results in a smaller pumping head. Thus, the vertical lowering the water level inside the bore well (pump drawdown) should be kept as small as possible to get maximum efficiency from the submersible pump. In the case of three bowl-type mechanical attachments, we measured the lowest drawdown (1.73 m), which results in maximum efficiency (58.02%) in 8-inch bore well. A same trend in nature is obtained from other mechanical attachments as well. Thus, the functions of mechanical attachment are to create a barrier to lowering the water inside the bore well, i.e. to keep the drawdown as small as possible. In every condition, three sets of data were measured at different times of a day for better accuracy and found almost the same trend in nature. Therefore, it can be concluded that the functions of mechanical attachment are to create a barrier for vertical water lowering and provide smaller drawdown values, which indirectly increase the pumps performance. Thus, there is an inverse relationship between the pumping head and pump performance.

3.3. Impact assessment using mechanical devices

The integration of mechanical attachments in the delivery pipe in front of the pump improves the efficiency of the submersible pumping system. In this research work, the efficiency of the submersible pumping system could be improved by 8% with the integration of three bowl-type mechanical attachments at a time, as discussed earlier. Therefore, the impact of using three bowl-type attachments at two pumping sites of RWASA and BMDA (two major supply agencies in Bangladesh) has been assessed. Site 1 represents the Binodpur Bazar pumping site, RWASA, and site 2 represents the Amtoli-1 site, Godagari, BMDA. The impact of using three bowl-type mechanical attachments at two sites of RWASA and BMDA is presented in Table 2. It has been found that the efficiency of these two pumping sites is only 23.94% and 37.91% (site 1 and site 2). The integration of three bowl-type mechanical attachments could save around 8,896 kWh, and 3,289.92 kWh of energy per year in site 1 and site 2, respectively. In addition, the annual cost savings for these two sites would be 747.26 USD and 276.35 USD, respectively. Thus, a considerable amount of energy, as well as costs, could be saved by implementing these types of mechanical attachments. Therefore, the integration of mechanical attachments in the pumping system could improve

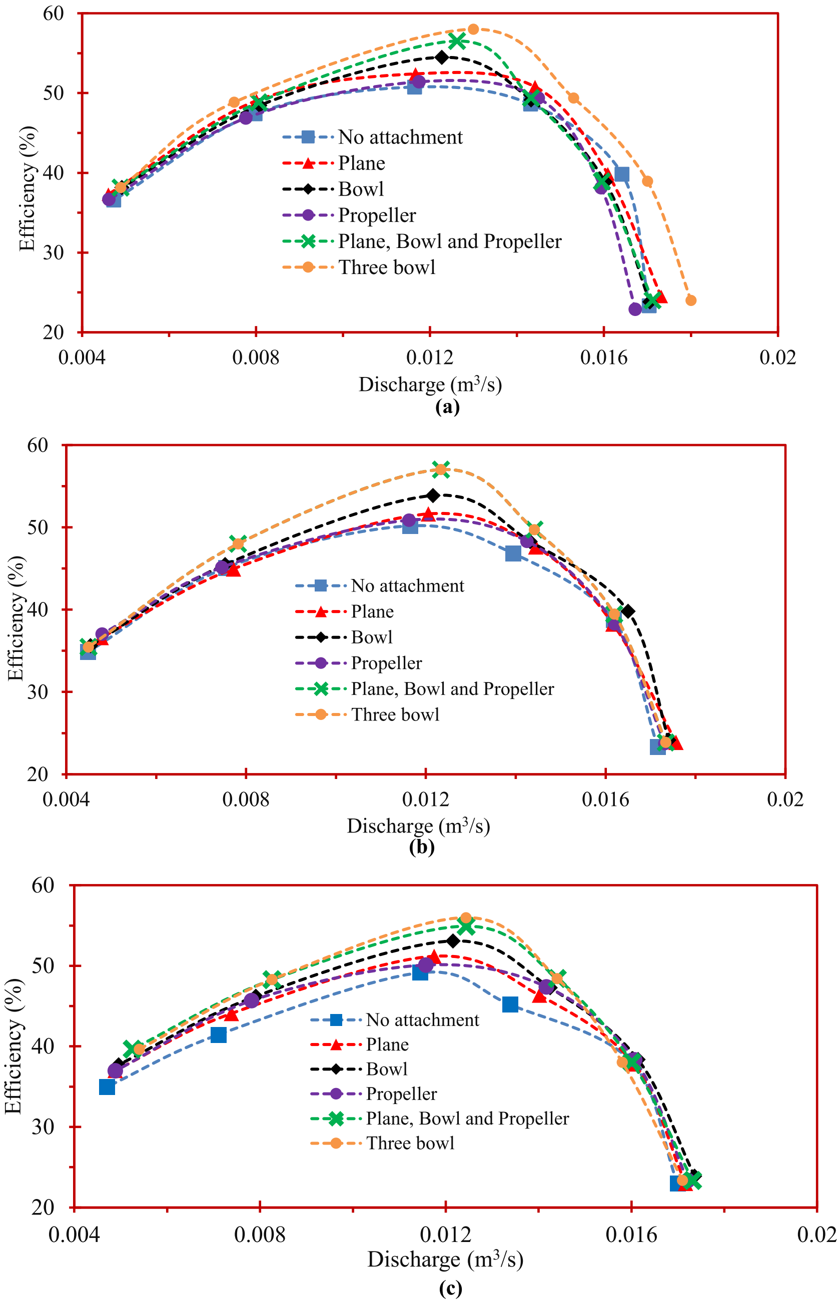


Fig. 7. Pump Performance by attaching various types of mechanical attachment in (a) 8-inch, (b) 10-inch, and (c) 12-inch bore well.

Table 2
Impact of using mechanical attachment.

Parameters	Units	Site-1, RWASA	Site-2, BMDA
Average discharge	m^3/month	36291.67	19054.41
Average energy consumption	kWh/month	9266.67	3427.00
Average electric bill	USD	778.40	287.87
Average efficiency	%	23.94	37.91
Impact of 8% energy savings			
Average energy consumption	kWh/month	8525.33	3152.84
Average electric bill	USD	716.13	264.84
Resultant cost savings	USD	62.27	23.03
Annual cost savings	USD	747.26	276.35
Annual energy savings	kWh/year	8896.00	3289.92

the energy efficiency of the pumping system. Since energy efficient water pumping is a major requirement for sustainable cities and societies for irrigation, drinking, household, and industrial applications. Therefore, this novel technique for energy efficiency improvement could play a great role in creating sustainable cities and societies.

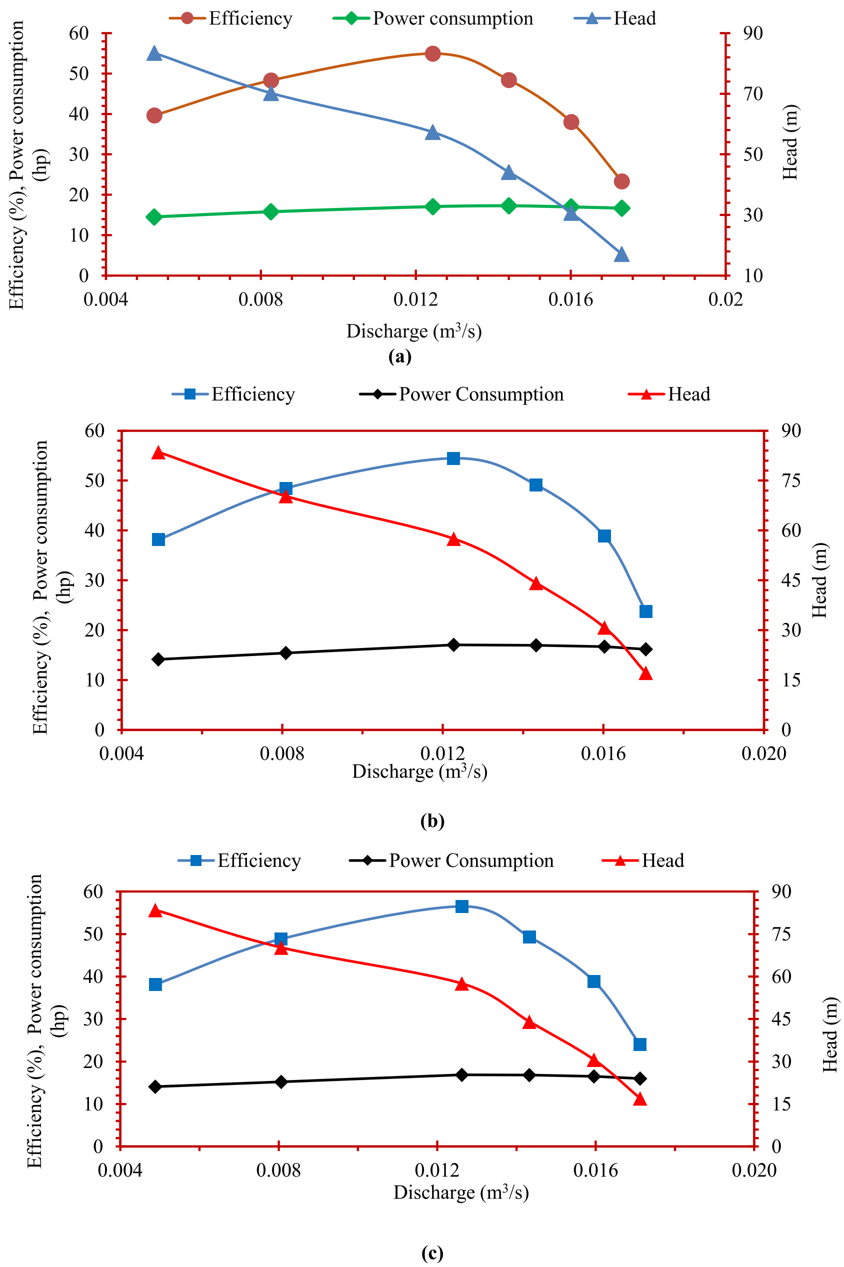


Fig. 8. Operating characteristics curves of an 11 kW submersible pump in 8 inch (0.2032 m) bore well with (a) bowl type, and (b) plane, bowl and propeller at a time, and (c) three bowl at a time mechanical attachment in front of the pump in the delivery pipe.

3.4. Optimization of the input parameters for obtaining efficiency and mathematical modeling

The effects of various operating parameters were studied using design expert software-based response surface methodology (RSM). The response efficiency was measured considering five major factors, which are head, discharge, input power, bore well diameter, and mechanical attachment types. Utilizing Design Expert software called Central Composite Design (CCD), optimization work was carried out. It is possible to identify which variables (discharge, head, bore well diameter, input power, and mechanical attachment types) have the greatest influence on efficiency. With the help of trial run results (108 no.), "Design Expert" software-based RSM modeling was created. Table 3 summarizes the model fit-sequential for assessing pumping efficiency. The recommended Quadratic versus Linear model was determined to be an acceptable starting point for modeling in the Analysis of Variance (ANOVA) model. The ANOVA results for pumping efficiency will play an important role in examining the influence of process parameters.

3.4.1. RSM modeling for determining response for efficiency of suggested model (2FI) through ANOVA

Table 4 illustrates the ANOVA table for modeling pumping efficiency. It has been found that the F-value of the model is 679.78, which indicates that the model is significant. This enormous model F-value has a 0.01% chance of occurring, owing primarily to noise. The model has a *P*-value of 0.0001, indicates that the model is significant. A P-Value greater than 0.0001 suggests that the model is not relevant. The process factors discharge (A), head (B), bore well diameter (C), input power (D), and mechanical connection (E) suggest notable model variables in this current ANOVA model. ANOVA also shows the primary effects of these process components, their interaction behavior, and the presence of error

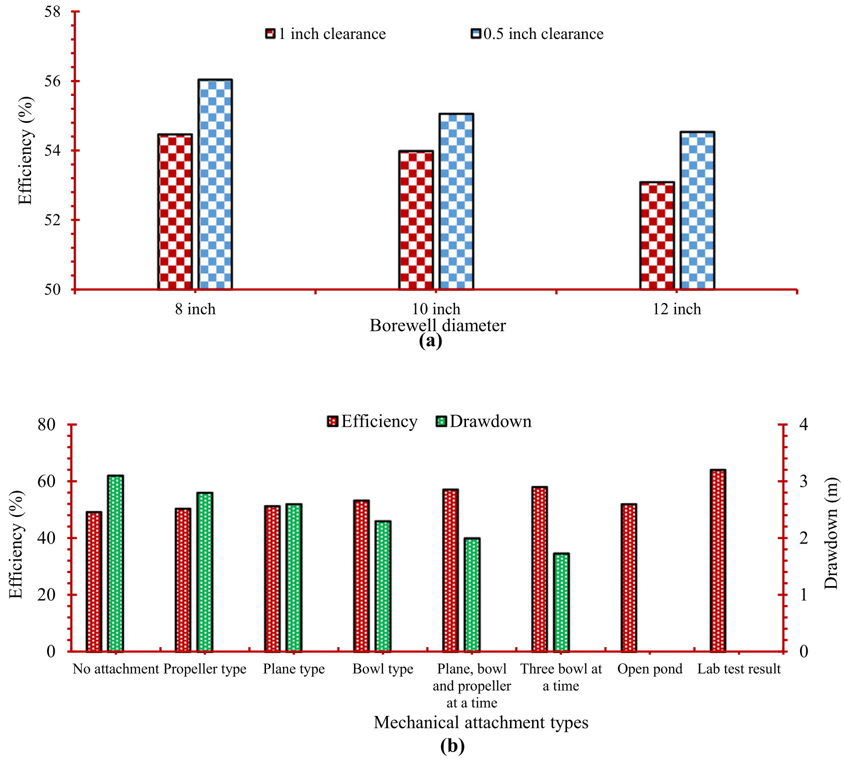


Fig. 9. Effect of (a) clearance and (b) drawdown on submersible pump performance by attaching different types of mechanical attachment.

Table 3
Summary for model fit-sequential model for Pumping efficiency.

Source	Sum of Squares	df	Mean Square	F-value	*p*-value	
Mean vs Total	183205	1	183210			
Linear vs Mean	10283.68	5	2056.74	193.09	< 0.0001	
2FI vs Linear	984.80	10	98.48	89.11	< 0.0001	
Quadratic vs 2FI	12.50	5	2.50	2.44	0.0406	Suggested
Cubic vs Quadratic	62.77	34	1.85	3.71	< 0.0001	Aliased
Residual	26.40	53	0.4982			
Total	194605	108	1801.47			

Table 4
The analysis of variance (ANOVA) of the suggested model for pumping efficiency.

Source	Sum of Squares	**df**	Mean Square	F-value	**p-value**	
Model	11268.48	15	751.23	679.78	< 0.0001	significant
A: Discharge	31.04	1	31.04	28.09	< 0.0001	
B: Head	87.51	1	87.51	79.19	< 0.0001	
C: Bore well diameter	15.31	1	15.31	13.85	0.0003	
D: Input power	1.79	1	1.79	1.62	0.2067	
E: Mechanical attachment	0.1343	1	0.1343	0.1216	0.7281	
AB	629.28	1	629.28	569.43	< 0.0001	
AC	2.26	1	2.26	2.05	0.1557	
AD	0.2029	1	0.2029	0.1836	0.6693	
AE	1.03	1	1.03	0.9358	0.3359	
BC	1.16	1	1.16	1.05	0.3092	
BD	1.90	1	1.90	1.72	0.1926	
BE	1.83	1	1.83	1.66	0.2014	
CD	7.34	1	7.34	6.64	0.0116	
CE	2.19	1	2.19	1.98	0.1628	
DE	0.0223	1	0.0223	0.0202	0.8873	
Residual	101.67	92	1.11			
Cor Total	11370.15	107				

terms in the model. The response approach may correctly depict the process elements competent to impact pumping efficiency. The fact that process factor B has the highest F-Value (79.19) of the five process factors (A, B, C, D, and E) indicates that the head has the greatest influence on efficiency. On the contrary, the lowest F-Value (0.1216) for process factor E indicates that mechanical attachment has the least influence on efficiency response. The following is the order of affecting factors, from high to low: > head > discharge > bore well diameter > input power > mechanical attachments.

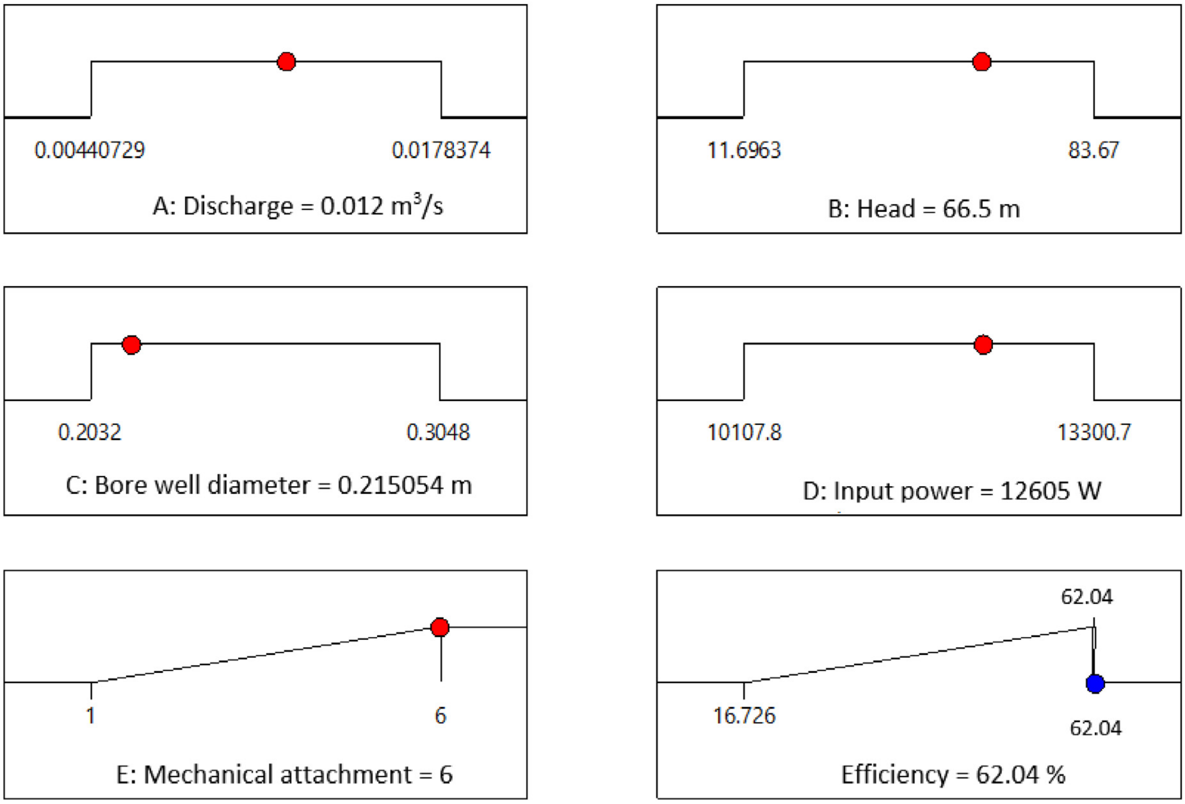


Fig. 10. The optimum process parameter with the response for pumping efficiency.

3.4.2. Optimization assessment for process variables for pumping efficiency

The optimum conditions for the dependent variable were obtained with the integration of the suggested model prediction equation based on experimental results and response analysis of the surface plot as well. The optimum process parameters with respect to the response (outcome) have been illustrated in Fig. 10. The red dots indicate the optimum values of the process factors. The utilization of 0.012 m^3/s discharge, 66.5 m pumping head at the borewell of 0.215054 m with 6 nos. types of mechanical attachment (3 bowl type attachments at a time) could provide the best value of efficiency of 62.04% when the electrical power consumption of the pump is 12,605 W. It has been observed that the efficiency increases when the discharge (A) and the head (B) increase. It is also evident from the graphical analysis, that the discharge has major effects on the efficiency, whereas the bore well diameter has less impact. Moreover, the efficiency increases when the input power value is decreased.

3.4.3. Effect of process variables on efficiency

The effect of process parameters on pumping efficiency is shown in Fig. 11. It has been found that the highest value of pumping efficiency (62.04%) was obtained for a bore well diameter of 0.215054 m, input power of 12,605 W, head of 66.5 m, discharge of 0.012 m^3/s with three bowl-type mechanical attachments at a time in front of the pump. The effect of head and discharge on pumping efficiency on the response surface, keeping the remaining parameters at their center points, is illustrated in Fig. 11(a). The maximum pumping efficiency of 62.04% can be obtained for discharge of 0.012 m^3/s and head of 66.5 m. It has been found that pumping efficiency increases with increasing discharge and head as well. The effect of head, and input power on pumping efficiency on the response surface while keeping the remaining parameters at their center points is presented in Fig. 11(b). It has been found that pumping efficiency increases with increasing head and decreasing input power as well. Moreover, On the other hand, the effect of discharge and mechanical attachment on pumping efficiency on the response surface while keeping the remaining parameters at their center points is presented in Fig. 11(c). It has been observed that pumping efficiency increases with increasing discharge and mechanical attachment types. The maximum 62.04% pumping efficiency can be obtained for discharge of 0.012 m^3/s and 6 nos. of mechanical attachment (three bowl at a time). Moreover, the effect of bore well diameter and head on pumping efficiency on the response surface, keeping the remaining parameters at their center points, is illustrated in Fig. 11(d). It is possible to obtain a maximum of 62.04% pumping efficiency for a borewell diameter of 0.215054 m and a head of 66.5 m. It has been found that efficiency decreases with increasing bore well diameter and decreasing head.

3.4.4. Mathematical modeling

The input parameters are optimized for maximum pumping efficiency using Design Expert software. The desirability function tool in Design expert software was used to forecast the optimum set of process variables within the given operating range with the goal of optimizing efficiency. The results were thoroughly examined using analysis of variance (ANOVA). The final equation in terms of actual factors is presented in Eqs. (7)–(10) for overall grand equation, for an 8-inch bore well, for a 10-inch bore well, and for a 12 inch bore well, respectively.

$$\begin{aligned}\eta_{overall} &= -7.1941 - (3944.39105 \times A) - (0.051221 \times B) + (112.3388 \times C) \\ &+ (0.009415 \times D) - (3.84126 \times E) + (93.84608 \times A \times \\ &B) + (8018.29903 \times A \times C) - (0.109811 \times A \times D) \\ &+ (134.37511 \times A \times E) + (0.921519 \times B \times C) - (0.000067 \times B \times D) + \\ &(0.028521 \times B \times E) - (0.023583 \times C \times D) \\ &+ (2.49534 \times C \times E) + (0.000035 \times D \times E)\end{aligned} \tag{7}$$

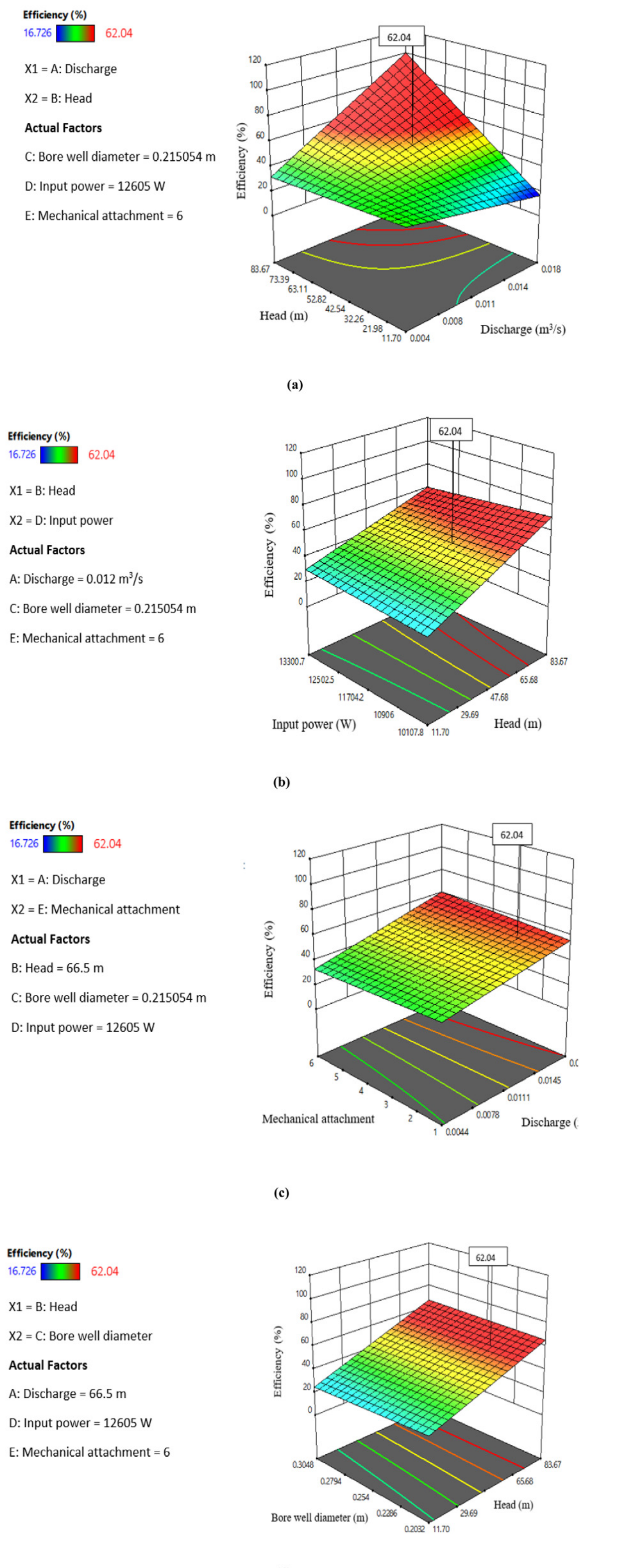


Fig. 11. Effect of process variable on efficiency with respect to (a) head and discharge, (b) input power and head, (c) mechanical attachment and discharge, (d) bore well diameter and head.

Where, A = discharge, B = head, C = bore well diameter, D = input power, E= mechanical attachment

$$\eta_{8inch} = -128.76 + (5029.34 \times A) + (1.48 \times B) + (0.018 \times C) - (3.71 \times D) + (107.02 \times A \times B) - (0.79 \times A \times C) + (150.14 \times A \times D) - (0.000194 \times B \times C) + (0.026 \times B \times D) + (0.000063 \times C \times D) \quad (8)$$

$$\eta_{10inch} = -118.42 + (6068.94 \times A) + (1.57 \times B) + (0.012 \times C) - (3.87 \times D) + (89.75 \times A \times B) - (0.63 \times A \times C) - (59.29A \times D) - (0.000156 \times B \times C) - (0.00874 \times B \times D) + (0.000425 \times C \times D) \quad (9)$$

$$\eta_{12inch} = 211.84 - (10971.78 \times A) - (1.38 \times B) - (0.0136 \times C) - (1.046 \times D) + (88.72A \times B) + (0.715 \times A \times C) - (50.91 \times A \times D) + (0.00007.12 \times B \times C) + (0.00926 \times B \times D) + (0.000141 \times C \times D) \quad (10)$$

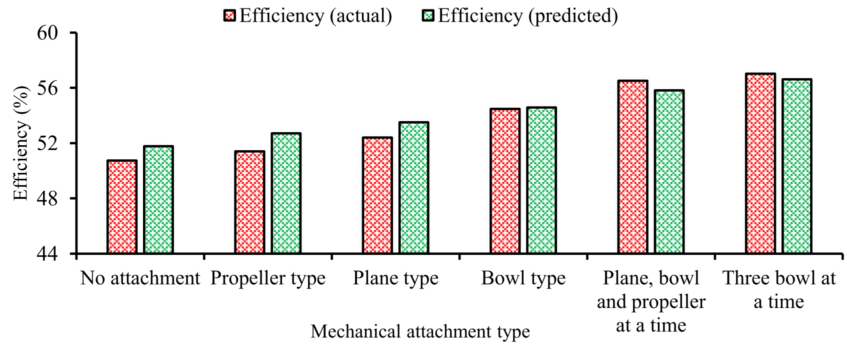
Where, A = discharge, B = head, C = input power, and D = mechanical attachment.

The graphical representation of the experimental and predicted responses is illustrated in Fig. 12 for overall grand, 8-inch, 10-inch, and 12-inch bore wells. It has been found that there are no unexpected changes occurring in the model; thus, the actual and predicted efficiency are at a satisfactory level. Moreover, the difference between actual (experimental) and predicted results is negligible. The actual values are in close agreement with the predicted ones, which indicates that the model is an effective model for estimating the response. Therefore, finally, without any hesitation, it can be said that the mathematical modeling for pumping efficiency is correct.

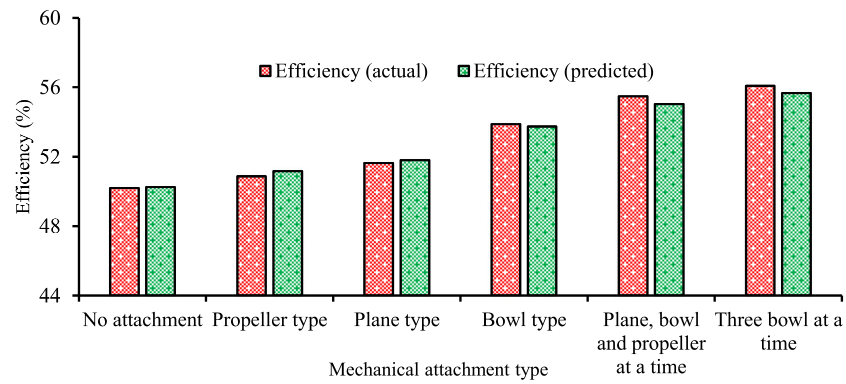
A reasonable level of correlation between the actual value and the projected response can be discovered. The model does not reveal any unexpected variation in the continuous variance. The linear model is a useful model for predicting the response of the independent variables since the actual data points closely match the predicted ones. As a result, it has been discovered that there is very little variation between actual (experimental) and expected results.

4. Conclusions and future recommendations

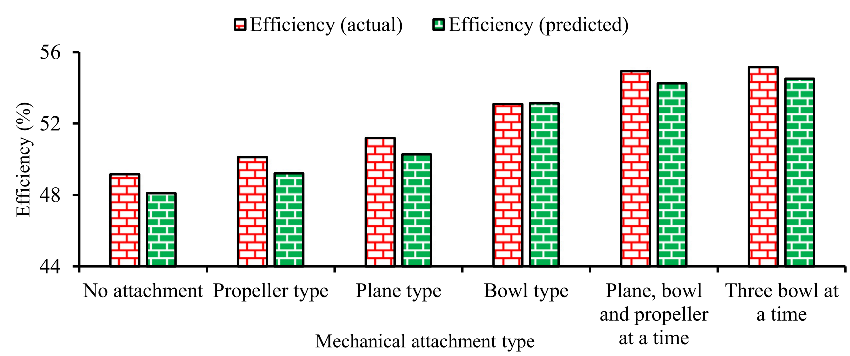
The performance of an 11-kW submersible pump was studied in 8-inch, 10-inch, and 12-inch tube well, respectively, and compared with the standard conditions results (lab test) as well as with an open pond. The different types of mechanical attachments were attached to the delivery pipe in front of the pump, and the performance of the submersible was measured. It has been found that the integration of mechanical attachments increases the efficiency of the pumping system while consuming the same amount of input power. Thus, the energy efficiency of the pumping system could be improved. It has been found that in most of places, the water level is declining day by day, and it is impossible to lift water for this region by means of centrifugal pumps. Moreover, the performance of the pump in various locations was found unsatisfactorily below standard test conditions. Thus, we have to focus on this point and come forward to solve the problem of making an energy-efficient pumping system since water is the prime requirement for various reasons. In this research work, various types of mechanical attachments were designed and fabricated, and fastened in the delivery pipe to reduce the vertical fall down of water inside the bore well, i.e., to reduce drawdown as well as pumping level, as the pump efficiency is inversely related to the drawdown as well as the pumping head. Moreover, optimization of the pump input parameter as well as mathematical modeling were performed to get maximum efficiency. Finally, an impact assessment was performed to determine its suitability for commercial applications.



(a)



(b)



(c)

Fig. 12. Comparing the actual and predicted value from multiple regression analysis for (a) 8-inch, (b) 10-inch and (c) 12-inch bore well.

After analyzing experimental data, the following conclusions are drawn:

- The integration of mechanical attachments improves the pumping efficiency of the submersible pump. The bowl-type mechanical attachment shows better performance when used in different bore wells. The efficiency of the submersible pump decreases with an increase in bore well diameter.
- It is possible to obtain 55% efficiency from a 15 HP (11 kW) submersible pump by attaching a bowl-type mechanical attachment in an 8-inch bore well that is 5% higher than using no attachment.
- It is possible to obtain 57% efficiency of a 15 HP (11 kW) submersible pump by attaching the plane, bowl, and propeller-type mechanical attachment at a time in an 8-inch bore well, that is 7% higher than using no attachment.
- It is possible to obtain 58% efficiency of a 15 HP (11 kW) submersible pump by attaching three bowl-type mechanical attachments at a time in an 8-inch bore well that is 8% higher than using no attachment.
- The optimization of the process input parameters was done and found a maximum of 62.04% efficiency when the input parameters of the process are head 66.5 m, discharge 0.012 m^3/s, input power 12,605 W, bore well diameter 0.215054 m, and three bowl type attachments at a time in front of the pump in the delivery pipe.
- The mathematical model was performed using ANOVA and found to have a very low difference between actual and predicted performance. That is the model is correct, and we can predict performance for different bore well diameters as well as for different mechanical attachments of the submersible pumping system.

- The impact of using mechanical attachment was evaluated at two pumping sites in Bangladesh and found that a huge amount of energy could be saved at a single pumping site. Therefore, its application at the commercial level at all the pumping sites could save a considerable amount of energy, which is essential for sustainable cities and societies.

Finally, the following recommendations and steps are suggested for improving Submersible pump performance:

- The operation of the submersible pump should be done as closely as possible in laboratory test conditions.
- The drawdown phenomenon of the submersible pump should be reduced as much as possible.
- The positioning of a pump in a region should be done at the required level, following the groundwater condition of that region throughout the year.

Future research may be necessary to look into the water quality at various pumping locations and how it compares to WHO and BDS standards. Future research could examine how the water's quality has improved. In addition, performance-enhancing strategies other than mechanical attachment would be investigated.

5. Nomenclature table

Symbols	Meanings
f_{ls}	The effect of screen factor.
f_m	The friction factor
f_{lb}	The factor due to bend.
f_{lf}	The flange factor.
f_{lo}	The factor at outlet of discharge pipe.
d_1	Diameter of the well (m)
d_2	Diameter of the discharge pipe (m)
g	Gravitational acceleration (m/s^2)
H_p	Pump head gain (m of water)
H_2	Pumping level (m)
h_{fm}	Major head loss due to friction in the discharge pipe (m of water)
h_{ls}	Head loss at pump inlet including the effect of the screen (m of water)
h_{lb}	Head loss at the bend (m of water)
h_{lf}	Head loss in flange joints (m of water)
h_{lo}	Head loss at the outlet of discharge pipe (m of water)
L	Length of discharge pipe (m)
n	The number of flange joints
P	Electricity Consumption (watt)
P_1	Suction pressure at datum line (m of water)
P_2	Delivery pressure in water distribution line (m of water)
Q	Discharge (m^3/hr.)
S	The specific gravity of water
V_2	The velocity of water at the delivery pipe (m/s)
ρ	The density of water (kg/m^3)
η_c	Combined Efficiency (%)

Credit authorship contribution statement

Md. Sanowar Hossain: Conceptualization, Investigation & conduction- major activities. **Mohammad Rofiqul Islam:** Review. **Arnob Das:** Writing and calculation. **Hasibul Hasan Himel:** Writing and calculation. **Barun K. Das:** Review and editing. **Tamal Krishna Roy:** Design and modeling. **Md. Sabit Hasan:** Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

See Tables A.1 and A.2.

Table A.1
Experimental design matrix and results.

Experimental run	A: Discharge (m^3/s)	B: Head (m)	C: Bore well diameter (m)	D: Input power (W)	E: Attachment type	Efficiency (%)
1	0.017	16.96	0.203	12565.2	No (1)	23.32
2	0.016	30.27	0.203	12713.3	No (1)	39.81
3	0.013	43.82	0.203	12557.9	No (1)	48.60
4	0.012	57.14	0.203	13163.4	No (1)	50.74
5	0.007	69.98	0.203	11945.8	No (1)	47.40
6	0.005	83.30	0.203	11262.1	No (1)	36.56
7	0.017	16.82	0.203	12117.0	Propeller (2)	22.88
8	0.016	30.45	0.203	12409.8	Propeller (2)	38.12
9	0.014	43.63	0.203	12718.8	Propeller (2)	49.38
10	0.012	56.90	0.203	12913.5	Propeller (2)	51.40
11	0.008	69.80	0.203	11497.5	Propeller (2)	46.86
12	0.005	83.14	0.203	10780.2	Propeller (2)	36.66
13	0.017	16.84	0.203	12377.6	Plane (3)	24.50
14	0.016	30.43	0.203	12628.2	Plane (3)	39.88
15	0.014	43.65	0.203	12765.4	Plane (3)	50.79
16	0.012	56.93	0.203	12753.0	Plane (3)	52.40
17	0.007	69.61	0.203	11643.0	Plane (3)	49.04
18	0.005	83.13	0.203	10988.9	Plane (3)	37.30

(continued on next page)

Table A.1 (*continued*).

Experimental run	A: Discharge (m^3/s)	B: Head (m)	C: Bore well diameter (m)	D: Input power (W)	E: Attachment type	Efficiency (%)
19	0.017	16.89	0.203	11867.1	Bowl (4)	23.81
20	0.016	30.50	0.203	12315.7	Bowl (4)	38.85
21	0.014	43.89	0.203	13110.6	Bowl (4)	49.15
22	0.012	57.07	0.203	12764.1	Bowl (4)	54.47
23	0.008	69.83	0.203	11679.7	Bowl (4)	48.44
24	0.005	83.15	0.203	10804.7	Bowl (4)	38.15
25	0.017	16.94	0.203	12380.6	Plane, Bowl and Propeller (5)	23.99
26	0.016	30.48	0.203	12496.5	Plane, Bowl and Propeller (5)	38.94
27	0.014	43.95	0.203	12631.0	Plane, Bowl and Propeller (5)	49.38
28	0.012	57.19	0.203	12581.8	Plane, Bowl and Propeller (5)	56.51
29	0.008	70.01	0.203	11807.4	Plane, Bowl and Propeller (5)	48.84
30	0.005	83.34	0.203	10872.1	Plane, Bowl and Propeller (5)	38.14
31	0.017	11.70	0.203	11579.4	Three bowl (6)	17.29
32	0.017	25.55	0.203	12332.3	Three bowl (6)	34.67
33	0.015	39.00	0.203	12824.7	Three bowl (6)	46.74
34	0.013	52.33	0.203	12957.5	Three bowl (6)	54.31
35	0.011	65.51	0.203	12601.2	Three bowl (6)	58.02
36	0.007	78.28	0.203	11048.9	Three bowl (6)	46.27
37	0.017	17.09	0.254	12214.1	No (1)	23.32
38	0.016	30.79	0.254	12550.2	No (1)	38.73
39	0.014	43.74	0.254	12667.7	No (1)	46.84
40	0.012	57.02	0.254	12893.2	No (1)	50.20
41	0.007	69.85	0.254	11400.3	No (1)	45.10
42	0.004	83.67	0.254	10700.1	No (1)	34.91
43	0.017	17.23	0.254	12367.7	Propeller (2)	23.76
44	0.016	30.82	0.254	12786.1	Propeller (2)	38.28
45	0.014	44.11	0.254	12596.5	Propeller (2)	48.32
46	0.012	57.24	0.254	12720.4	Propeller (2)	50.87
47	0.008	70.13	0.254	11516.1	Propeller (2)	45.14
48	0.005	83.56	0.254	10983.6	Propeller (2)	37.04
49	0.018	17.37	0.254	12385.2	Plane (3)	23.89
50	0.016	30.83	0.254	12859.0	Plane (3)	38.27
51	0.014	44.11	0.254	13300.7	Plane (3)	47.63
52	0.012	57.47	0.254	13294.2	Plane (3)	51.63
53	0.008	70.29	0.254	12027.5	Plane (3)	44.96
54	0.005	83.62	0.254	11039.5	Plane (3)	36.62
55	0.018	17.24	0.254	12100.0	Bowl (4)	24.17
56	0.017	30.90	0.254	12871.4	Bowl (4)	39.82
57	0.014	44.16	0.254	12857.8	Bowl (4)	48.29
58	0.012	57.37	0.254	12755.1	Bowl (4)	53.88
59	0.007	70.10	0.254	11482.4	Bowl (4)	45.49
60	0.005	83.55	0.254	10715.3	Bowl (4)	35.64
61	0.017	16.77	0.254	12002.2	Plane, Bowl and Propeller (5)	23.88
62	0.017	30.49	0.254	12095.1	Plane, Bowl and Propeller (5)	39.47
63	0.015	43.79	0.254	12246.4	Plane, Bowl and Propeller (5)	49.73
64	0.012	57.08	0.254	12545.6	Plane, Bowl and Propeller (5)	55.47
65	0.008	69.81	0.254	11134.4	Plane, Bowl and Propeller (5)	48.01
66	0.005	83.14	0.254	10366.4	Plane, Bowl and Propeller (5)	35.47
67	0.017	11.70	0.254	11579.3	Three bowl (6)	17.01
68	0.017	25.55	0.254	12332.3	Three bowl (6)	34.10
69	0.015	39.00	0.254	12824.6	Three bowl (6)	45.97
70	0.013	52.33	0.254	12957.4	Three bowl (6)	53.42
71	0.011	65.51	0.254	12601.2	Three bowl (6)	56.08
72	0.007	78.28	0.254	11049.0	Three bowl (6)	45.51
73	0.017	16.85	0.305	12353.6	No (1)	23.00
74	0.017	30.74	0.305	12282.1	No (1)	38.15
75	0.015	44.06	0.305	12802.1	No (1)	45.20
76	0.012	57.14	0.305	12850.4	No (1)	49.16
77	0.008	70.14	0.305	11557.5	No (1)	41.46
78	0.005	83.63	0.305	10401.0	No (1)	34.97
79	0.016	16.78	0.305	12053.4	Propeller (2)	23.37
80	0.016	30.61	0.305	12346.7	Propeller (2)	38.35
81	0.014	44.10	0.305	12383.0	Propeller (2)	47.41
82	0.012	57.21	0.305	12756.3	Propeller (2)	50.11
83	0.007	69.93	0.305	10921.6	Propeller (2)	45.69
84	0.005	83.65	0.305	10163.0	Propeller (2)	36.97
85	0.017	17.06	0.305	11987.6	Plane (3)	23.00
86	0.016	30.69	0.305	12246.3	Plane (3)	37.81
87	0.015	44.08	0.305	12287.3	Plane (3)	46.35
88	0.012	57.25	0.305	12674.7	Plane (3)	51.20
89	0.008	70.16	0.305	11133.1	Plane (3)	44.09
90	0.005	83.62	0.305	10107.8	Plane (3)	37.01
91	0.017	17.04	0.305	11955.1	Bowl (4)	23.88
92	0.016	30.71	0.305	12462.7	Bowl (4)	38.35
93	0.015	44.19	0.305	12823.0	Bowl (4)	47.29
94	0.012	57.54	0.305	12867.4	Bowl (4)	53.10

(*continued on next page*)

Table A.1 (*continued*).

Experimental run	A: Discharge (m^3/s)	B: Head (m)	C: Bore well diameter (m)	D: Input power (W)	E: Attachment type	Efficiency (%)
95	0.008	70.36	0.305	11908.8	Bowl (4)	46.21
96	0.005	83.56	0.305	10756.0	Bowl (4)	37.72
97	0.017	16.92	0.305	11776.3	Plane, bowl and propeller (5)	23.36
98	0.016	30.58	0.305	12332.0	Plane, bowl and propeller (5)	38.03
99	0.014	44.02	0.305	12429.8	Plane, bowl and propeller (5)	48.41
100	0.013	57.44	0.305	12697.1	Plane, bowl and propeller (5)	54.93
101	0.008	70.21	0.305	11535.6	Plane, bowl and propeller (5)	48.29
102	0.005	83.48	0.305	10589.7	Plane, bowl and propeller (5)	39.65
103	0.017	11.70	0.305	11579.3	Three bowl (6)	16.73
104	0.017	25.55	0.305	12332.2	Three bowl (6)	33.54
105	0.015	39.00	0.305	12824.6	Three bowl (6)	45.21
106	0.013	52.33	0.305	12957.4	Three bowl (6)	52.54
107	0.011	65.51	0.305	12601.3	Three bowl (6)	55.16
108	0.007	78.28	0.305	11049.0	Three bowl (6)	44.76

Table A.2
Uncertainty analysis of the measuring devices.

Parameters	Unit	Uncertainty comments
Current	A	±0.44
Voltage	V	±0.20
Power factor	–	±0.35
Time	Sec	±0.26
Volume	m^3	±0.04
Water level	m	±0.36
Pressure	Pa	±0.46
Power	W	±0.27

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